Technology, Implementation and Operation of Small-Scale Sanitation in India

Performance Analysis and Policy Recommendations

Small-Scale Sanitation Scaling-Up (4S) – Project Report Vol. I

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ABOUT THE 4S PROJECT

The project *Small-Scale Sanitation Scaling-Up* (4S) is the first holistic assessment of small-scale sanitation systems in South Asia. The research project was carried out from 2016 to 2018 with the aim to develop evidence-based policy recommendations for the successful implementation of small-scale wastewater treatment and reuse systems at scale. This was achieved based on the technical field evaluation of more than 300 sanitation units, as well as an in-depth governance and financial analysis. 4S was implemented under the auspices of the Indian Ministry of Housing and Urban Affairs by the Swiss Federal Institute of Aquatic Science and Technology (Eawag), the Indian Institute of Technology Madras, BORDA (Germany), CDD Society (India), ENPHO (Nepal) and other partners.

What is Small-Scale Sanitation (SSS)?

A SSS system refers to a **sanitation system that collects and treats sewage at or near its point of generation, using a small-scale sewerage network and a small-scale sewage treatment plant** (SSTP). A complete SSS system also includes a **solution (on-site or off-site) for managing the sludge** generated at the SSTP. SSS systems are sometimes also known as decentralised or distributed sanitation systems. Depending on the context, a SSS system can be designed to enable local water reuse, as well as energy and/or nutrient recovery (see Figure 1). In 4S, a SSS system is defined as one that serves **10-1'000 households (or 50-5'000 person equivalents, i.e. treating about 5-700 KLD [=m^3/day] of wastewater)**. SSS systems can be installed for clusters of buildings or for individual buildings, as well as for special applications such as public toilets.

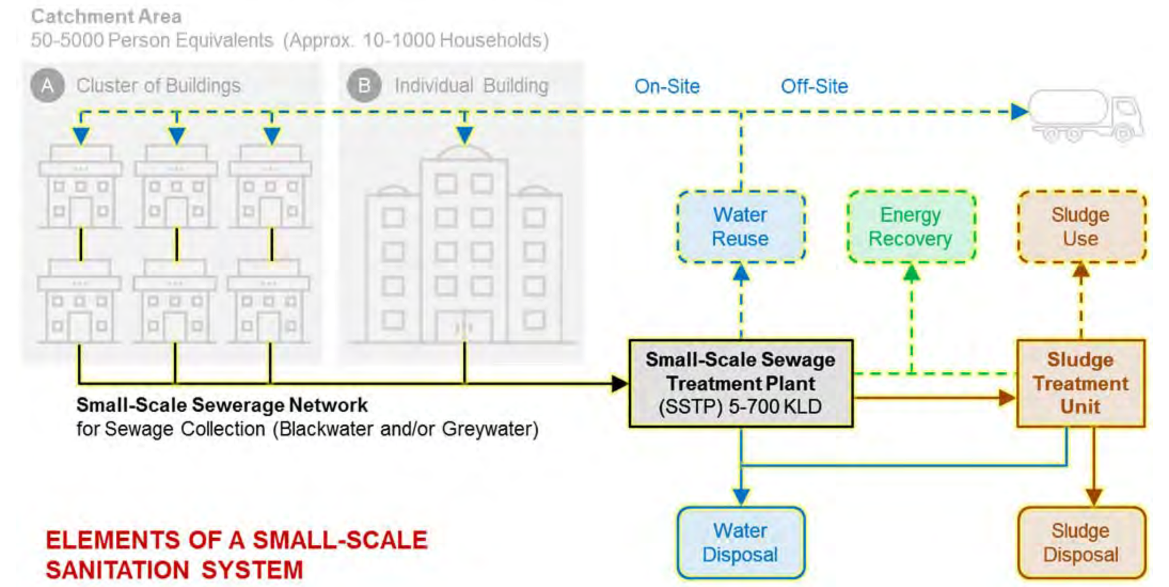


Figure 1: A SSS system is a sewer-based sanitation system that uses a small-scale sewage treatment plant inside or near the catchment area, and that can be designed for water reuse, as well as energy and/or nutrient recovery.

Why this Project? In increasingly urbanised South Asia, conventional approaches to water supply and sewerage are reaching their limits, manifested by water scarcity and slow progress of wastewater infrastructure provision. At the same time, the number of SSTPs is increasing rapidly, and water reuse becomes more and more important, especially in India. However, **there is currently a limited understanding of i) the specific role that SSS systems should best play in the future, ii) how good performance and cost-effectiveness can be ensured, and iii) how the ever-growing number of systems can be optimally regulated and managed.**

4S aims to establish the current status of SSS, and what is needed for it to fulfil its potential for healthy and water-secure cities. By learning from the current challenges and opportunities, 4S aims to help develop a roadmap towards an enabling environment for successful and thriving SSS at scale.

The 4S Approach

4S aims to look at SSS in a holistic way, by integrating a mixed-method approach that combines sanitation system assessments on the ground with analyses at the governance level (see Figure 2). Thereby, the study considers all components that are needed for sanitation systems to achieve the desired performance:

- ✓ An enabling environment (see the six elements in Figure 2)
- ✓ The design and implementation as well as operation and maintenance (O&M) phases of a sanitation project
- ✓ Adequate technology and management schemes
- ✓ The planning, monitoring and evaluation cycle

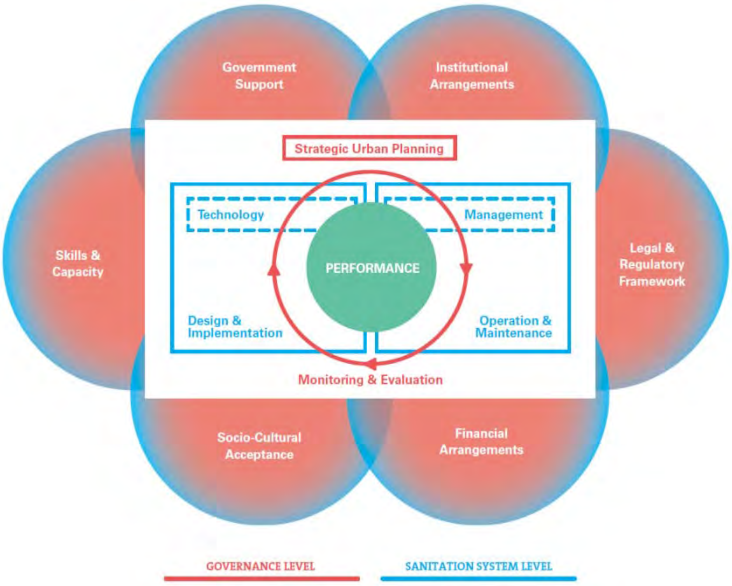


Figure 2: Visualisation of the 4S analysis framework. It builds on the six elements of an enabling environment (Lüthi et al., 2011) and takes into account factors at the sanitation system level (blue) as well as at the governance level (red). Sanitation system performance (in the centre of the figure) can get affected by any of the depicted elements.

The 4S Project includes the following study components:

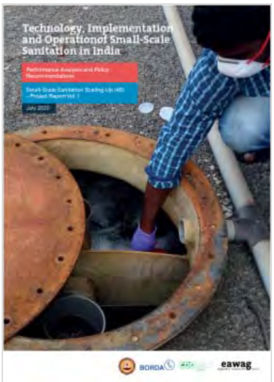
I. **Technology, Implementation and Operation**:
   A. Desk-based **landscape study** of SSS in India, Nepal, Pakistan and Bangladesh
   B. **Basic assessment** of 279 systems in India and 30 in Nepal: site inspection and stakeholder interviews
   C. **In-depth performance analysis** of 35 systems in India and 5 in Nepal: sampling campaigns

II. **Governance**: policy, institutional and stakeholder analysis

III. **Financial Sustainability**: financial analysis and study of life cycle cost

4S Publications

This report is one of four main publications from the 4S Project. All documents can be downloaded from www.sandec.ch/4S.



Vol. I: Technology, Implementation and Operation of Small-Scale Sanitation in India – Performance Analysis and Policy Recommendations

Vol. II: Governance of Small-Scale Sanitation in India – Institutional Analysis and Policy Recommendations

Vol. III: Financial Sustainability of Small-Scale Sanitation in India – Life Cycle Cost Analysis and Policy Recommendations

Synthesis Report: A Roadmap for Small-Scale Sanitation in India: Fulfilling its Potential for Healthy and Water-Secure Cities

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Abbreviations and Acronyms

ABR	Anaerobic Baffled Reactor
ACF	Activated Carbon Filter
AF	Anaerobic Filter
AN	Ammoniacal Nitrogen
AOP	Advanced Oxidation Process
ASP	Activated Sludge Process. In this report the abbreviation ASP generally refers to the *conventional* activated sludge process (see Table 8). Please note that in the sampling results ASP as part of the sample ID also includes other members of the technology family “Activated Sludge (Suspended Growth) Processes” (see Table 1).
BGS	Biogas Settler
BOD	Biochemical Oxygen Demand
CAACO	Chemo-Autotrophic Activated Carbon Oxidation
CAMUS-SBT	(Continuous Advanced Multistage System using) Soil Biotechnology
CBO	Community-Based Organisation
CL	Chlorination
COD	Chemical Oxygen Demand
Com	Commercial
CPCB	Central Pollution Control Board
CSF	Critical Success Factor
DEWATS	Decentralised Wastewater Treatment System
DO	Dissolved Oxygen
DRDO	Defence Research and Development Organisation
DTS	Decentralised Treatment System
EA	Extended Aeration
EADOx	Electrolytically Activated Degenerative Oxidation
EC	Electrocoagulation
FC	Faecal Coliforms
FICCO	Fluidized Immobilized Catalytic Carbon Oxidation
HFCW	Horizontal-Flow Constructed Wetland
HRAR	High-Rate Anaerobic Reactors
Inst	Institutional
KLD	Kilolitres per Day [= m^3/day]
KSPCB	Karnataka State Pollution Control Board
Low-Res	Low-Income Residential
NA	Not Available
NAP	Not Applicable
NGO	Non-Governmental Organisation
MBBR	Moving Bed Biofilm Reactor. *Syn.:* Fluidised Aerobic Bioreactor (FAB), Fluidised Bed Bio Reactor (FBBR)
MBR	Membrane Bioreactor
MLD	Million Litres per Day [= 1’000 m^3/day]
MLSS	Mixed Liquor Suspended Solids

MoEFCC	Ministry of Environment, Forests and Climate Change
MPN	Most Probable Number
Mun	Municipal
OD	Oxidation Ditch
O&G	Oil and Grease
O&M	Operation and Maintenance
OOB	Out-Of-Bag. The OOB error is a measurement for the prediction error of the Random Forest model.
PCB	Pollution Control Board
PGF	Planted Gravel Filter
PO	Performance Objective
PP	Polishing Pond
PSF	Pressure Sand Filter
PST	Primary Sedimentation Tank
PT	Public Toilet
RBC	Rotating Biological Contactor
Res	Middle- or High-Income Residential
RF	Random Forest
RO	Reverse Osmosis
RTI	Right to Information
SAFF	Submerged Aerated/Aerobic Fixed Film Reactor
SBR	Sequencing Batch Reactor
SBT	Soil Biotechnology, see CAMUS-SBT
sCOD	Soluble part of the Chemical Oxygen Demand
SDG	Sustainable Development Goal
SEP	Solar Evaporation Ponds
SIBF	Solid Immobilised Bio-Filter
SPISF	Single Pass Intermittent Sand Filter
SSS	Small-Scale Sanitation
SST	Secondary Sedimentation Tank
SSTP	Small-Scale Sewage Treatment Plant
STP	Sewage Treatment Plant
T	Temperature
tCOD	Total Chemical Oxygen Demand
TF	Trickling Filter
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
UASB	Upflow Anaerobic Sludge Blanket
UF	Ultrafiltration
UV	Ultraviolet
VFCW	Vertical-Flow Constructed Wetland
WASH	Water, Sanitation and Hygiene
WSP	Waste Stabilisation Ponds

Executive Summary

Introduction – In addition to underground drainage and large-scale sewage treatment plants (STPs) and the management of faecal sludge and septage from non-sewered on-site systems, small-scale sanitation (SSS) systems are becoming more and more important. Such systems consist of small-scale sewerage networks and STPs and can be implemented incrementally and flexibly. They offer significant potential for cost-effective local wastewater treatment and reuse. SSS systems, therefore, have a key role to play in increasingly water-stressed urban India.

The establishment of a policy to promote small sewage treatment plants (SSTPs) in India in 2006 has led to a remarkable growth in the number of installations in the country's rapidly expanding urban areas, especially in big cities. However, many of these existing systems are underperforming or have failed.

Until today, SSS sector developments in India have not been informed by a holistic, in-depth assessment of lessons learned, and there has been very little research on the enabling conditions for the successful long-term operation and management of SSS systems at scale. The main goal of the "Technology, Implementation and Operation" component of the 4S Project is to evaluate the SSS systems and develop evidence-based policy recommendations for their successful design, implementation, operation and maintenance at scale.

Methods – The 4S Project compiled and analysed information on SSS from the broader sector level down to the specifics of individual installations. The study approach of this performance analysis consisted of three main data collection steps:

1) A landscape study: a desk-based study of the SSS landscape in India
2) A basic assessment of SSS systems: a qualitative evaluation of 279 SSS systems in India with site inspections and stakeholder interviews
3) An in-depth performance analysis: three rounds of 24 h wastewater sampling at 40 systems, representing all main SSS technologies

The data was analysed with the objective to understand the necessary requirements for the long-term successful performance of SSS systems, and the main causes of failure. The development of a cause – effect framework was part of this analysis.

Key Results and Conclusions –

- **Findings – landscape study**
  - There is no systematic documentation of SSS systems in India's states and cities, and government databases are patchy. It is estimated that more than 20'000 SSTPs exist in India. In Bangalore, an estimated 10-20% of the wastewater is treated by such systems.
  - A wide range of treatment technologies is used. The activated sludge process (including extended aeration), sequencing batch reactors and moving bed biofilm reactors are most prevalent.
- **Findings – performance analysis**
  - SSS systems are exposed generally to higher feed fluctuations than larger systems; they often treat more concentrated wastewater, especially in low-income communities and from public toilets. This can lead to higher effluent concentrations than in large systems (even if the removal rate is the same).
  - A majority of the systems analysed achieved removal rates of about 90% for biochemical oxygen demand (BOD), chemical oxygen demand (COD) and total suspended solids (TSS). Most technologies can achieve removal rates of about 95% for BOD, 90% for total COD and 95% for TSS. The results indicate that any of the technologies studied (if combined with the right post-treatment units and operated correctly) have the potential to achieve quite stringent BOD, COD and TSS standards.

  - The results for ammoniacal (AN) and total nitrogen (TN) show lower removal and higher variability than the removal rates for organics and suspended solids. None of the investigated systems was designed with a denitrification step, with the consequence that TN standards are almost never met. High TN concentrations are generally linked to high effluent AN concentrations.
  - The faecal coliform standard is consistently not met by all of the assessed treatment plants. Systems with disinfection steps (chlorination in most cases) do not ensure a better microbial removal rate and effluent quality than systems that do not disinfect.
- **Findings – cause-effect analysis**
  - 14 so-called critical success factors for SSS systems were identified through literature review and expert consultation: quality of design, quality of implementation, system startup and handover, skills of personnel, motivation of personnel, accessibility of maintenance services, availability of energy and chemicals, skills of management entity, supervision of O&M activities, human resources management, documentation, user behaviour, user satisfaction and O&M cost recovery.
  - Systems implemented in low-income residential settlements and public toilets are a lot more sensitive and score poorly for many of the success factors.
  - Besides the treated water quality, adequate loading, resource recovery and solids management are important indicators of a fully functional SSS system. The consideration of these performance objectives can be useful for a holistic perspective of performance.
  - Given the data, models and methods used, it was not possible to correlate statistically the fulfilment of critical success factors with the fulfilment of performance objectives. While this highlights the complexity of the cause-effect relationships, it is likely that the non-fulfilment of certain factors does not lead to immediate poor performance, but that this can occur over a period of time.
- **Key challenges – planning, design and implementation**
  - There is a lack of guidance material for SSS technology choices. Today, technology selection typically takes place based on the experience and preference of consultants. This may result in solutions being implemented that are not optimal for the local context.
  - The crucial system startup and handover phase in which ownership and/or responsibility are transferred from the designer/builder to the management entity is frequently neglected.
  - Systems are often underloaded during the first years of operation, leading to performance issues, high per capita operating costs and possibly late discovery of underdimensioned systems.
  - Water reuse for toilet flushing and irrigation is well implemented, but 100% on-site water reuse is difficult. Options for off-site reuse are limited.
  - Sludge management is a major issue. Due to the lack of alternatives, untreated sludge is commonly disposed of in uncontrolled ways, posing potential high public health and environmental risks.
- **Key challenges – operation, maintenance and management**
  - At least 40% of the systems are intermittently run to reduce cost and noise nuisances; this can affect the biological treatment process.
  - O&M personnel and management entities are often not sufficiently informed about the functioning of SSS systems and the requirements for good performance, and operators are often not clearly instructed and supervised.
  - Poor documentation of O&M activities and financial flows is very common.
  - Clear responsibility for organising spare parts, as well as for planning and budgeting scheduled maintenance services, is frequently lacking.
- **Conclusion** – Having been a relatively unmanaged process until now, it is evident that there are major challenges to the scale-up of SSS. Taking control of the process and implementing targeted measures both at the sanitation system level and at the governance level can lead to tremendous

benefits in terms of public health, environmental protection and water reuse. The findings of the 4S Project confirm that there is enormous opportunity for SSS in the Indian water and wastewater sectors.

Key Recommendations – Targeted measures have the potential to improve the current sustainability and performance issues of SSS systems. The following table summarises the key sanitation system level and governance level measures proposed based on the findings.

	Sanitation System Level Measures	Governance Level Measures
Planning, Design and Implementation	☞ Consider life cycle cost in technology choice ☞ Consider contextual factors in design decisions ☞ Ensure correct design of disinfection units ☞ Promote more automation ☞ Implement modular and standardised designs ☞ Implement appropriate on-site sludge management equipment ☞ Provide user-friendly handbooks	☞ Licence vendors ☞ Prepare informed choice materials and design guides ☞ Create incentives for sustainable SSS systems ☞ Standardise procedure for approval of technology choice and design ☞ Standardise procedure for handover of plants ☞ Plan & implement semi-centralised sludge management facilities
Operation and Maintenance	☞ Train operators ☞ Ensure correct operation of disinfection units	☞ Create mandatory operator training programs ☞ License operators
Management and Monitoring	☞ Train managers ☞ Provide backstopping engineer for each system ☞ Establish performance-based contracts between owners and operators	☞ Adapt water quality standards for SSS systems ☞ Create online database for SSS system management ☞ Support development of centralised management structures ☞ Develop market for treated water ☞ Develop holistic and problem-oriented monitoring approach ☞ Make documentation of O&M activities and financial details mandatory ☞ Create and incentivise manager training programs

Limitations of the study – Getting access to systems for data collection was a major challenge, as study participation was voluntary. Accordingly, it has to be assumed that access was higher to well-functioning systems than poorly functioning ones and that the dataset holds a bias towards the good examples. On the other hand, the advantage of voluntary study participation is that interview answers are likely to be more authentic and honest. Performance data is based on three rounds of 24 h sampling only and may not be able to account for all possible variations. For logistical reasons, most field data was collected in southern India. The data collected is, therefore, not fully representative for the entire country. More balanced and more long-term data would provide further insights, for example to better understand and measure the influence of the factors influencing successful performance. An institutionalised monitoring database would be a good starting point for a continuous analysis, learning and optimisation process.

1 Introduction

1.1 Small-scale sanitation – an increasingly relevant alternative to conventional urban wastewater management

In 1992, the Indian Ministry of Environment and Forests stated: 'For a country like India, conventional [wastewater] treatment plants are costly. In fact, these are beyond the financial means of many small towns' (MoEF, 1992). That is still true today. Alternative sanitation systems are needed to achieve city-wide sanitation, and for accelerating progress towards the ambitious Sustainable Development Goal 6.3 target of halving the proportion of untreated wastewater by 2030 (Andersson et al., 2018).

In addition to underground drainage and large-scale sewage treatment plants (STPs) and the management of faecal sludge and septage from non-sewered on-site systems, small-scale sanitation (SSS) systems are becoming increasingly important. Such systems consist of small-scale sewerage networks and STPs, allowing for incremental, modular and flexible implementation. Therefore, they have significant potential for cost-effective local wastewater treatment and reuse. In order to improve public health, relieve water stress and protect the environment in urban India, SSS systems have a key role to play.

In the past two decades SSS systems have proven to be a viable alternative to conventional large-scale centralised systems (Gikas and Tchobanoglous, 2009; Larsen et al., 2016, 2013; Newman, 2001; Parkinson and Tayler, 2003; Singh et al., 2015; van de Meene et al., 2011; Wilderer and Schreff, 2000), and thus have gained more attention. Since a policy drive for small sewage treatment plants (SSTPs) in India beginning in 2006 (see 4S Project Report Vol. II on governance (Chandragiri et al., 2020)), there has been a remarkable growth in the number of installations in the country's rapidly expanding urban areas, especially in big cities. However, it is known that many of the existing systems are underperforming or have failed for various reasons.

1.2 Making small-scale sanitation technology work

At a time where the number of small STPs is growing rapidly in India, it is crucial to understand to what extent the requirements are met and whether the related policies have translated into functioning systems on the ground. Thus far, SSS sector developments in India have not been informed by a holistic, in-depth assessment of lessons learned, and there has been very little research on the enabling conditions and implications for the successful long-term operation and management of SSS systems at scale.

This report analyses existing SSS systems and what is needed to ensure good performance. It deals with the technology used for SSS and aspects related to its successful implementation and operation. In order for an SSS system to achieve its desired performance, it is important to consider

- ✓ the correct design and implementation, including the choice of appropriate technology and
- ✓ the correct operation and maintenance (O&M), including the necessary management structures.

This, in turn, also requires an enabling environment, particularly

- ✓ sufficient skills and capacity of all stakeholders involved,
- ✓ social acceptance of the system, and
- ✓ financial arrangements to cover the life cycle cost.

As all these aspects are relevant for making SSS systems work on the ground, they are included in this performance analysis (see Figure 3).

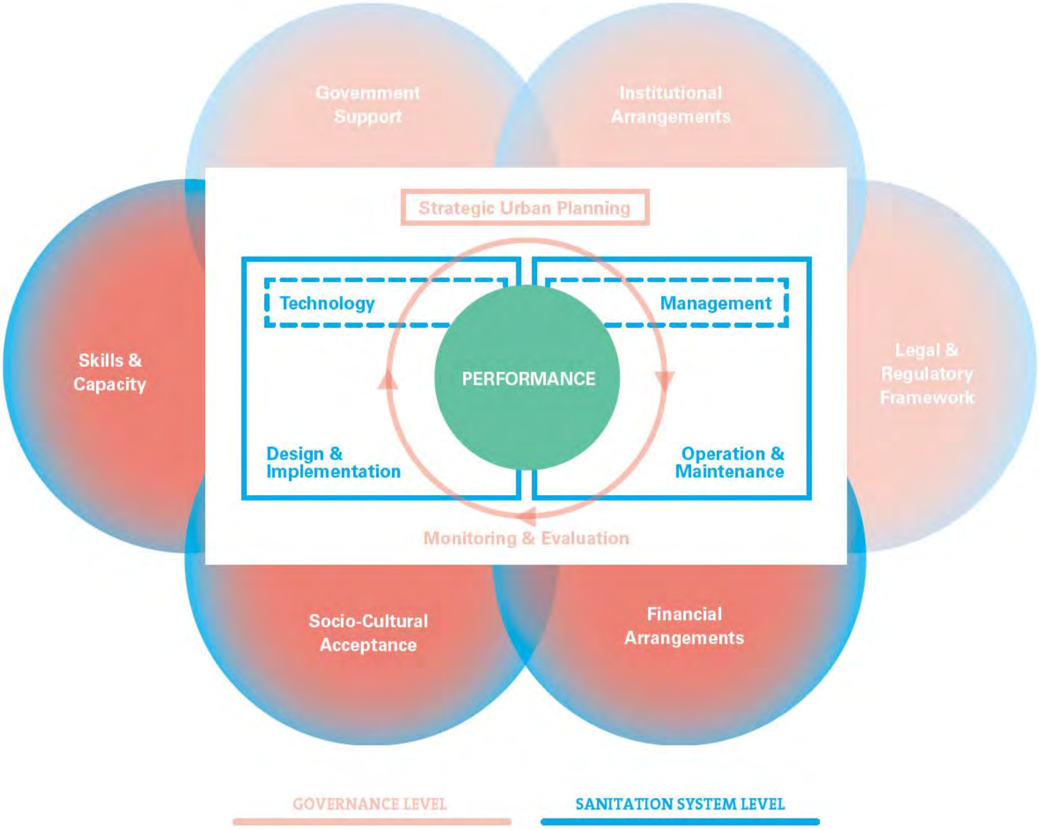

Figure 3: Visualisation of the 4S analysis framework (see Figure 2 for a detailed explanation). It builds on the six elements of an enabling environment (Lüthi et al., 2011). This technical analysis studies the aspects that are accentuated in the figure, focusing on performance at the sanitation system level.

1.3 Purpose and objectives of this performance analysis

The main goal of the "Technology, Implementation and Operation" component of the 4S Project is to evaluate present experience with SSS systems and to develop evidence-based policy recommendations for their successful design, implementation, operation and maintenance at scale. This will allow

- design and implementation stakeholders to realise sustainable systems,
- sanitation system owners, managers and operators to take the right decisions to achieve long-term performance of their assets, and
- decision-makers to advance SSS and to accelerate the provision of city-wide collection, treatment and reuse services for used water and sludge.

The **specific objectives** of the analyses documented in this report are

1. to review the current SSS landscape and status of knowledge in India,
2. to get an in-depth understanding of the performance of existing small-scale sanitation systems of various technologies and in various application contexts,
3. to investigate the conditions for sustainable SSS system performance, how well they are fulfilled, and what the main challenges are,
4. to develop a cause-effect framework for the success and failure of SSS systems, and
5. to translate the results into recommendations for different stakeholders operating at the sanitation system level and at the governance level (see Figure 2).

This report aims to answer the following **research questions**:

1. What does the current SSS landscape in India look like (in terms of numbers and geographical distribution of systems, technologies used, capacities, contexts of application, private sector stakeholders, management models, knowledge gaps etc.)?
2. What is the technical performance of various types of existing SSS systems, and what quality of the treated wastewater can be expected?
3. What are the main challenges and success factors of SSS systems (including enabling environments, management, organisational, financial and technical factors)?

Figure 4: Successful organisation of ice for the preservation of wastewater samples during their transport to the laboratory (Photo: Sunil Kumar).

2 Methods

In order to answer the various research questions, the 4S Project compiled and analysed information on SSS from the broader sector level down to specifics of individual installations. The study approach included several levels of analysis, following three main steps of data collection:

i) **Landscape study: desk-based study of the SSS landscape in India (see section 2.1)**
Collation of information on the current status of the SSS sector, including the compilation of lists of existing SSS systems and private sector service providers.

ii) **Basic assessment of SSS systems: site inspection and stakeholder interviews (see section 2.2)**
Visit of 279 existing sanitation systems in India (plus 30 in Nepal[1]) with fully structured stakeholder questionnaires and an inspection checklist.

iii) **In-depth performance analysis: sampling campaigns (see section 2.3)**
Detailed performance assessment of 40 selected systems (35 in India and 5 in Nepal[2]) across all common technologies, with analyses of the relevant biochemical and microbial parameters.

Using the data collected, a cause-effect framework is elaborated with the objective to better understand the conditions needed for long-term performance of SSS systems, and the main causes of failure (see section 2.4). The cause-effect analysis aims at disentangling the relationship between performance and the numerous factors that influence it.

2.1 Landscape study: desk-based study of the SSS landscape in India

Brief Methodology

- Thorough desk-based review of information on the SSS sector in India
- Compilation of a list of SSS systems in India from various sources
- Compilation of a list of private companies in the SSS sector

2.1.1 Desk-based review of information on the SSS sector in India

The desk-based landscape study mainly tried to gather information on the past and presence of small-scale sanitation in India. This included the review of academic studies, policy documents, newspaper articles and other grey literature to understand the current status of knowledge and challenges facing the sector.

2.1.2 Compilation of a list of SSS systems in India

To get an overview of the SSS systems and technologies used, their numbers and geographical distribution, treatment capacities and contexts of application, a list of SSS systems was compiled.

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[1] The basic assessment dataset from Nepal is not used in the India-specific analyses of this report (section 3.2). However, it is used for the more generic analysis of the conditions for system performance (section 3.4), in order to have a larger dataset.

[2] The performance data from Nepal is included in this report in order to have an increased sample size and to allow for comparison of the results.

Due to the lack of comprehensive official databases, systems were inventorised and consolidated from various scattered sources:

- Existing lists from project partners (compiled in previous projects)
- State Pollution Control Boards (the Pollution Control Boards of ten states with an expected large numbers of SSS systems were approached with a so-called “Right to Information” (RTI) petition[3])
- Government websites (including the websites of Pollution Control Boards and State Environmental Impact Assessment Authorities which publish incomprehensive databases)
- Private players who design and implement SSS systems (through personal contacts and information retrieved from their websites)
- 4S field work (some of the interviewed SSTP operators and managers were aware of / involved in further SSS systems)
- A call for information on the SuSanA forum and in Indian sanitation networks and mailing lists
- Other public sources and grey literature

2.1.3 Compilation of a list of private companies in the SSS sector

To understand the private sector’s role and involvement in SSS, a list of private players was compiled. The information gathered includes the technologies implemented and services provided by the different companies. Private players were identified through personal contacts of project partners and extensive web research (private company websites, company indexes as indiamart.com, etc.).

2.2 Basic assessment of SSS systems: site inspection and stakeholder interviews

Brief Methodology

- Qualitative evaluation of 279 SSS systems in India, covering a wide range of treatment technologies, capacities, ages and application contexts
- Data collection through fully structured interviews with managers, operators and users as well as with inspection checklists
- Topics assessed: (i) Planning, design and implementation, (ii) Management arrangements, (iii) Operation and maintenance, (iv) Technical performance, (v) Condition of plant infrastructure, (vi) Socio-cultural aspects, (vii) Financial aspects
- Validation and pre-processing of collected data in preparation for analysis

2.2.1 Structuring of questionnaires and inspection checklist

Existing questionnaires from the project partners served as a starting point for the 4S questionnaires. 4S-specific research questions were translated into specific priority indicators and questionnaire questions covering seven thematic areas:

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[3] https://rti.gov.in/

1. Planning, design and implementation
2. Management arrangements
3. Operation and maintenance
4. Technical performance
5. Condition of plant infrastructure
6. Socio-cultural aspects
7. Financial aspects

Three different fully structured questionnaires were designed for different stakeholders involved with SSS systems, namely managers/owners, operators and users of SSS systems. The user questionnaire was only applicable for systems in the residential context, as the users of commercial or institutional treatment systems usually don't know about the system's existence, or are only temporary users without sufficient experience. Additionally, an inspection checklist was prepared to provide a structured format for capturing the direct observations by field staff.

Certain questions were included in more than one of the questionnaires, which allowed for data cross-checking and validation (see section 2.2.5).

All questionnaires and the inspection checklist were implemented in the mobile data collection application KoBoToolbox.

The basic assessment questionnaires were designed to collect information specifically regarding the sanitation system level. For data collection regarding the governance level, different questionnaires were used. These are described in the 4S Project Report Vol. II on governance (Chandragiri et al., 2020). Regarding financial aspects, cost data was also collected separately from private companies. The 4S Project Report Vol. III on finance (Rajan et al., 2020) provides more information on the respective data collection templates.

2.2.2 Selection of study sites

The selection of sites to be visited during the basic assessment was based on the following hard criteria:

Established technology

A wide range of SSS technologies is being implemented across the country (see Table 8). Only established technologies with at least 40 implemented systems were selected. Lab-scale units, research pilots or experimental systems were excluded.

Table 8 shows which technologies are represented in the 4S basic assessment dataset (some may not be represented due to the impossibility to access them).

Capacity range

For this project, SSS systems were defined to treat 5 to 700 KLD (kilolitres per day [= m^3/day]) of wastewater (i.e. serving approximately 10 to 1'000 households, or 50 to 5'000 person equivalents).

Minimum age

It was assumed that the issues linked to design, implementation, O&M or management of a system don't usually appear during the first years of operation. In India, systems are typically handed-over to final managing entities after one or two years of operation. Only systems that were operational since at least two years were therefore selected.

Wastewater source

Industrial effluent treatment plants were excluded.

Apart from these hard selection criteria, a number of further criteria were also considered whenever possible, namely:

- ✓ A sound representation of every technology family according to its relevance.
- ✓ Representation of different technology providers
- ✓ Representation of different geographical locations
- ✓ Representation of different contexts of application
- ✓ Representation of different system scales
- ✓ The inclusion of operational as well as non-operational systems

2.2.3 Accessing study sites

All SSS systems voluntarily participated in the 4S data collection. The advantage of voluntary study participation over forced participation (e.g. through Pollution Control Boards who have the right to inspect systems) is that interview answers are likely to be more authentic and honest, as participants did not have to fear sanctions. Therefore, this approach was preferred for the data collection.

Finding SSS systems willing to participate was, however, a major challenge (in total, the 4S team tried far more than 1’000 systems). This, among others, made a fully randomised approach impossible. Often, there was also only very limited information about systems available (e.g. their location and fulfilment of hard selection criteria). A number of methods were adopted to obtain access to systems:

Contacting system owners on phone and via email

Initially, 500 systems were pre-selected from the 4S system database (see section 2.1.2) to carry out the basic assessment. System owners were contacted via phone and/or email to obtain permission to visit the systems for basic assessment. This method was considered least biased, but also perhaps least successful.

Unannounced visits and direct interview

Having available key information (e.g. geographic location), field staff paid unannounced visits and interacted with managers and/or operators to assess the systems. Owing to less preparedness, not all the stakeholders were available for interviews or sometimes did not have all the required information handy. Data incompleteness is a weakness of this method.

Unannounced visits by “messengers” to schedule appointments

As the location information of some systems was available, field staff paid direct visits to meet the manager of the system and schedule a field visit upon his willingness.

Access through private players

When private players were interviewed, some of them also agreed to grant access to systems. Furthermore, members of the Association of Decentralised Sanitation Infrastructure and Service Providers (ADSIS) were also approached. Partial or full lists of implemented systems were obtained. Whenever possible the 4S team randomly selected systems to visit from such lists.

Recommendations from managers of visited systems

When site managers and operators of previously visited systems supported accessing systems through their acquaintances, such systems were included in field work only after meeting the hard and soft selection criteria.

Section 3.2.1 provides some background information on the sites that were eventually accessible and characterises the resulting dataset.

2.2.4 Field work

Basic assessment data collection was carried out by trained field staff hired through IIT Madras, CDD Society and ENPHO (Environment and Public Health Organization, for Nepal only), with coordination and supervision by Eawag. In order to ensure an unbiased assessment, all data collection on DEWATS (anaerobic baffled reactor bases systems) and similar technologies in India was carried out by IIT Madras staff.

2.2.5 Validation and pre-processing of collected data

Prior to analyses, multiple data validation procedures were put in place. Missing information was verified during the validation phase (e.g. personal errors during data entry, check for technical issues during data upload). Then, pre-processing of datasets for statistical analyses was done (e.g. categorizing text answers in relevant formats of multiple choice questions, formatting question and answer codes, merging information of different questionnaire versions). Final consolidation of the database included the merging of country-specific questionnaires (merging data from India and Nepal for some parts of the analyses) and the triangulation of answers provided by different stakeholders.

The procedure for validation and consolidation of the database included the following five steps:

1. Automatic formatting.
2. Manual validation of the data from each project using validation templates in order to identify mistakes, contradictions (intra and inter-questionnaire), missing information or uncommon answers. Datasets were then completed with the available information.
3. Formatting answers into standard code formats to ease statistical analysis process.
4. Merging of the different questionnaire versions (country-wise; updates) for statistical analysis.
5. Triangulation of answers provided by different interviewees on the same question.

More information is provided in Appendix 1.

2.2.6 Analysis of the collected data

The data collected from the 279 assessed SSS systems were then analysed using descriptive statistics. Findings and trends were drawn on the following aspects of SSS systems:

- technologies, context and age
- design and current idle capacities
- operational status and reasons of complete failure
- treated water reuse application
- training and capacity of managers and operators
- occurring issues as well as operational and maintenance requirements
- sludge management
- money flow in residential context
- management schemes

2.3 In-depth performance analysis: sampling campaigns

Brief Methodology

- 40 SSS systems (35 in India and 5 in Nepal) from all main technology families were selected for wastewater sampling. Three rounds of sampling were carried out at each system.
- 24 h flow-proportional composite sampling of system in- and outlets
- Four grab samples of inlet and outlet of the treatment plant taken at 6 hour intervals to account for daily variations of treatment
- One-time grab samples at the inlet of each treatment unit at 8 pm for more detailed understanding of treatment performance pattern
- Parameters analysed on-site: flow, pH, temperature (T), dissolved oxygen (DO), turbidity
- Parameters analysed off-site: biochemical oxygen demand (BOD), total chemical oxygen demand (COD), soluble chemical oxygen demand (sCOD), total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), ammoniacal nitrogen (AN), faecal coliforms (FC), oil and grease (O&G)
- Relevant wastewater parameters were compared to Indian CPCB discharge standards (BOD, COD, TSS, AN, TN and FC)

2.3.1 Site selection

Out of all systems visited for basic assessment (see section 2.2), 40 units (35 in India and 5 in Nepal[4]) were selected for an in-depth assessment of their treatment performance (see Table 1). The selection criteria (in addition to those for the basic assessment, see section 2.2.2) were as follows:

- Systems are fully operational (no obviously poorly performing or failed systems were selected)
- Representation of the spectrum of all major technology families found during the basic assessment
- Representation of different contexts of application (for more details on contexts see Table 7)
- Geographical proximity to the laboratory analysing the samples (see section 2.3.4): since biochemical activity can alter the properties of wastewater, samples have to be analysed within 24 h from the time of collection (APHA, 2012).

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[4] The performance data from Nepal is included in this report in order to have an increased sample size and to allow for comparison of the results.

Table 1: Presentation of all 40 treatment plants sampled, with identification number (ID), context and treatment sequence. Primary treatment and settling units are in *italic*, main treatment in **bold**, post-treatment in regular font, and systems from Nepal in orange. For abbreviations, see the Abbreviations and Acronyms section, or Table 7 and Table 8.

ID	Context	Treatment sequence	ID	Context	Treatment sequence
SBR-1	Res	*PST*-**SBR**-*SST*-CL	**MBR-1**	Com	**MBR**
SBR-2	Res	**SBR**-ACF-CL	**MBR-2**	Res	**MBR**-CL
SBR-3	Com	**SBR**-*SST*-UF-RO	**EADOx-1**	Res	**EC**-*SST*-PSF-ACF
SBR-4	Inst	*UASB*-**SBR**-*SST*-PSF-ACF-RO	**Soil-filtration-1**2)	Inst	**SIBF**-PSF-ACF
MBBR-1	Res	**MBBR**-*SST*-PSF-ACF-CL	**Soil-filtration-2**	Low-Res	**SPISF**
MBBR-2	Res	**MBBR**-*SST*-PSF-ACF-CL	**Soil-filtration-3**	Inst	*PST*-**SBT**
MBBR-3	Inst	*PST*-**MBBR**-PSF-ACF	**Soil-filtration-4**	Inst	*PST*-**HFCW**
MBBR-4	Com	**MBBR**-*SST*-CL-PSF-ACF	**Soil-filtration-5**	Mun	BGS-**HFCW-VFCW**
MBBR-5	Com	*PST*-**MBBR**-*PSF*-CL-ACF	**ABR-based-1**	Inst	*PST*-**ABR-HFCW**-PP
MBBR-6	Com	*PST*-**MBBR**-*SST*-PSF-CL-CAACO	**ABR-based-2**	Inst	*PST*-**ABR-AF-HFCW**-PP
MBBR-7	Inst	*PST*-**MBBR**-PSF-CAACO	**ABR-based-3**	Inst	*PST*-**ABR-HFCW-VFCW**-PP
MBBR-8	Com	**MBBR**-CL-PSF-ACF	**ABR-based-4**	PT	*BGS*-**ABR-HFCW**
MBBR-9	Com	**MBBR**-*SST*-PSF-ACF	**ABR-based-5**	PT	*BGS*-**ABR-HFCW**
ASP-11)	Res	**EA/ASP**-*SST*-PSF-ACF-UF	**ABR-based-6**	Com	*PST*-**ABR**-Vortex-PSF
ASP-2	Res	**EA/ASP**-*SST*-PSF-ACF-CL	**ABR-based-7**	Com	*PST*-**ABR-AF-HFCW**
ASP-3	Inst	**EA/ASP**-*SST*-PSF-ACF	**ABR-based-8**	Com	*PST*-**ABR-AF**-Vortex-PP
ASP-4	Res	**EA/ASP**-*SST*-PSF-ACF-CL	**ABR-based-9**	Com	*PST*-**ABR-HFCW**
ASP-5	Res	**EA/ASP**-*SST*-PSF-ACF	**ABR-based-10**	Low-Res	*PST*-**ABR-AF-HFCW**
ASP-6	Res	**EA/ASP**-*SST*-PSF-ACF	**ABR-based-11**	Low-Res	*PST*-**ABR-AF-HFCW**
ASP-7	Inst	**Oxidation Ditch**-*SST*-PP	**ABR-based-12**	Mun	*PST*-**ABR-AF-HFCW**

1) Please note that the ID "ASP" includes all members of the "Activated Sludge (Suspended Growth) Processes" technology family (see Table 8), i.e. ASP and EA (in practice, the difference is often hard to identify) as well as oxidation ditch systems.

2) Please note that the ID "Soil-filtration" includes all members of the "Constructed Wetlands and Soil Filtration Systems" technology family, i.e. SIBF, SPISF, SBT and CW systems.

2.3.2 Sampling pattern and wastewater parameters studied

Grab samples are not able to give a representative picture of an SSTP's performance, as they cannot capture the large fluctuations typically occurring in small systems and carry high uncertainties. The analysis of 24 h flow-proportional composite samples can overcome some of these limitations and provide a better picture by evening out diurnal fluctuations. Three 24 h rounds of sampling were therefore conducted for all systems to investigate their long-term performance as well as potential seasonal and daily variations. The three sampling visits at each site were scheduled between one and 11 months apart. Besides the flow-proportionally composited samples over 24 hours, several grab samples were collected during each visit.

The type of samples taken as well as the parameters analysed are presented in Table 2 below, as well as in Appendix 2. In addition to these parameters, descriptive information such as the system appearance, weather conditions as well as sample colour and odour were also noted down.

The authors are aware of the increasing diversity of chemical pollutants in domestic wastewater, including micropollutants that are present in very low concentrations (e.g. trace organic compounds). As the analysis of such pollutants is very costly and complex, it was not included in the present study.

Table 2: Sampling scheme applied during the in-depth performance analysis. This sampling pattern was applied during three 24 h visits at each of the selected systems.

Sampling type		Composite	Grab	Grab	Grab
Sampling spots		Inlet and outlet	Inlet	Outlet	Inlet of all (n) treatment units
Number of samples		2 x 12, flow-proportionally composited into 2	4	4	1 x n
Interval of sampling / time of sampling		2 h	6 h	6 h	8 pm
Parameters analysed on-site	Flow	x	x	x	-
	pH	x	x	x	x
	T	x	x	x	x
	DO	x	x	x	x
	Turbidity	x	x	x	x
Parameters analysed off-site	BOD	x	-	-	x
	COD	x	-	x	x
	sCOD	x	-	x	x
	TSS	x	-	x	x
	TP	x	-	-	x
	TN	x	-	-	x
	AN	x	-	-	x
	FC[1]	x	-	-	x
	O&G	-	x	x	x

[1] Faecal coliforms (FC) are an indicator for faecal contamination but one should not forget that they do not represent all faecal pathogens. It has been proven that other faecal pathogens, such as protozoan cysts, helminth eggs or viruses, will be removed by other mechanisms and be more resistant to treatment than FC (Von Sperling, 2007).

2.3.3 Flow measurement

In most cases, SSS systems are not equipped with flow meters. Therefore, volumetric flow was estimated during the flow-proportional sampling campaigns by measuring the time for a 20 litre bucket to fill. This was done one to three times every two hours during 24 hours.

2.3.4 Field work and sample analysis

Sampling field work was carried out by trained field staff hired through IIT Madras, CDD Society and ENPHO (for Nepal), with coordination and supervision by Eawag. In order to ensure an unbiased assessment, all data collection on DEWATS (anaerobic baffled reactor bases systems) and similar technologies in India was carried out by IIT Madras staff.

Three laboratories were contracted for sample analysis: IIT Madras, Bangalore Test House in Bengaluru and the laboratory of ENPHO. The sampling teams and personnel from the three laboratories followed a two days training workshop to guarantee the homogeneity of sampling and analysis procedures.

All samples were collected, preserved (stored in ice box and refrigerated), transported and analysed according to the APHA standard methods (APHA, 2012). For quality control, the analyses were done in duplicates.

The results were compared to the Central Pollution Control Board's (CPCB) effluent discharge standards (MoEFCC, 2017) that are applicable for the effluent quality of any wastewater treatment plant[5] (see Table 3). Further information on the number of laboratory analyses conducted for the different samples is presented in Appendix 2.

Table 3: CPCB discharge standards for domestic wastewater applicable to SSS systems effluent.

Parameter	Discharge Standard		
	CPCB 2015 (Draft)	**CPCB 2017 (Metro Cities)**	**CPCB 2017 (Non-Metro Cities)**
BOD [mg/L]		20	30
COD [mg/L]	50		
TSS [mg/L]		50	100
AN [mg/L]	5		
TN [mg/L]	10		
FC [MPN/100ml]		1'000	1'000

2.3.5 Analysis of sampling results

The graphs displaying overall performance and effluent quality are based on three rounds of 24 h flow-proportional composite sampling. The averages used are conventional arithmetic means for non-microbial parameters (BOD, COD, TSS, AN and TN). For FC concentration and reduction rate calculations, the geometrical mean was used, as it better represents microbiological data than the conventional arithmetic mean (APHA, 2012). Practically, this leads to the use of the average log concentrations instead of the log of the average of concentrations.

2.3.6 Investigating the relationship between observed system status and measured effluent quality

The potential of using observations of wastewater treatment effectiveness (e.g. odour, colour and turbidity of the treated wastewater, or presence of non-functional units, etc.) to complement or even partly replace expensive sampling campaigns was investigated. To do so, on-site observations of the status of the system were carried out by trained field staff at the time of sampling. This qualitative assessment was then compared to BOD quality of the treated effluent for the 40 sampled systems. A cross-table was generated to understand the relationship between the two variables (see section 3.3.6).

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[5] An updated set of discharge standards is under discussion but not yet in force at the time of the preparation of this report.

2.4 Conditions for sustainable SSS system performance: a cause-effect analysis

Brief Methodology

- Investigation of the requirements that need to be fulfilled for ensuring long-term SSS system performance, and the factors that can positively or negatively impact performance
- Definition of system performance, covering wastewater treatment, resource recovery and solids management, through 9 performance objectives (PO)
- Identification of conditions for performance: 14 so called critical success factors (CSF) that need to be fulfilled were elaborated in five performance enabling realms: (i) Planning, design and implementation, (ii) Operation and maintenance, (iii) Management and monitoring, (iv) Socio-cultural aspects, (v) Finance
- Scoring of the PO and CSF fulfilment of the studied SSS systems, using the data collected in the basic assessment and in-depth performance analysis
- Cause-effect analysis to investigate the potential interlinkages between the fulfilment of the CSF and the performance outcome: statistical analysis of the relationship between CSF and PO scores

In order to explain the measured performance of a system, or to know the reasons behind good or poor performance, it is important to understand the underlying cause-effect relationships. Sustainable SSS system performance is only possible when a number of conditions are fulfilled, and performance can get positively or negatively impacted by numerous factors. Figure 2 on p. 4 visualises the analysis framework used in the 4S Project. Performance as the central goal of an SSS system is displayed in the middle of the illustration. All the other elements shown in the figure can have a direct or indirect influence on performance. Figure 3 on p. 18 highlights those elements that are of particular, direct relevance for an SSS system's performance.

This part of the 4S Project investigates the requirements that need to be fulfilled for ensuring long-term SSS system performance, and the factors that can positively or negatively impact performance. This is done in the following steps, using the data collected in the basic assessment of SSS systems (see section 2.2) and the in-depth performance analysis (see section 2.3):

1. Definition of performance (see section 2.4.1) and development of a scoring system (see section 2.4.3)
2. Identification of conditions for performance (i.e. so called critical success factors that need to be fulfilled, see section 2.4.2) and development of a scoring system (see section 2.4.3)
3. Cause-effect analysis to investigate the potential interlinkages between the fulfilment of the critical success factors and the performance outcome (see section 2.4.4).

2.4.1 Performance objectives: defining SSS system performance

The performance of wastewater treatment systems is typically assessed by measuring different water quality parameters, and by comparing the concentration of wastewater constituents in the effluent with the applicable thresholds as defined in the discharge standards. Such an approach is described in section 2.3.

Besides efficient wastewater treatment, SSS systems may also have other objectives. Therefore, for the analysis of the conditions of sustainable SSS system performance, a wider perspective of performance was taken. The 4S Project identified a set of nine ***performance objectives*** **(PO)** in three different performance areas:

1. **Wastewater treatment:** this is often the primary objective of SSS systems. It can be assessed through qualitative considerations (based on observations and questionnaire data – PO 1.1-1.2) and quantitative considerations (compliance with standards, based on sampling data – PO 1.3-5) considerations
2. **Resource recovery:** If an SSS system is designed for water reuse, nutrient recovery or energy recovery, the fulfilment of these objectives can also be assessed – PO 2.1-2.3.
3. **Solids management:** Any SSS system generates sludge, solid wastes and/or scum and should adequately manage these by-products in order to avoid environmental pollution or public health risks – PO 3.

The nine PO are described in Table 4 below. In a next step a scoring system was developed which allows to assess the fulfilment of each of these performance objectives (see section 2.4.3).

Figure 5: Solids management issues at an SSS system (Photo: Shreyas Kumar).

Table 4: Overview and description of the performance objectives of SSS systems (based on Fettback, 2017).

Performance Area	Performance Objective (PO)	Description
1. Wastewater Treatment	**PO 1.1: Treatment Effectiveness**	**Objective:** All treatment stages of an SSS system should be operational and the appearance of the treated wastewater should be normal. **Assessment:** Qualitative evaluation of the overall treatment effectiveness through observations and questionnaire data (e.g. based on operational status of system components, odour, colour, froth, turbidity, operator judgements).
	PO 1.2: Adequate Loading	**Objective:** An SSS system should be fed with the quantity and quality of wastewater it is designed for (e.g. correct connection of all households). It should treat the complete amount of wastewater generated and should not bypass any untreated wastewater. **Assessment:** Estimation of current hydraulic and organic load of the system vs. its design load.
	PO 1.3: Effluent Organic and TSS Quality	**Objective:** Organics and solids concentrations in the effluent should not exceed thresholds prescribed in the discharge standards. **Assessment:** Quantitative based on the analysis of BOD, COD and TSS in wastewater samples, comparison with discharge standards.
	PO 1.4: Effluent Nutrient Quality	**Objective:** Nutrient concentrations in the effluent should not exceed thresholds prescribed in the discharge standards. **Assessment:** Quantitative based on the analysis of AN and TN1) in wastewater samples, comparison with discharge standards.
	PO 1.5: Effluent Microbial Quality	**Objective:** Microbial concentrations in the effluent should not exceed thresholds prescribed in the discharge standards. **Assessment:** Quantitative based on the analysis of FC in wastewater samples, comparison with discharge standards.
2. Resource Recovery	**PO 2.1: Active Water Reuse**	**Objective:** The equipment for wastewater reuse (if available) is correctly used as per the design. **Assessment:** Only if water reuse is foreseen in the system design. Qualitative evaluation through observations and questionnaire data; water metering if possible.
	PO 2.2: Active Nutrient Recovery	**Objective:** Nutrient recovery (e.g. through land application of treated sludge) is correctly practiced as per the design (if applicable). **Assessment:** Only if nutrient recovery is foreseen in the system design. Qualitative evaluation through observations and questionnaire data.
	PO 2.3: Active Energy Recovery	**Objective:** Energy recovery (e.g. through a biogas system) is correctly practiced as per the design (if applicable). **Assessment:** Only if energy recovery is foreseen in the system design. Qualitative evaluation through observations and questionnaire data; gas metering if possible.
3. Solids Management	**PO 3: Appropriate Management of Solids**	**Objective:** Sludge, scum, screenings and other potentially hazardous solids generated at an SSS system are safely managed (including removal, transport and disposal). **Assessment:** Qualitative evaluation of the correct use of solids management equipment (e.g. sludge filter press, drying beds) and related practices through observations and questionnaire data.

1) At the time of this study no phosphorus limits were applicable. Therefore, only nitrogen parameters are considered for PO 1.4 scoring.

2.4.2 Critical success factors: conditions for sustainable SSS system performance

Sustainable SSS system performance is only possible when a number of conditions are fulfilled. Performance can get positively or negatively, and directly or indirectly impacted by numerous factors. In a literature review and expert consultation undertaken as part of the 4S Project, 99 such factors with a potential direct or indirect influence on SSS system performance were identified (Fettback, 2017). All of these factors can be allocated to one of the following **five realms**:

- Planning, design and implementation
- Operation and maintenance (O&M)
- Management and monitoring
- Socio-cultural aspects
- Finance

As each of these realms are crucial for enabling SSS system performance, they are here called ***performance enabling realms***.

The large number of factors demonstrates the enormous complexity of the causal connections and chain of effects. The 4S Project aimed to reduce this complexity by organising and grouping the factors according to their hierarchy in the cause-effect chain. Appendix 3 explains how this was done. This process allowed to identify 14 main, superordinate factors that are here called ***critical success factors*** **(CSF)**. A CSF is here defined as a **factor whose fulfilment is expected to be critical for the successful long-term operation of an SSS system, or a key condition for sustainable SSS system performance**. Figure 6 presents an overview of the identified CSF, and Table 5 provides some additional descriptions.

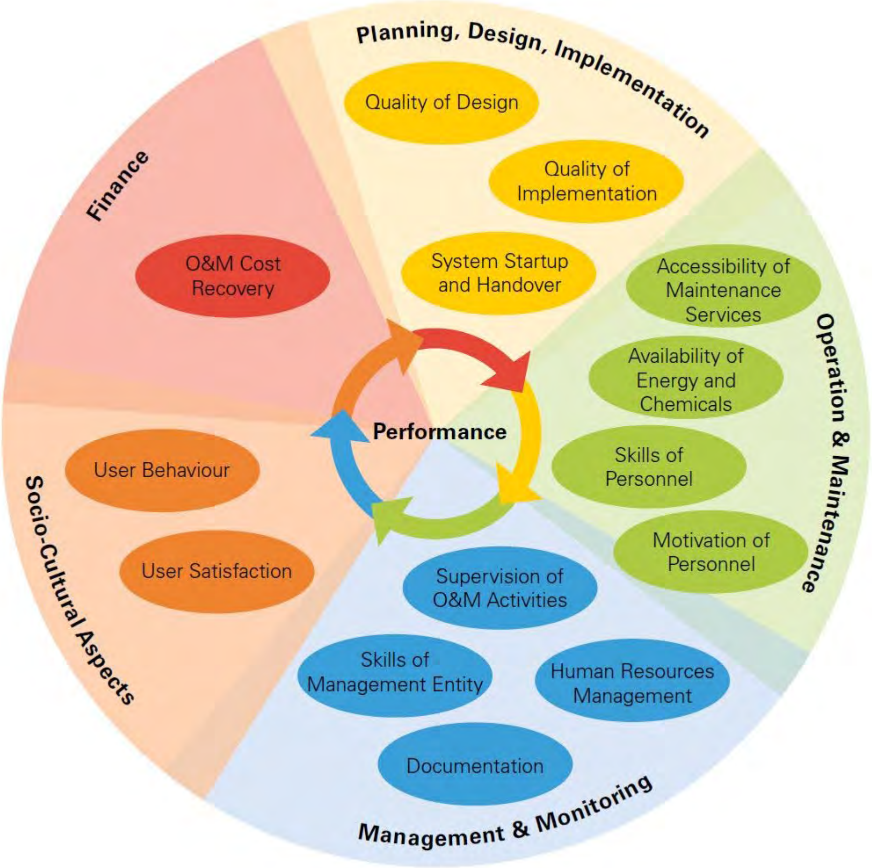


Figure 6: Visualisation of critical success factors (CSFs) within the five performance enabling realms.

Table 5: Overview and description of the critical success factors of SSS systems (based on Fettback, 2017).

Performance Enabling Realm	Critical Success Factor (CSF)	Description
Planning, Design and Implementation	**CSF 1: Quality of Design**	Correct system sizing considering wastewater source, variability and storm water; Design errors; Designed for accessibility (reactors desludging and sampling); Potential nuisances taken into account in design.
	CSF 2: Quality of Implementation	Construction quality; Quality of materials; Quality of work, Quality of supervision, Completeness of construction; Installation errors; Consent of establishment.
	CSF 3: System Startup and Handover	Instructions, manual and project documentation (e.g. flow sheet) given to future owner; Support after handover.
Operation and Maintenance	**CSF 4: Skills of Personnel**	O&M personnel can do what it is supposed to do, has the knowledge about system components as well as regarding prevention, identification and solving of problems.
	CSF 5: Motivation of Personnel	O&M personnel wants to do a good job; Site is clean; Happiness of operator. O&M personnel is reliable.
	CSF 6: Accessibility of Maintenance Services	Clear responsibility for maintenance; Operator and/or manager know whom to contact and how to organize required maintenance tasks (e.g. desludging, repairs, replacements). Required outsourced services and expertise are locally available.
	CSF 7: Availability of Energy and Chemicals	Energy adequately available as per system need; Chemicals available as needed for the process; Sufficient stock of fuel and chemicals.
Management and Monitoring	**CSF 8: Skills of Management Entity**	Management entity can do what it is supposed to do, identifies problems, can provide good answers why things are done this way, has knowledge about the system.
	CSF 9: Supervision of O&M Activities	Operators are correctly instructed and know what tasks they have to do, their work is supervised; Maintenance tasks are scheduled; Presence and work of operator are supervised; Training of Operator; Adequate supervision of system performance.
	CSF 10: Human Resources Management	Sufficient number of operators is always available; Adequate working hours and salaries
	CSF 11: Documentation	Performance, O&M and financial information are documented and available when needed
Socio-Cultural Aspects	**CSF 12: User Behaviour**	Users follow instructions (e.g. what not to throw into the toilet – solid waste, chemicals). Users are paying wastewater fees. Users are not impacting on the well-functioning of the system.
	CSF 13: User Satisfaction	Users accept the system (including different reuse); Users like the system and don't reject it. Complaints (if any) are addressed
Finance	**CSF 14: O&M Cost Recovery**	Costs are covered (no matter how high they are) by generating the required income. Money is put aside for long-term maintenance activities. User's ability to pay is not overstretched.

In a next step a scoring system was developed which allows to assess the fulfilment of each of these 14 CSF (see section 2.4.3).

2.4.3 Development of a scoring system for PO and CSF

Knowing for an SSS system how well all their CSF and PO are fulfilled would help to

a) get an overview of the system's performance, with insights beyond laboratory reports
b) get an overview of the system's sustainability and potential risks for long-term success
c) raise awareness of all the relevant aspects of a sanitation system, beyond the effluent quality of the STP itself
d) monitor strengths and weaknesses and highlight key areas of improvement, both at sanitation system level (e.g. improvement of user behaviour, or documentation) and at governance level (e.g. development of targeted training programs for operators if found to be an issue)
e) look for statistical cause-effect relationships between the fulfilment of CSF and performance outcomes

The fulfilment of the identified CSFs and PO was therefore quantified through scores. A simple scoring system with three categories was implemented:

🟢 Good (1)
🟡 Caution (0.5)
🔴 Insufficient (0)

The traffic light concept with green, orange and red colours allows to get a quick overview of the strengths and weaknesses of a system. The information can also be visualised in scorecards, presenting the fulfilment of all CSF and/or PO at a glance (see Figure 63 on p. 106 for an illustration of what a scorecard could look like for the PO).

The data from the basic assessment (interview data and field observations from 309 plants in India and Nepal, see section 2.2) and, for some PO, in-depth performance analysis data from the sampling campaigns (40 plants, see section 2.3) were used for scoring.

Each CSF and the two qualitative PO were described by a number of "topics", and each topic was scored with question(s) from the basic assessment questionnaire or inspection checklist. The answers to these questions were then scored either *good* (score 1), *caution* (score 0.5), *insufficient* (score 0), *not applicable* or *not available*. The scores obtained for all questions were then aggregated into a topic score and finally into a score for the CSF/PO. The aggregation was done by using the SWING weighting method (Eisenführ et al., 2010; Marttunen et al., 2017). Figure 7 provides an exemplary schematic explanation of how the CSF and PO were scored, from the answers of specific interview questions down to the final CSF/PO score.

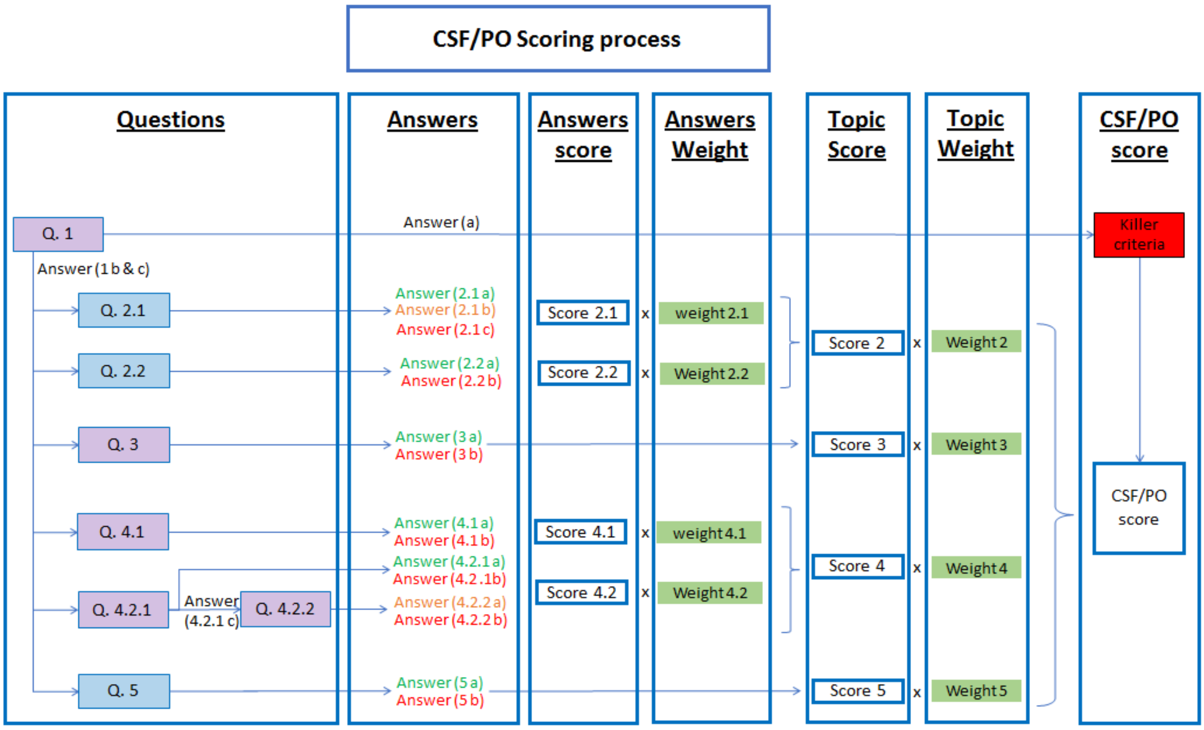


Figure 7: Visualization of the CSF/PO scoring methodology (fictitious example), from questionnaire questions to final score.

The three quantitative PO which measure the compliance of the effluent quality with discharge standards (1.3-1.5, see section 2.4.1) were scored differently, because of the availability of sampling results (only for 40 systems). Based on the latest CPCB effluent standards (MoEFCC, 2017) the results of each round of composite sampling was scored as presented in Table 6.

Table 6: Quantitative PO scoring matrix based on sampling results and CPCB effluent discharge standards (2015 or 2017 non-metro city values, depending on the parameter) and a 10% buffer.

	Parameters	Good	Caution	Insufficient	Weights
PO 1.3 Organic and TSS	BOD [mg/L]	<= 33	> 33; <= 45	> 45	0.33
	COD [mg/L]	<= 55	> 55; <= 75	> 75	0.33
	TSS [mg/L]	<= 110	> 110; <= 150	> 150	0.33
PO 1.4 Nutrient[1]	AN [mg/L]	<= 5.5	> 5.5; <= 7.5	> 7.5	0.5
	TN [mg/L]	<= 11	> 11; <= 15	> 15	0.5
PO 1.5 Microbial	FC [MPN/100mL]	<= 1'100	> 1'100; <= 1'500	> 1'500	1

[1] At the time of this study no phosphorus limits were applicable. Therefore, only nitrogen parameters are considered for PO 1.4 scoring.

Details of the scoring procedures for all PO and CSF can be found in Appendix 4.

2.4.4 Cause-effect analysis: investigating the potential interlinkages between the fulfilment of critical success factors and the performance outcome

Sustainable SSS system performance is only possible when a number of conditions are fulfilled, and performance can get positively or negatively impacted by numerous factors. The potential correlation between the conditions for sustainable SSS system performance and the performance outcome is statistically tested by examining the relationship between the identified CSFs and POs. The corresponding cause-effect framework applied in this study is visualised in Figure 8.

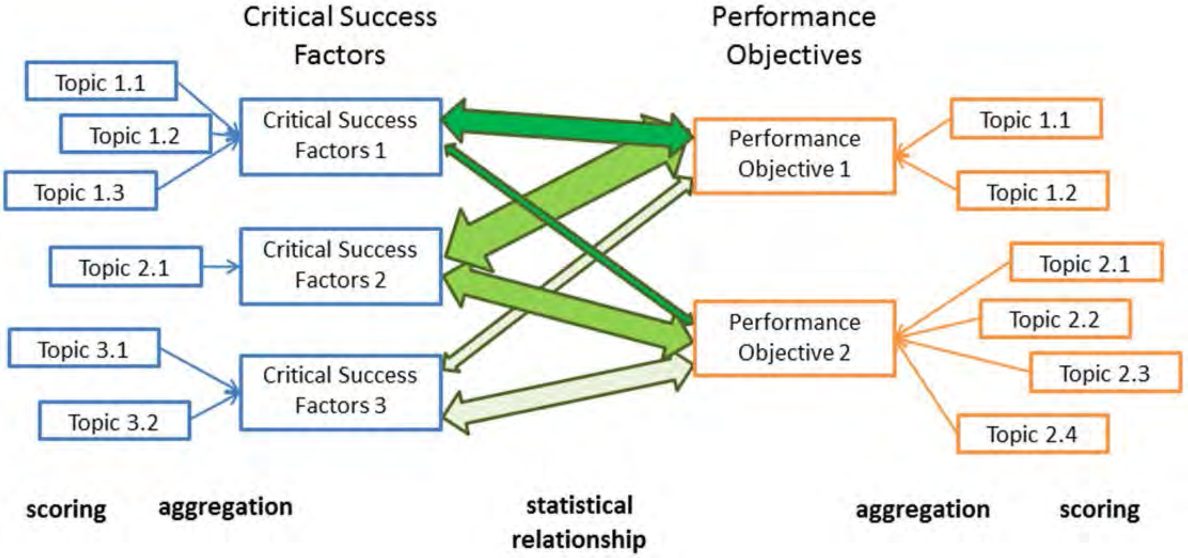


Figure 8: Cause-effect framework concept visualizing the scoring and aggregation of CSF and PO and statistical relationships.

Both CSFs and POs can theoretically take three values (*insufficient*, *caution*, *good*), i.e. the data analysed is ordinal. In order to disentangle the relationship between the CSF and PO scores, statistical methods were used that both fit the data and support the context specific theory behind.

Bivariate correlations, by creating cross tables, were used to detect relationships between two variables. Spearman Rank correlations show how strong relationships between two variables are. Its coefficient ranges between -1 and +1, where -1 represents a perfect negative relationship and +1 a perfect positive relationship.

The Random Forest (RF) method was applied to detect specific effects of CSF on PO. RF analyses build on so-called Decision Trees. Decision Trees are reflected as simple flowchart-like diagrams, showing the number of outcomes of decisions. They are also learning algorithms. The algorithm starts with a root node at the top which contains all data, then scans all included predictors and uses the one that leads to the node below which is most 'pure' (James et al., 2013, pp. 311-312), i.e. reflecting either the most *insufficient*, *caution* or *good*. The index used to decide which node is the purest is the Gini index, measuring how unequal a distribution is. The algorithm always takes the predictor that decreases heterogeneity first. It might be, however, that a better decision tree could have been grown if the split on the predictor occurred later. Decision trees can describe the used data very well but fail to predict relationships due to overfitting. RF analysis uses multiple decisions trees and "randomly" generates these trees in order to balance out the above mentioned disadvantages.

RF analysis introduces two ways of randomness: one concerning the included cases, the other one regarding the included variables (James et al., 2013, p. 320). Each tree that is grown includes a randomly chosen set of cases and variables, therefore looking differently. RF analysis then decides on which class to predict by aggregating the individual trees. For classification, the majority vote is chosen. RF is an ‘ensemble-method’, i.e. in an ensemble of trees, a mistake by one tree carries no weight. RF is known to be a very powerful and robust tool for predictions. The accuracy is evaluated by the out-of-bag error, which is an estimated error of prediction and shows how many cases are correctly predicted by the RF. It can lead to “false accuracy”. If one class is overrepresented, putting all cases into that class yields a high accuracy although it is the most simple model. A better measure is to use the “balanced accuracy” which is defined as the average of the class accuracies.

Figure 9: Park irrigated with treated wastewater (Photo: Rohan Sunny).

3 Results and Discussion

3.1 Landscape study: desk-based study of the SSS landscape in India

Chapter Summary

- A 2006 environmental impact assessment policy change by the MoEFCC triggered the widespread implementation of SSS in urban India, mainly in large residential, commercial and institutional buildings. Individual states and cities have formed their own SSS regulations.
- Available academic and grey literature on SSS tends to exclusively deal with either conventional or innovative technologies, with very few comparative studies. There is a lack of holistic SSS studies that includes technological studies and engineering analyses, coupled with the institutional, economical and policy aspects.
- There is no systematic documentation of SSS systems in India's states and cities, and government databases are patchy. Based on an incomplete list of almost 9'500 systems compiled during the 4S Project, it is estimated that more than 20'000 SSTPs exist in India. In Bangalore an estimated 10-20% of the wastewater is treated by such systems.
- Treatment technologies used vary from zero- or low-energy processes (including anaerobic reactors, plant-based systems or ponds) to highly automated and mechanised processes (including sequencing batch reactors (SBRs) or membrane bioreactors). They can be classified into seven technology families based on the main treatment process. The conventional activated sludge process (ASP, including extended aeration designs), SBRs and moving bed biofilm reactors (MBBR) are most prevalent.
- Over 300 private companies involved in SSS in India were listed, many of them headquartered in the big cities with a large market. They provide services ranging from consulting to turnkey solutions.
- There is no comprehensive and impartial guidance material for informed choice according to context-specific parameters and the implications of all the different SSS technologies. Today, technology selection typically takes place based on the experience and preference of the consultant in charge. This leads to intransparent decision-making and possibly not the most appropriate solutions being implemented.

3.1.1 Past and present of small-scale sanitation in India

SSS systems have had a history of at least 30 years in India, mainly commissioned in rural or poorer urban neighbourhoods by research institutes and non-government organisations (NGOs) such as National Environmental Engineering Research Institute (NEERI), IIT Bombay, Shrishti Eco-Research Institute (SERI) and the Consortium for DEWATS Dissemination (CDD) Society, for research and community development purposes. Numerous successful case studies of small-scale wastewater treatment systems have been reported (CSE, 2014).

However, until recently, small-scale sanitation was not reflected in the policies of the national, state or local government. Although there is no dedicated legal framework around SSS, several new regulations on wastewater treatment have been introduced, creating an increase in the adoption of small-scale sewage treatment systems, especially in the urban and peri-urban areas of India.

The first major SSS policy was adopted by the Ministry of Environment, Forest and Climate Change (MoEFCC) which introduced the environmental impact assessment in 2004 and an amendment in 2006, directing all new buildings with built up area over 20'000 m^2 to implement SSS systems (MoEF, 2006). This triggered the installation of thousands of privately owned and operated SSS units, particularly in the peripheral areas of large cities where the biggest construction boom took place.

No other formal national policy was introduced that was directed at SSS. Overall, urban wastewater management infrastructure and strategy are largely influenced by policies and schemes such as the 2008 National Urban Sanitation Policy (NUSP) (Dasgupta and George, 2014) and the Jawaharlal Nehru National Urban Renewal Mission (Wankhade, 2015).

Sanitation is a state subject as per the Indian constitution. Andhra Pradesh, Tamil Nadu, Karnataka, Kerala and Goa are among the states which developed their individual SSS policies in order to promote urban water reuse and/or environmental protection. Cities such as Bengaluru, Chennai, Pune, Delhi and Hyderabad have their own mandates on SSS through the local municipal corporations, and water supply and sewerage boards. These become the final end of line agencies to support the SSS implementation (Bhullar, 2013). The 4S Project Report Vol. II on governance (Chandragiri et al., 2020) provides a more detailed institutional and policy analysis of the SSS sector.

3.1.2 Academic studies and grey literature on small-scale sanitation systems in India

Internationally, research on SSS has been carried out to investigate an alternative approach to centralised infrastructure (Sharma et al., 2013) and many case studies have been studied in detail (Nhapi, 2004; Sheehan, 2011; Van Afferden et al., 2010). Large amount of research work has been dedicated to developing comprehensive decision support systems such as economies of scale (Eggimann et al., 2016) and multi-criteria analysis to suit sanitation needs (Borsuk et al., 2008). Various toolkits have also been developed for aiding in technology and sanitation system selection by different agencies (Berekteab et al., 2013; Fadel Ndaw, 2016).

With respect to India, research on small-scale systems has generally focused on technology comparison and performance assessment of non-conventional innovative wastewater treatment systems (Arghyam, 2013; Kadam et al., 2008a, 2008b; Miller, 2011; Reynaud, 2014; Singh et al., 2015; Starkl et al., 2013b, 2013a). For example, Reynaud (2014) presents a detailed engineering analysis of existing DEWATS systems under tropical conditions in India and Indonesia to consolidate the basis of future design, operation and maintenance issues for successful operation of these technologies.

However, only few rigorous academic studies from India exist on conventional aerobic small-scale systems, using different variations of suspended or attached growth technologies (Kuttuva et al., 2018; Sivacoumar et al., 2014; Suneethi et al., 2015). Kuttuva (2015) presents a socio-economic analysis of existing small-scale systems in the city of Bengaluru. Although the sample size is small (only 17 systems were studied), the research concludes that without policy measures which support the operation of small-scale systems, such as economic incentives, subsidies, and rigorous enforcement, decentralized options face considerable challenges in achieving successful operation. Sivacoumar et al. (2014) modelled the installation and operation costs of over 50 fluidised aerobic bed technology based small-scale wastewater systems in tsunami-affected regions of Tamil Nadu. However, no additional information about these systems, including current functionality, operational issues or even institutional/policy factors, is provided.

Barringer (2014) provides a detailed review of the policies supporting domestic/commercial water reuse in Pune, along with a short history and current status of water supply and wastewater management in the city. Apart from the fact that it is based on just two small-scale sanitation systems, it does not provide any additional technological or economic information regarding the treatment process, which could provide additional insights on the functionality and efficiency of the reported systems. Studies from other cities in India where there are reportedly many small-scale systems are conspicuously absent.

Evans et al. (2014) present the institutional frameworks of both centralised and small-scale water reuse systems in Bengaluru, but with no economic or technical information about the systems employed. Ravishankar and Nautiyal (2015) try to understand water use patterns in peri-urban Bengaluru using an extensive domestic survey, and how wastewater reuse can help reduce water consumption of the city. While no systems have been analysed in that study, it helps to understand the importance of SSS systems for sustainable water usage of the city. Drangert and Sharatchandra (2017) also elaborate the key role that SSS systems have to play for the future water sustainability of Bengaluru.

Grey literature on small-scale systems is predominantly presentations by practitioners or small-scale systems developers promoting specific technologies. Hence, these generally tend to be biased towards specific technologies and in some cases they are not rigorous enough. Kodavasal (2015) argues that given current techno-economic considerations and availability of skilled operators, the extended aeration activated sludge process provides the most optimal choice for SSS systems in apartment complexes for at least the forthcoming future, while Pasupathiraj (2014) contends that power-optimized and fully automated SSS systems based on sequencing batch reactor technology are the best choice for small-scale wastewater treatment. Similarly, Biniwale (2013) presents a detailed technological and design analysis and advantages of so-called Phytorid systems (type of baffled constructed wetland) only.

Thus, available literature tends to exclusively deal with either conventional or innovative technologies, with very few comparative studies. This disconnect is visible among practitioners, too, who mostly either have the conventional set of technologies in their portfolios or promote specific alternative solutions and innovations (see also section 3.1.6). While there is considerable research/academic interest in innovative technologies, it is lesser in conventional technologies used at small scale. Further, there is a fundamental lack of a holistic review of small-scale sanitation in India that includes technological studies, engineering analyses, and couples them with the institutional, economical and policy aspects of the same. The challenges are associated not just with technology, but also implementation at scale, operation and maintenance particularly that greatly influence compliance, failure and longevity. Therefore, there is a need for further research and scholarly work on small-scale sanitation in India.

3.1.3 Typical application contexts for small-scale sanitation systems in India

Based on this landscape study, the four main categories of application contexts presented in Table 7 were identified for SSS in India. About 50% of the units listed in the system database belong to the middle- and high-income residential context. 40% are commercial (25%) or institutional (15%) applications, and less than 10% are low-income residential systems and public toilets (see Figure 10). These statistics are, however, not representative for India, due to the limitations of the list of systems (see section 3.1.4).

The technology choice and design of SSS vary by context, as shown later in section 3.2.2. The motivation for uptake of SSS also depends on legal and regulatory requirements, reuse opportunities, cost effectiveness, lack of existing sewer systems, temporary installations such as public toilets for gatherings, or intermediary solutions until centralised infrastructures are put in place.

Table 7: Application contexts for small-scale sanitation in India.

Context	Sub-Categories (used in 3.3)	Abbreviation	Description
Low-Income Residential and Public Toilets	Low-Income Residential Public Toilet	Low-Res PT	This context comprises sanitation systems in both formal and informal low-income settlements, i.e. notified and non-notified slums (Nolan, 2015), as well as community and public toilets in a similar context. The sites of this context are usually not required by law to build their own wastewater plants. Sanitation projects usually are implemented by government or by NGOs, but often further on managed by the community.
Middle- or High-Income Residential		Res	This is the most represented category in the landscape study findings, with multi-storeyed buildings in a majority of cases. It is expected that more than financial constraints, management and operation aspects are more prone towards contributing to failure.
Institutional and Commercial	Institutional Commercial	Inst Com	Including public and non-public institutions such as schools or hospitals or offices as well as commercial centres, hotels and restaurants, this category is assumed to have a good organisational entity and therefore an appropriate managerial body. Such sites can have wide range of financial flexibility depending on the size of the organization/company.
Municipal		Mun	This category is defined based on mixed wastewater sources that are connected to the treatment plant, including households, restaurants and small businesses. These communal systems are often implemented and/or managed by municipalities. Compared to the residential, insitutional and commercial contexts, only few municipal systems exit due to the lack of SSS policies for this context.

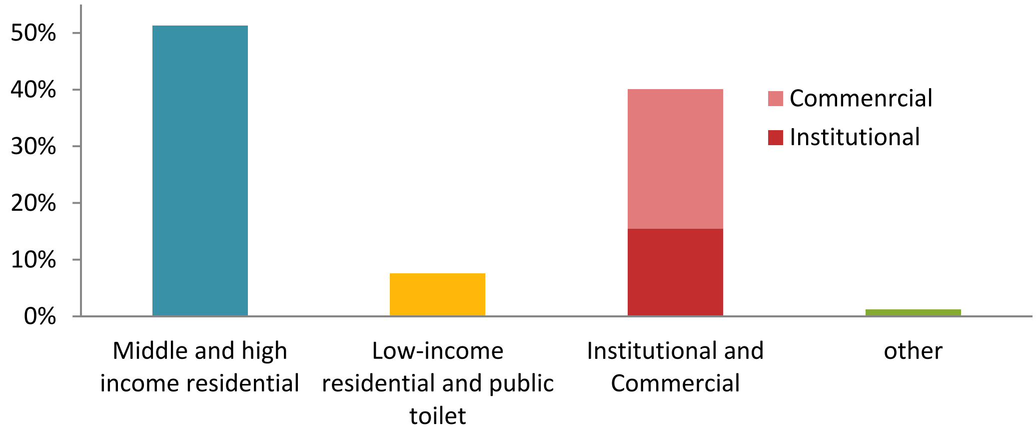


Figure 10: Context of small-scale sanitation systems in India from the landscape study database (n=2558).

3.1.4 Overview of small-scale sanitation systems and technologies used in India

As there are no comprehensive databases of SSS systems, a list of close to 9'500 SSS units was compiled from different scattered sources (see section 2.1.2) throughout the 4S Project. Figure 11 shows the major information sources for the database.

The following points are important to highlight:

- One third of the systems are from a list of residential complexes in Bengaluru which project partners had earlier obtained from the Karnataka State Pollution Control Board (KSPCB). It is not clear how many of them are actually required to establish SSTPs. According to Kuttuva et al. (2018) who refer to the same data source, at least 2'200 of them have installed or are installing SSS systems. On the other hand, in 2013 the KSPCB was only aware of 626 systems in Bengaluru (Shankar and Yathish, 2013), and in 2016 a KSPCB representative stated during an SSS workshop that at that time there were around 740 systems with consents to operate.
- A majority of the list entries provide almost no data about the system implemented (e.g. lacking information on technology used, capacity, exact location, context, operational status, performance etc.), depending on the source. This also makes it difficult to ensure there are no duplicates in the list.
- This illustrates that the list of systems compiled as part of the 4S Project does not allow to make precise, representative statistics about SSS systems in India, technologies used etc.
- The responses to RTI petitions contributed only about 4% of the entire list, clearly showing that Pollution Control Boards are not yet maintaining consolidated, comprehensive and electronic databases of SSS systems. Some PCBs do not maintain lists at all. This highlights the difficulties PCBs are facing with their limited human and financial resources to do a rigorous follow-up of large numbers of privately owned and operated SSS systems.

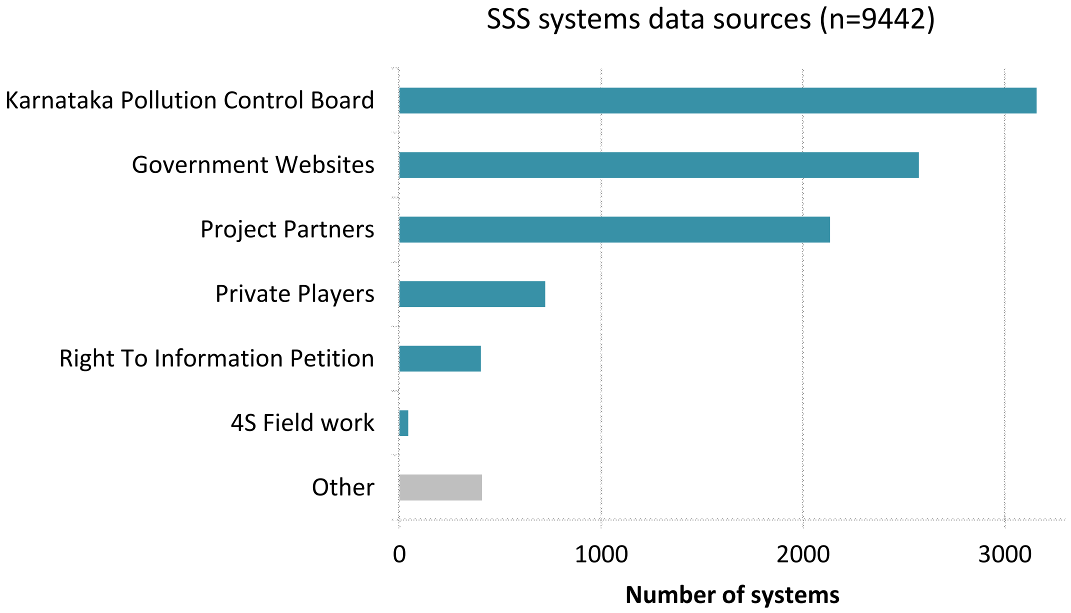


Figure 11: Total number of SSS systems inventorised in India as part of the 4S Project, classified by information sources.

Although the 4S list of systems is probably the most comprehensive dataset on SSS systems in India, it is by far not complete, with very limited and sometimes questionable information about individual projects. Therefore, it is hard to put a correct number on the total treatment capacity of such systems for the whole country, a state or a city. For instance, in Bengaluru (4677 list entries, potentially including some duplicates), SSS has an installed capacity to treat up to an estimated 10-20% of the city's sewage (Kuttuva et al., 2018; The Hindu Business Line, 2018).

Based on the database compiled and the observed challenges of rigorously documenting a quick private sector driven scale-up process, the authors estimate that overall probably more than 20’000 SSTPs exist throughout India.

A wide variety of technologies exists on the Indian SSS market. Table 8 presents an overview of all the different technologies identified during the 4S Project, classified into seven technology families based on the main treatment process. The table also highlights the most important technologies used in India.

Technologies vary from zero-energy or low-energy processes (including anaerobic reactors, plant-based systems or ponds) to highly automated and mechanised processes (including sequencing batch reactors or membrane bioreactors).

Technology providers have also come up with interesting variations of conventional processes and their own brand names to market themselves more effectively. In addition, several providers offer packaged/ready to install components or entire systems for treatment as well.

Several technology innovations are also on the market, using a variety of different biological, chemical, mechanical and electrolytic process combinations. A number of these innovative and proprietary technologies are marketed as cutting-edge high-tech systems but with unclear, non-transparent and secretive process descriptions.

Although many different technologies are found to be used in SSS in India, the conventional activated sludge process (ASP, including extended aeration designs), sequencing batch reactors (SBR) and moving bed biofilm reactors (MBBR) are identified to be the most prevalent SSS technologies. From the 4S database (which is not representative but reflects the information compiled through the various sources listed in Figure 11), close to 75% of the 2314 SSS systems where technological information is available are either ASP (32%), Anaerobic baffled reactor based systems (22%) or SBR (18%) (see Figure 12). The rest of the systems cover the entire range of technologies as presented in Table 8.

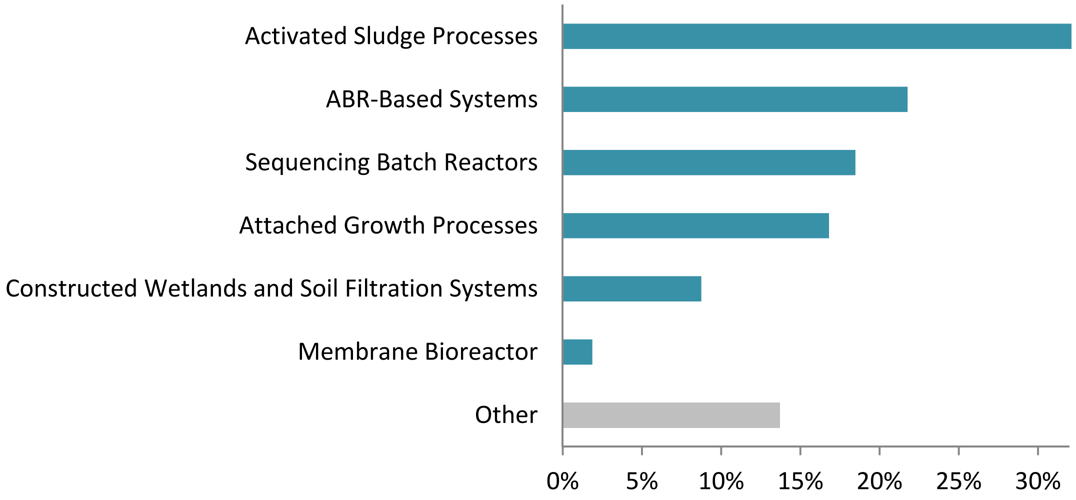


Figure 12: Technology family repartition in India from the 4S landscape study dataset (n=2314). This is not representative for India, it just reflects the information collected.

Table 8: Overview of small-scale sanitation technologies, classified into technology families. Package plants and prefabricated versions are included in the respective technology categories (e.g. prefabricated DEWATS under ABR-based systems, and Sintex PSTP NBF Series under MBBR). **Bold font** highlights the most common SSS technology families and technologies. Grey font means no system of the corresponding technology was visited for basic assessment data collection.

Technology Family	Technologies	Abbreviations	Synonyms/ Brand Names
A. Suspended Growth Processes			
A.1 Activated Sludge Processes	**Conventional Activated Sludge Process**	**ASP**	
	Extended Aeration	**EA**	
	Oxidation Ditch	OD	
A.2 Sequencing Batch Reactor	**Sequencing Batch Reactor**	**SBR**	
A.3 Membrane Bioreactor	**Membrane Bioreactor**	**MBR**	
B. Attached Growth Processes	**Moving Bed Biofilm Reactor**	**MBBR**	*Syn.:* Fluidised Aerobic Bioreactor (FAB), Fluidised Bed Bioreactor (FBBR)
	Submerged Aerated/Aerobic Fixed Film Reactor	SAFF	
	Rotating Biological Contactor	RBC	
	Trickling Filter	TF	
C. Anaerobic Baffled Reactor (ABR) Based Systems[1]	**Combinations of ABR with Anaerobic Filter (AF), Planted Gravel Filters (PGF)/Constructed Wetlands, Biogas Settlers (BGS), Polishing Ponds (PP) and Vortex**	**ABR-Based Systems**	*Brands:* Decentralized Wastewater Treatment Systems (DEWATS™), High-Rate Anaerobic Reactors (HRAR), Decentralised Treatment System (DTS)
D. Other Anaerobic Processes	Upflow Anaerobic Sludge Blanket Reactor	UASB	
	Defence Research and Development Organisation Biodigester	DRDO Biodigester	*Brands:* Various, e.g. Banka Bioloo
E. Constructed Wetlands and Soil Filtration Systems[2]	**(Continuous Advanced Multistage System using) Soil Biotechnology**	**CAMUS-SBT**	*Brand:* CAMUS-SBT™
	Solid Immobilised Bio-Filter	SIBF	*Brand:* SIBF
	Single Pass Intermittent Sand Filter	SPISF	
	Horizontal-Flow Constructed Wetland	HFCW	
	Vertical-Flow Constructed Wetland	VFCW	*Brand:* Soil Scape Filter
	Hybrid (Horizontal/Vertical-Flow) Constructed Wetland	Hybrid-CW	*Brand:* Phytorid
F. Pond Systems	Solar Evaporation Ponds	SEP	
	Waste Stabilisation Ponds	WSP	
G. Other Systems (incl. Physico-Chemical Processes)	Chemo-Autotrophic Activated Carbon Oxidation / Fluidised Immobilised Cell Carbon Oxidation	CAACO/FICCO	*Brand:* CAACO / FICCO
	Electrocoagulation / Electrolytically Activated Degenerative Oxidation	EC / EADOx	*Brand:* EADOx
	Advanced Oxidation Process	AOP	

[1] This type of systems is widely known as *Decentralized Wastewater Treatment Systems* (DEWATS), since it has been implemented worldwide under this name. As DEWATS™ is a registered trademark in India and similar designs are being implemented under different names by various vendors, this study does not use DEWATS in the technology family name.

[2] Without Anaerobic Baffled Reactor (ABR).

3.1.5 Private sector involvement in small-scale sanitation in India

Private sector engagement in sanitation is of paramount importance worldwide, which is also in line with the WASH targets set by Goal 6 of the Sustainable Development Goals (SDGs) and the means of implementation through engagement and partnership set by Goal 17 of the SDGs (Mason et al., 2015). In India, the private sector has taken the lead in implementing SSS systems, with almost all of them built, operated and maintained by private players. This is mainly due to the SSS policies requiring the implementation and operation of SSTPs as part of large real estate projects, and these construction projects being entirely implemented by the private sector.

A total of 308 private companies involved in SSS in India were listed during the 4S Project. These companies offer a range of services that include consultancy, design, turnkey solutions (including design, engineering, procurement, construction and commissioning), operation and maintenance (Figure 13, left). Very few offer all of these services, and only 40 companies (out of the 223 where information about services was found) offer both design and O&M services.

The density of such companies also varies by city (Figure 13, right). The information shown in the graph may or may not be representative of the actual scenario, since information available was scattered and varied by city. However, Bengaluru having the highest number of private entities in SSS is in accordance with the finding of Bengaluru being the city with the largest number of SSS systems installed. In interviews conducted for the 4S governance analysis (Chandragiri et al., 2020), some of the Bengaluru-based companies claimed to have implemented several hundred SSTPs in Bengaluru alone. Interestingly, only two companies were found in the metro city of Kolkata, where there is also hardly any information available about SSS systems (only seven were identified).

The 4S Project Report Vol. III on finance (Rajan et al., 2020) provides more information on how private stakeholders are organised in the SSS market.

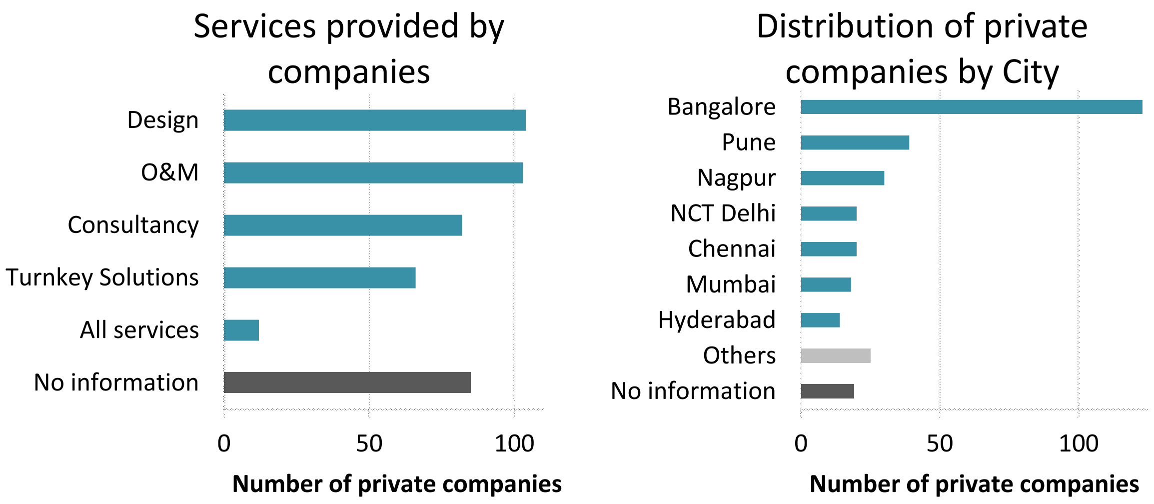


Figure 13: Range of services offered by private players (left; more than one option is possible) and city-wise distribution of companies involved in SSS in India (right) (n=308).

3.1.6 Technology choice: existing decision guides and current practice

There are plenty of reports that get into the details of specific technologies, functionality and engineering aspects (Cary et al., 2013; CPHEEO, 2013; Kodavasal, 2011a; MoUD, 2012; Philip et al., 2012). However, there are hardly any references that emphasise the importance of selecting the right SSS technology according to the context (Parkinson et al., 2008; Philip et al., 2012; Tare and Bose, 2009), and there is no comprehensive and impartial guidance material for informed choice according to context-specific parameters and the implications of all the different SSS technologies.

When designing an SSS system for a certain context, consultants and designers have the entire spectrum of treatment technologies to choose from. All these technologies have their implications in terms of life cycle costs (see 4S Project Report Vol. III on finance (Rajan et al., 2020)), footprint, O&M requirements, energy and consumables, treated water quality, noise, sludge generation etc.

Today, technology selection takes place based on the experience and preference of the consultant in charge. Rather than choosing the optimal solution from the entire spectrum based on clear criteria, consultants typically implement the technology they know best, partnering with their trusted vendors and technology providers. This leads to intransparent decision-making and possibly not the most appropriate solutions being implemented. Especially in the residential context, end users (who are not defined before the building is finished) do not have a say in STP technology selection. They are the ones, however, who eventually need to operate, maintain and pay for the system installed.

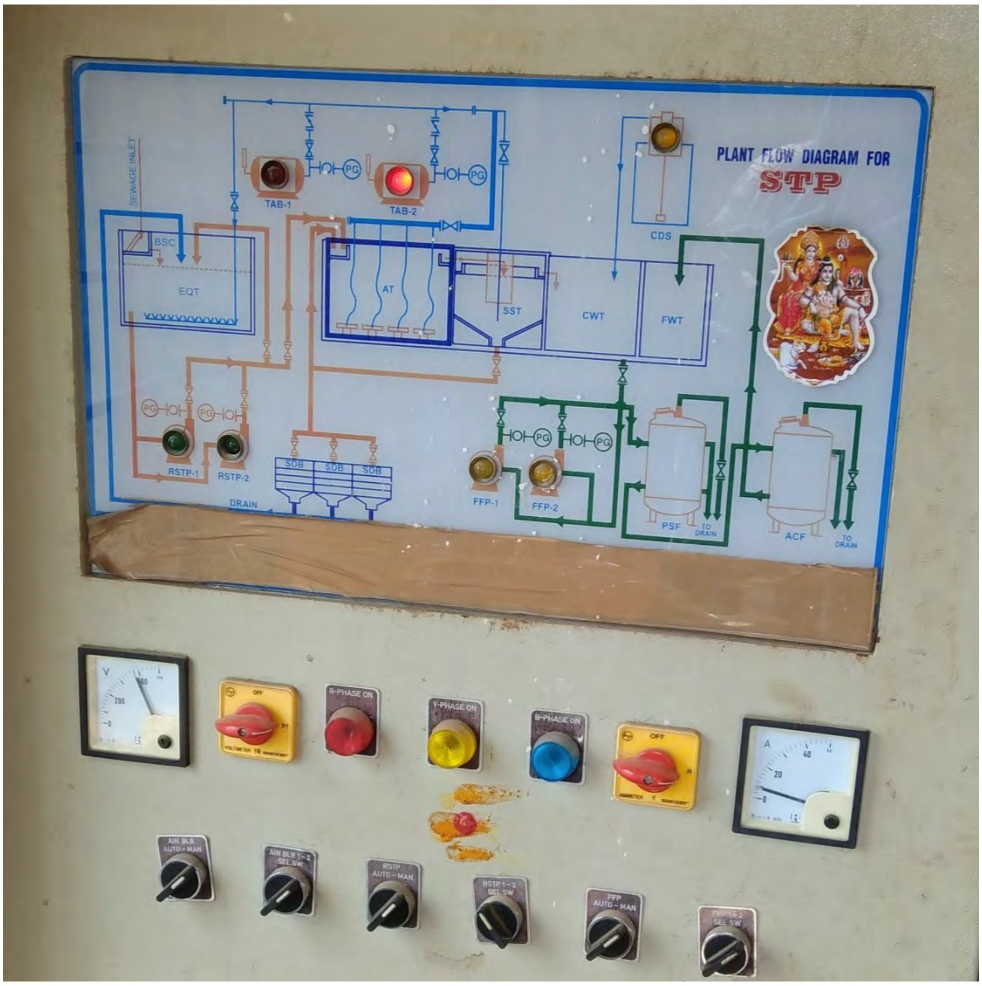


Figure 14: SSTP control panel with flow diagram (Photo: Sunil Kumar).

3.2 Basic assessment of SSS systems: site inspection and stakeholder interviews

Chapter Summary

- Most of the visited systems were built after 2006, when the first SSS policies came into force. The median capacity of the assessed systems is 100 KLD.
- It can be observed that recently commissioned systems often seem to be hydraulically underloaded, whereas older systems (8-11 years of activity) tend to reach a better equilibrium between the design and current loading, with a tendency to even be slightly overloaded. This reflects a characteristic of the real estate sector: it typically takes a few years for all apartments of a new residential building to get occupied.
- Most of the visited systems appear to be working properly even though an important number (at least 40%) is not run around the clock in order to save cost and because of noise nuisances.
- The reuse of treated wastewater seems to be quite well implemented with irrigation, toilet flushing and sometimes air conditioning as reuse options. However, it was observed that 100% on-site water reuse is difficult and that available options for its off-site reuse are limited. Systems in the low-income residential context and public toilets are often designed for wastewater treatment only and not for reuse.
- Many operators and managers are not properly trained to sustainably run their SSS systems.
- Sludge management appears to be a major issue. Only 32% claimed to treat their sludge to some degree on-site, and 6% stated to have access to an off-site treatment facility. For the rest, the untreated sludge is disposed of otherwise, potentially posing high public health and environmental risks.
- SSS systems in the commercial, institutional and middle- and high-income residential contexts are usually managed by the private sector, either in-house (by the resident welfare association or specific maintenance unit) or out-sourced to specialized companies. For the studied low-income residential systems and public toilets, local government was found to be responsible, or in few cases an NGO or CBO. In the low-income context, there was no user fee collection in most cases, whereas in the other residential contexts the users contributed to the operation and maintenance cost via a general apartment maintenance fee.

Not all interviews were completed for each site due to limited availability of interviewees and not all questions were answered:

- SSS systems assessed: 279
- Observation checklists filled: 279
- Manager interviews: 239
- Operator interviews: 240
- User interviews: 70 (only in the residential context, see section 2.2.1)

Accordingly, some of the graphs presented in the following are based on a smaller dataset, based on data availability.

3.2.1 Site selection and description

Using the selection criteria and accessing methods described in sections 2.2.2 and 2.2.3, a total of 279 SSS systems were visited and assessed. The systems are located in 8 states throughout India (Karnataka, Tamil Nadu, Kerala, Puducherry, Andhra Pradesh, Telangana, Maharashtra and National Capital Territory of Delhi), with a focus on south Indian states (see Figure 15). This geographical focus is due to several factors. As seen in the landscape study, most of the existing systems were built in the southern states because of their proactive policies in small-scale sanitation. With the project team being based in Bengaluru and Chennai, it was easier to contact and get access to systems from local players. The possibility to meet them in person increased the permission probability for site visits as compared to distant contacts available via email or phone. All visited sites were serving urban or peri-urban areas.

Figure 15: Location of visited sites during basic assessment phase (n=279).

The data collected is therefore not fully representative of the actual current status of small-scale sanitation all across India. Generally, for most of the systems assessed, the permission was granted by either designer, implementer or owner of small-scale sanitation systems, potentially leading to an overrepresentation of well working systems. While analysing the following results, one should have in mind that this is potentially the best case scenario and the reality is probably worse. About 13% of the visited systems were selected through the partner organization CDD Society which provided full access, without restriction, to all the DEWATS systems that they implemented or helped implementing. Potentially, results for these technologies may be worse than for the other technologies which were accessed through more biased sources.

3.2.2 Technology and context

Approximately half of the assessed SSS systems were treating wastewater from residential settlements (low-income housing and public toilets 14%, middle- or high-income 33%) whereas the other half were serving commercial or institutional buildings. This distribution cannot be assumed to be representative for India. Rather, the aim was to have an equal distribution in order to cover the spectrum of potential issues concerning the management and operation and maintenance of SSS systems.

Commercial, institutional, middle and high-income residential buildings were mostly equipped with aerated treatment systems whereas low-income residential buildings and public toilets mostly relied on non-mechanised ABR-based systems (see Figure 16). Goals of implementation were different. The first group needed to comply with the law and achieve stringent water quality and effluent standards from CPCB. They were also implemented with the objective of treated water reuse. On the contrary, systems built to cater for lower-income residential areas were mostly implemented by NGOs or governmental agencies during disaster relief interventions or in slum areas. Their aim was primarily to provide clean and affordable sanitation alternatives to the poor and vulnerable population rather than produce treated wastewater for reuse purposes. These differences were taken into account during the analysis where applicable.

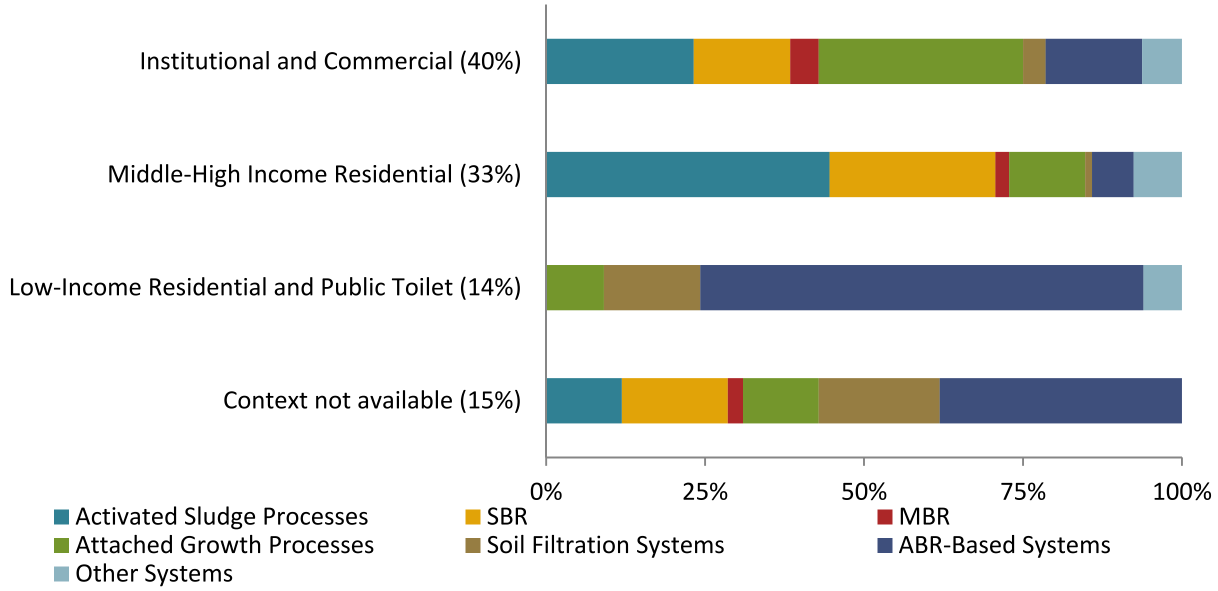


Figure 16: Distribution of treatment technologies in different contexts of application (n=279).

3.2.3 Age and design capacity of systems

Age of systems

Most of the studied systems were built after the 2006 MOEFCC EIA amendment notification (MoEF, 2006) which directed large construction projects to implement SSS systems (see section 3.1.1). Moreover, more than half of the assessed systems were started up after 2011 (see Figure 17). Even if not fully representative of the situation in India, this shows the growing enforcement of the 2006 policy especially in the states of Karnataka and Tamil Nadu over the last decade. The fact that most of the assessed systems are quite young also means their sustainability has yet to be confirmed.

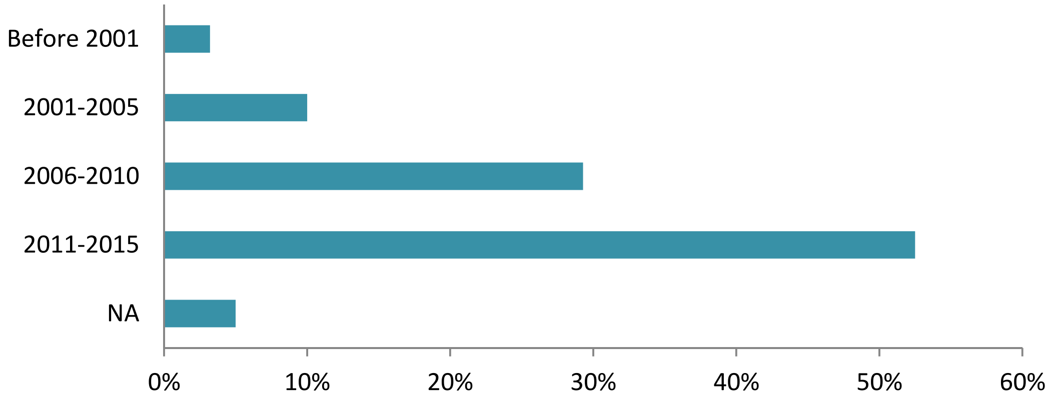


Figure 17: Age distribution of assessed systems, relating to the year of start of operation (n=279).

Capacity of systems

The capacity of the visited systems is mostly on the lower side of the overall capacity range considered in the 4S Project (5 to 700 KLD, see Figure 18). More than half (61%) of the known capacities are between 5 and 100 KLD and very few systems over 400 KLD were found (median = 100 KLD). It is quite likely that this distribution is a direct consequence of the 2006 policy promoting the building of single SSS systems for each construction project separately, without any incentive to cluster the treatment of the produced wastewater from the surrounding area. This leads to a high density of fairly small SSS systems. The financial analysis of the 4S Project showed that there is a high potential of economy of scale for SSS systems up to approximately 120 KLD plants (see 4S Project Report Vol. III on finance (Rajan et al., 2020)).

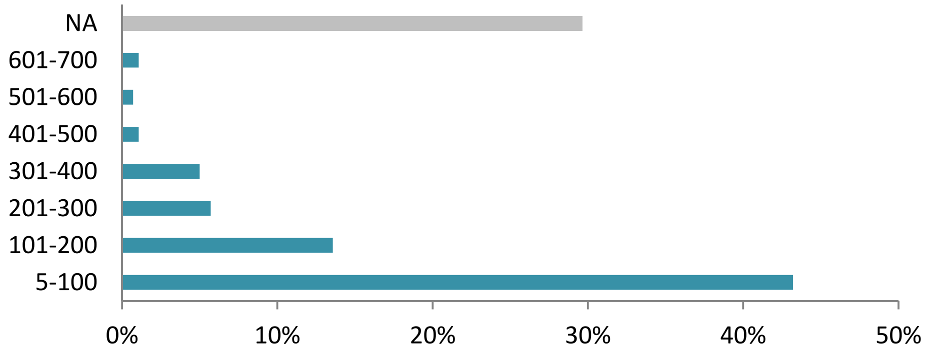


Figure 18: Capacity distribution of visited systems [range in KLD] (n=279).

System capacity utilisation versus system age

For systems treating residential wastewater, the ratio between the number of people connected to the system at the time of the site visit and the number of people the system is designed for was calculated where data was available (n=50). This ratio is an approximation of the capacity utilisation, indicating whether a system may be hydraulically under- (<1) or overloaded (>1). The ratio was plotted against the age of the system (see Figure 19). It can be observed that the youngest systems often seem to be hydraulically underloaded, whereas older systems (8-11 years of activity) tend to reach a better equilibrium between the design and current loading, with a tendency to even be slightly overloaded. This reflects a characteristic of the real estate sector: it typically takes a few years for all apartments of a new residential building to get occupied. Accordingly, the treatment system has idle capacity during this initial time of low occupancy rate. A similar trend might be expected for new commercial buildings. Another kind a variation (daily, weekly or seasonally) can be observed in institutions like schools, hospitals or in hotels with varying numbers of patients, students or hosts. This kind of fluctuations can affect the treatment efficiency of a system. In fact, as the treatment is biological, a lack of substrate (underloading) can inhibited microbial activity, and a too high flow (i.e. hydraulic overload) will flush microorganisms out of the system.

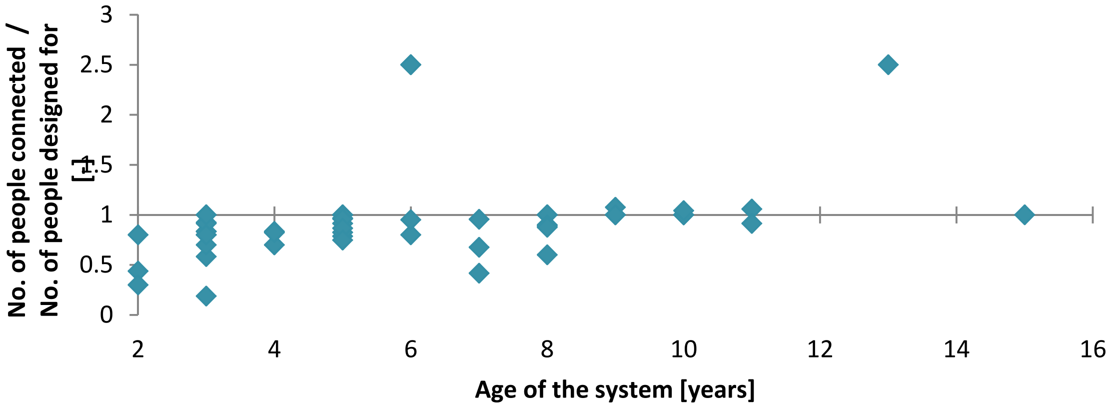


Figure 19: Capacity utilisation, approximated from the ratio between the number of people connected to the system and the number of people the system is designed for, plotted against the age of the system (residential systems only, n= 50).

3.2.4 Operational status of systems

A majority (59%) of the surveyed systems were reported to be fully functional and supposed to be running 24/7 (see Figure 20). Nevertheless, this data might be subject to a big bias and not really reflecting the daily reality of SSS systems. Indeed, during the following in-depth assessment, it was observed that most of the mechanised treatment systems were not operated around the clock and usually not running or in "standby mode" (e.g. only some aerators on) at night. Reasons were that managers and operators were pressured by the owners to reduce O&M costs or noise nuisances. This results in a lower performance as these systems require constant oxygen supply to maintain healthy micro-organisms to treat the wastewater.

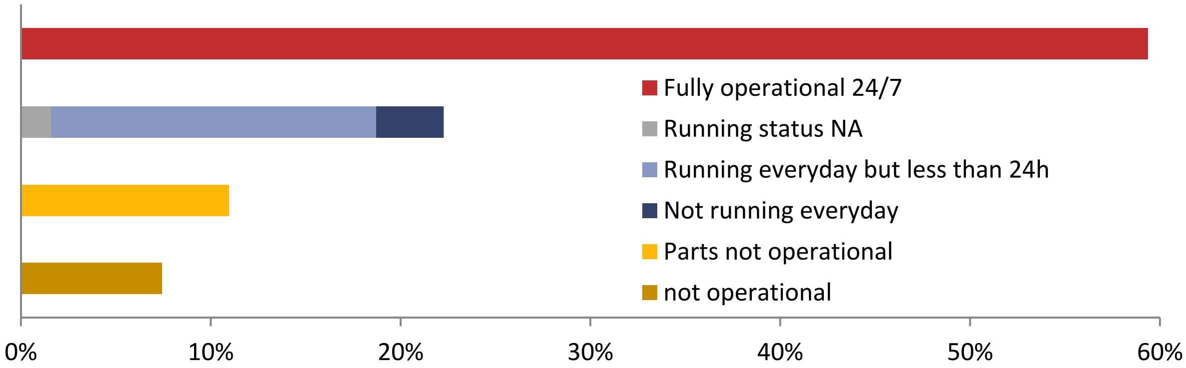
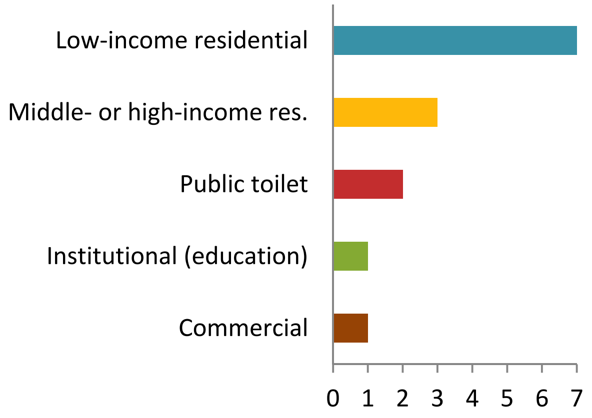


Figure 20: Operational status (fully/partially) and running pattern (24/7 or not) (n=279).

Non-operational systems

14 out of 279 systems were not operational, which meant they didn't have any wastewater going through the system anymore. These systems included institutions, commercial complexes and any residential settings with a predominance of low-income residential settlements (see Figure 21). The failure was usually permanent (see Figure 22) and due to unrepaired damages either to the treatment components, pumps or the sewer (see Figure 23). The main reasons cited to explain why nothing had been done to fix the issue were the lack of support from the implementing body (local government body), followed by a lack of interest for the sanitation system, no access to maintenance services, or lack of money (see Figure 24).



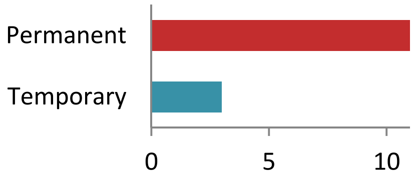
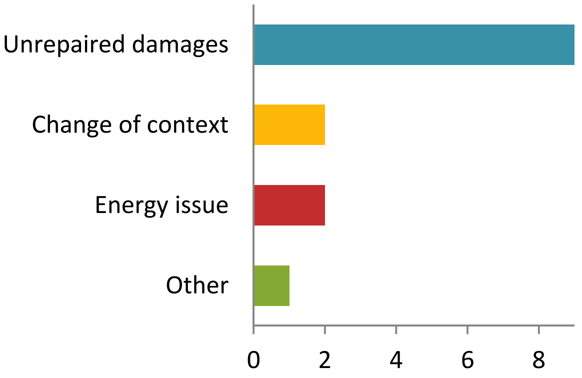


Figure 21: Application context of the non-operational systems (n=14).

Figure 22: Permanence of the failure of the non-operational systems (n=14).



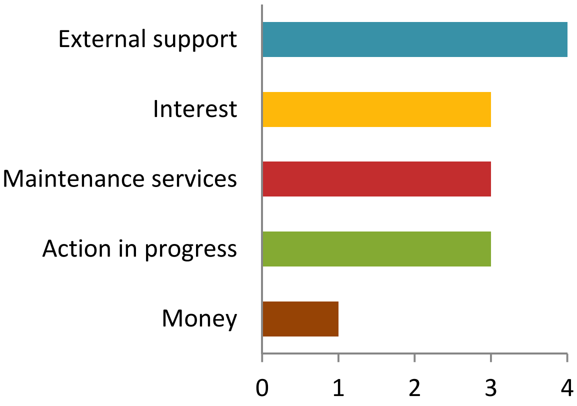


Figure 23: Initial reason of failure of the non-operational systems (n=14).

Figure 24: Reasons for no action since failure of the non-operational systems (n=14).

3.2.5 Treated water reuse practices

Figure 25 shows the different water reuse options, grouped by context. Irrigation and toilet flushing are the most present reuse applications for treated wastewater. Low-income residential blocks and public toilets which were mainly built by NGOs often don't have reuse objectives and were designed mainly to provide sanitation facilities to the poorest people. For urban commercial, institutional and residential buildings, the water reuse policies seem to show good results. Yet, not all water is reused. Even if the manager were usually reluctant to confess it, it was often observed that parts of the treated wastewater was discharged in the drains or into some neighbouring wasteland. Even though the pressure to reuse treated wastewater was high, it remained difficult as reuse options are quite limited and nothing is done to foster regional reuse.

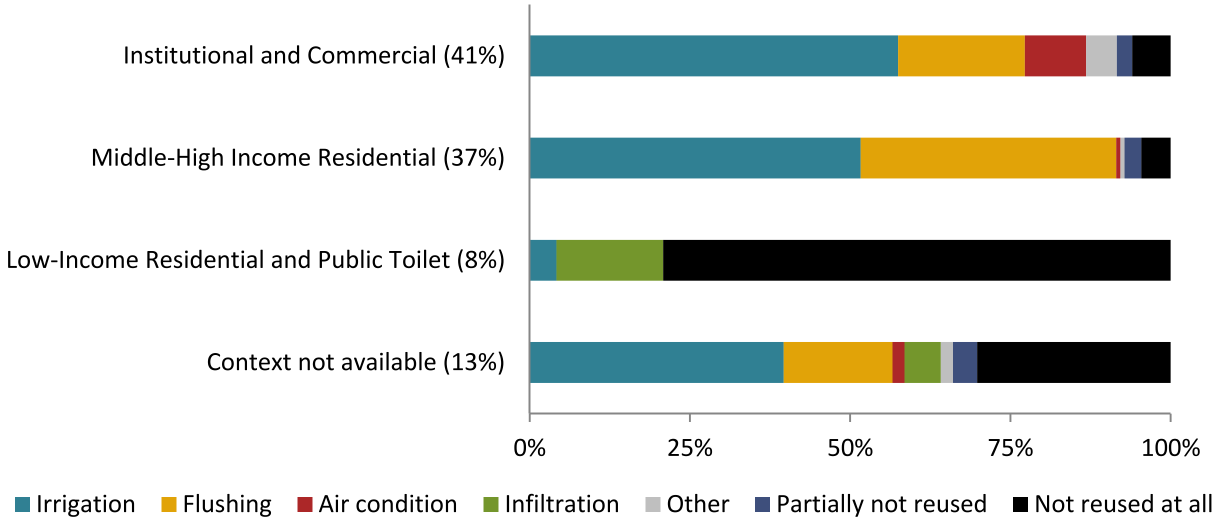


Figure 25: Treated wastewater reuse application (n=279). More than one reuse application per system was possible.

3.2.6 Training and capacity of managers and operators

Overall, the interviewed managers (n=239) were quite poorly trained; > 40% did not receive any training at all (see Figure 27). A majority of the operators (85%) attended at least one training (see Figure 26). Most manager trainings were technical trainings, and trainings about the operation or troubleshooting of the plant (see Figure 29). While useful and needed, almost no trainings about the financial management of plants were transferred. 39% of operators (n=272) received basic instructions (see Figure 28). More than half (54%) of the operator trainings were provided by in-house people (e.g. previous operator or manager) whereas most of the manager trainings were usually outsourced to external companies (75%).

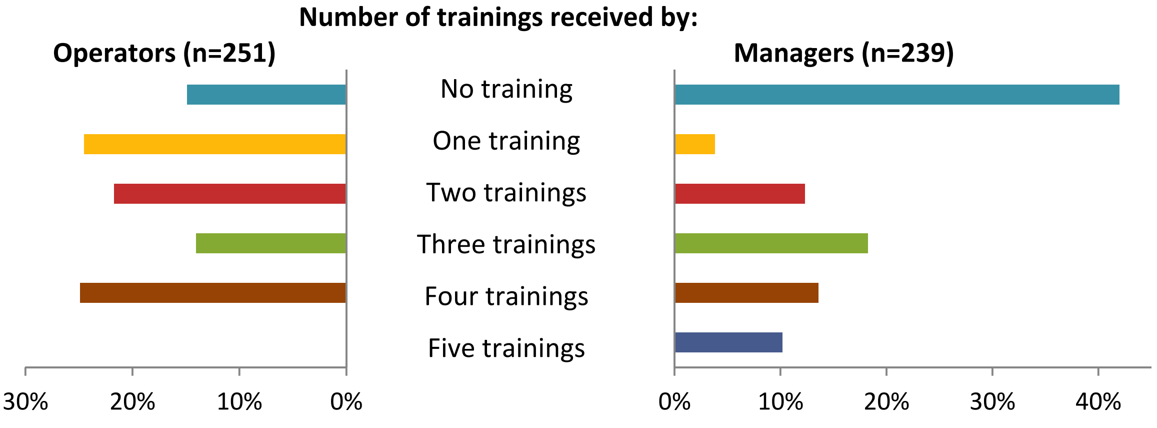


Figure 26: Distribution of total number of trainings received by operators.

Figure 27: Distribution of total number of trainings received by managers.

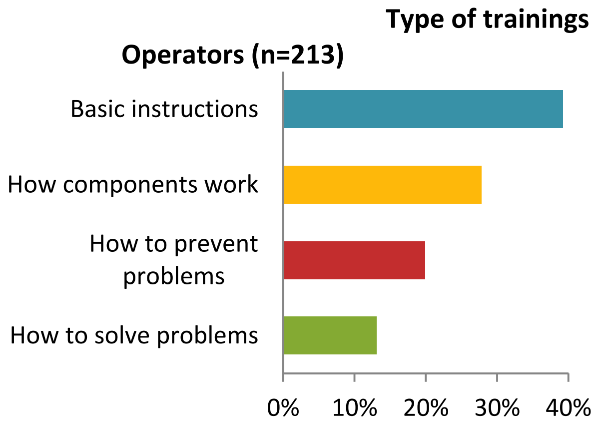


Figure 28: Type of trainings received by operators.

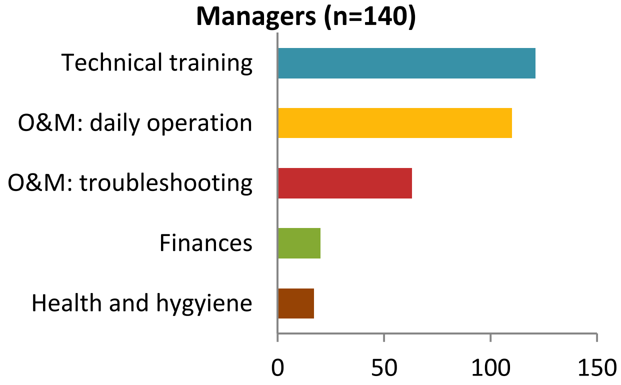


Figure 29: Type of trainings received by managers.

3.2.7 Common issues with small-scale sanitation systems

When asked, managers and operators were more prompt to say that there are no disadvantages with SSS systems, whereas users were more inclined to see issues. Nuisances (smells, insects, rodent, snakes) were the biggest concern for most of the interviewees. Clogging also appeared quite often (see Figure 30). These nuisances can be the result of a wrong design, but most often they are the consequence of poor operation and maintenance of the system.

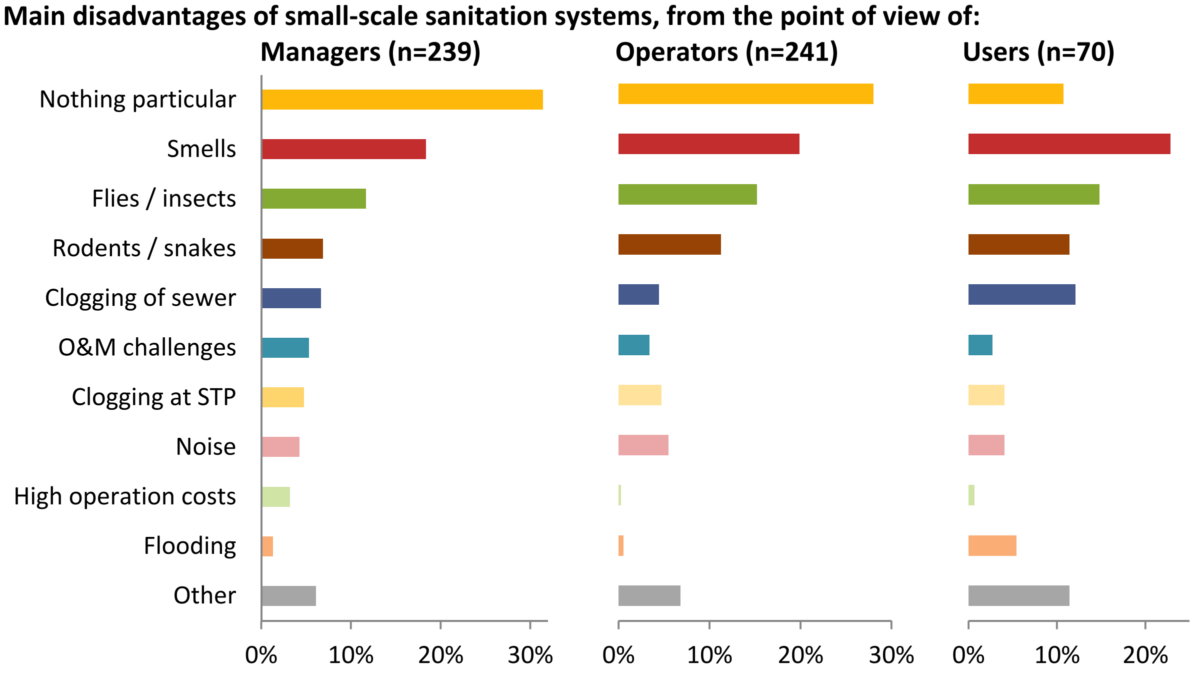


Figure 30: Main disadvantages of SSS systems from the point of view of the managers, operators and users.

Operational issues

Concerning operation, again, smell was the most recurring issue (see Figure 31), potentially indicating that operators and managers are lacking the knowledge to properly maintain the system so that it would not smell. Technical issues were the second most cited problem for operating the system, potentially due to low quality materials used during implementation and/or, again, poor knowledge on how to operate and manage the system. The lack of money and difficulties to provide consumables and spare parts were also important barriers to the proper functioning of the system. Inappropriate or lacking sludge disposal options was also raised as a major issue by the interviewees during site visits. This issue is further discussed in section 3.2.9 below.

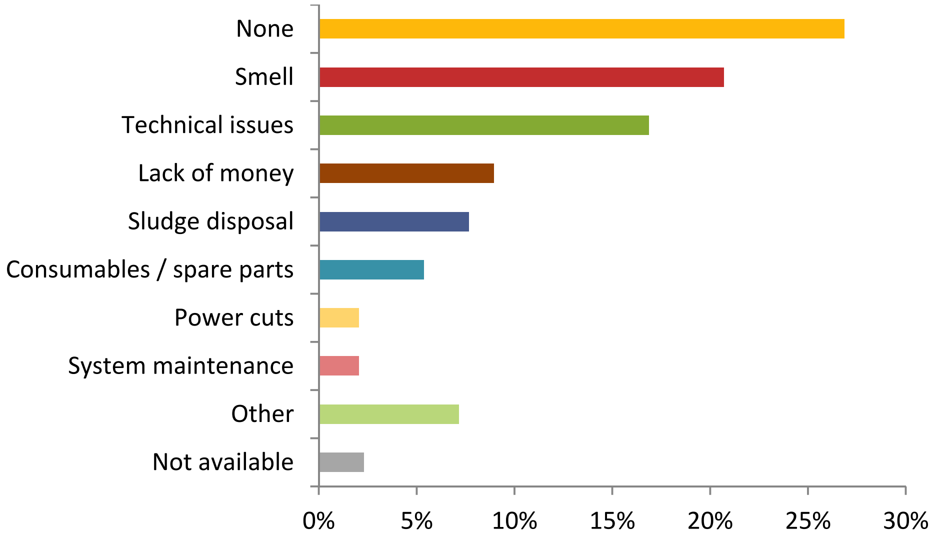


Figure 31: Main issues during daily operation from the point of view of managers and operators (n=279).

3.2.8 Major maintenance works

At one third of the systems assessed, the operator or manager knew of at least one major maintenance work done on the treatment plant they were currently operating/managing. Another third said no work had been done till now and the last third were not able to tell (see Figure 32). As the median age of the assessed systems was five years, one can roughly conclude from this data that the first major maintenance works usually occur after about five years. It would be an important figure to have in mind when planning maintenance expenses of a treatment system. Figure 33 presents the main types of major maintenance works required.

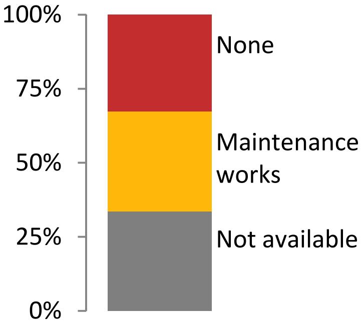


Figure 32: Proportion of systems with major maintenance work since start of operation (n=279).

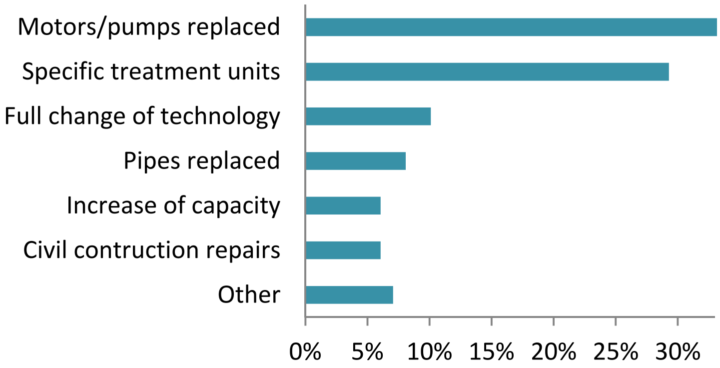


Figure 33: Types of major maintenance works done (n=94).

3.2.9 Sludge management: desludging and sludge treatment practices

More than 50% of all sites visited did not treat the sludge produced by the system (see Figure 34). This is an important issue as the sludge contains high concentrations of pathogens and organic pollutants and has a high contamination but also reuse potential. If the sludge produced by the treatment plant is not safely handled and disposed of, the goal of this system cannot be fulfilled. This highlights the lack of solutions for off-site sludge treatment options.

When the sludge was treated on-site, the most common technologies used were sludge filter presses and unplanted drying beds (see Figure 34). Such treatment processes dewater and partially stabilise the sludge. This makes it safer for handling and possibly end-use, even though it is not fully sanitized.

Only few systems sent their waste for off-site treatment. In this case it was mostly impossible to learn about the fate of the sludge as interviewees were usually not aware of where it was taken.

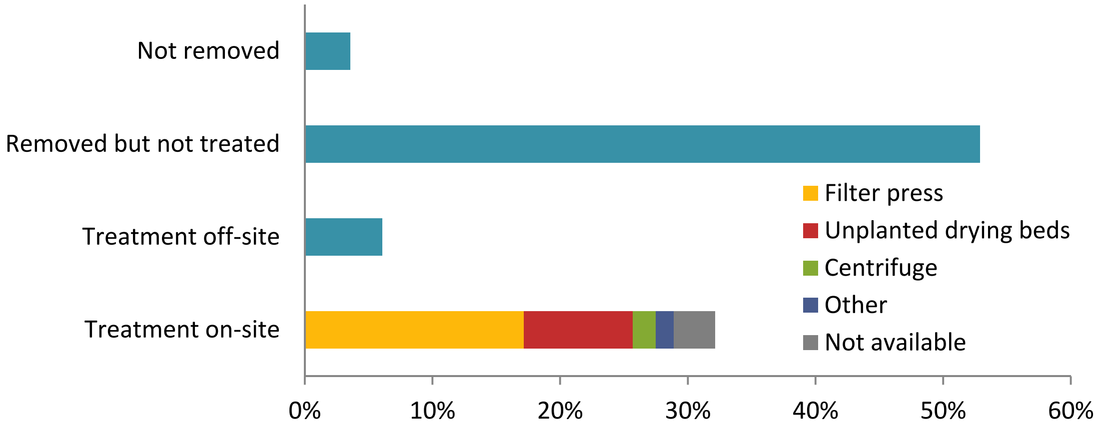


Figure 34: Desludging and sludge treatment practices (n=279).

3.2.10 Collection of funds for the operation of SSS systems in the residential context

The operation of residential treatment systems in most middle- and high-income settlements was funded through a wastewater fee that is usually collected by the resident welfare association, as part of the overall apartment maintenance fees (see Figure 35). Conversely, the lower-income residents were usually not paying for the sanitation system. This might lead to a lack of money to properly operate and maintain the system and can eventually lead to its failure.

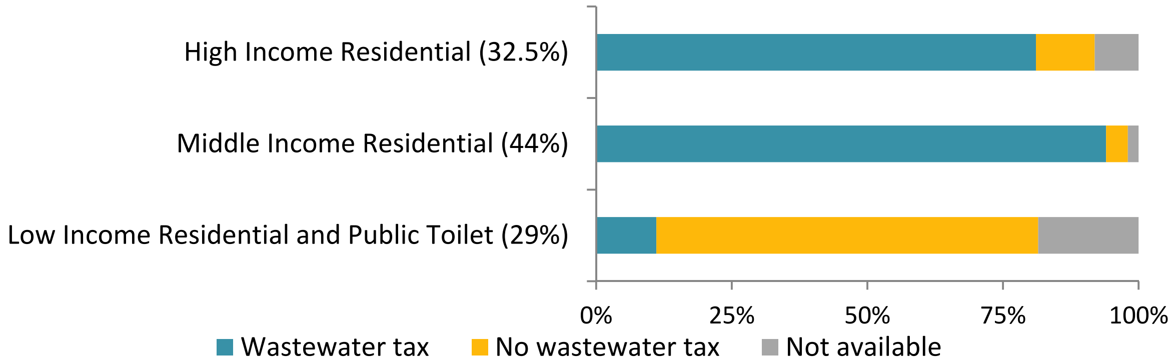


Figure 35: Fee ("wastewater tax") collection for SSS system management in the residential context, by level of income (n=70).

3.2.11 Management schemes for the operation of SSS systems

SSS systems in the commercial, institutional and middle- and high-income residential contexts were usually managed by the private sector, either in-house (by the resident welfare association or specific maintenance unit) or out-sourced to specialized companies (see Figure 36). The in-house management of SSS systems is probably cheaper but might lead to issues due to the absence of specific knowledge and expertise on the part of managers and operators of such systems.

Concerning lower-income settlements and public toilets, the management of systems was only done by local government bodies or NGOs/CBOs, indicating an often very distant management. Closer management would be meaningful due to the low level of awareness on the part of the users.

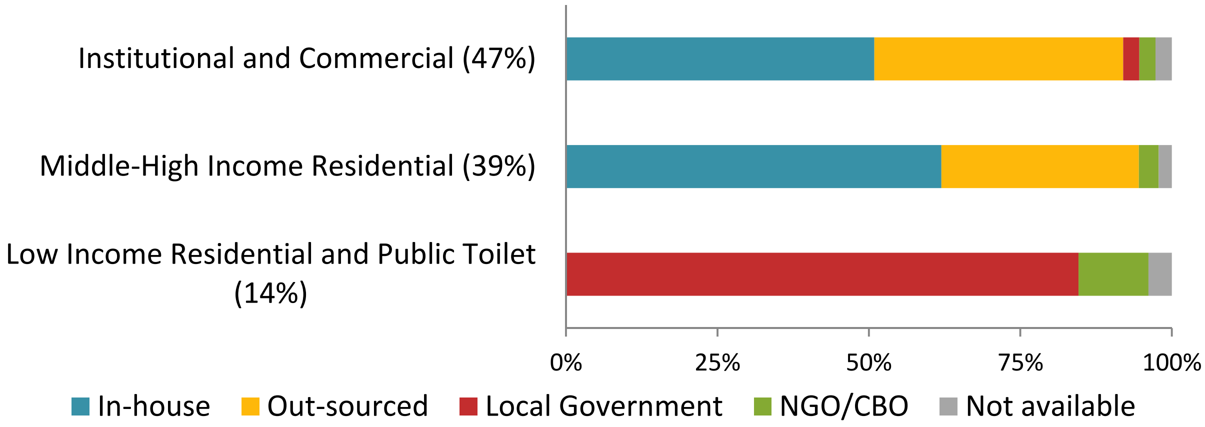


Figure 36: Management schemes for SSS Systems, by context of application (n=279).

More information on the different management schemes and their advantages and disadvantages is provided in 4S Project Report Vol. III on finance (Rajan et al., 2020).

3.3 In-depth performance analysis: sampling campaigns

Chapter Summary

- Inlet concentrations as well as the variability of organic and hydraulic loading are often much higher than what is typically observed at centralised treatment plants.
- Wastewater generated by low-income communities and especially public toilets is significantly more concentrated than wastewater generated by middle- to high-income communities.
- All technology families contain systems of very high and low treatment efficiency.
- The analysis of the results for treatment of organic pollutants (BOD, COD) and suspended solids (TSS) shows that most technologies can achieve a BOD removal rate of about 95% (90% for total COD; 95% for TSS) and that a majority of the systems analysed was achieving BOD, COD and TSS removal rates of about 90%. The results indicate that any of the studied technologies (if combined with the right post-treatment units and operated correctly) has the potential to achieve quite stringent BOD, COD and TSS standards.
- Both results for ammoniacal and total nitrogen removal rates present lower removal efficiencies as well as a higher variability than the removal rates for organics and suspended solids. None of the investigated systems is designed with a denitrification step, with the consequence that TN standards are almost never met. High TN concentrations are generally linked to high effluent ammonium concentrations.
- The FC concentration reduction results show a high variability of efficiencies between systems as well as for single systems in between rounds of sampling. The FC standard is systematically not met by all of the assessed systems with the only exception of one system which met the standard during two out of three rounds of sampling. Systems with disinfection steps (chlorination in most cases) do not ensure a better microbial removal rate and effluent quality than systems that do not disinfect.
- Precise measurement of the daily wastewater flow was found to be a challenge. The available data did not allow to reliably study the effect of hydraulic system loading on treatment efficiency.
- A qualitative assessment of treatment systems based on field observations has the potential to identify the worst-case systems but cannot replace sampling campaigns.

The performance of 40 small-scale wastewater treatment systems (35 in India and 5 in Nepal) is analysed in this section, covering a wide range of technologies used (ASP, SBR, MBBR, MBR, ABR-based systems, constructed wetlands and soil filtration systems, electrocoagulation). **An overview of the systems studied, including context and technology details (sequence of treatment units), is provided in Table 1.**

The influent characteristics and variability is analysed first. The removal efficiency as well as the compliance of the effluent quality with the most recent CPCB standards are then studied, followed by an analysis of the effect of inflow concentration and hydraulic system load on treatment efficiency. The chapter ends with an investigation of the relationship between the observed system status and measured effluent quality.

3.3.1 Inflowing wastewater characterisation

Understanding the characteristics of inflowing wastewater is very important for SSS systems. These characteristics are subject to a lot higher variations than conventional centralised treatment systems where the wastewater characteristics are buffered by population size and length of the sewer network (CPHEEO, 2013; Tchobanoglous et al., 2004). 24 h flow-proportional sampling repeated on different days (see section 2.3.2) can account for such variations to a certain extent. However, the following data is based on three days of measurement only, and therefore has to be interpreted accordingly.

Figure 37 shows the inlet wastewater characterization of the 40 sampled treatment systems. The box plots visualise the wide range of concentrations that can arrive at SSS systems (e.g. 80% of BOD concentrations are between 120 and 1’040 mg/L), determined by local contextual factors and possibly also temporal patterns (e.g. seasonal variations). The concentrations are often a lot higher than what could be expected at the inlet of a big centralised treatment plant.

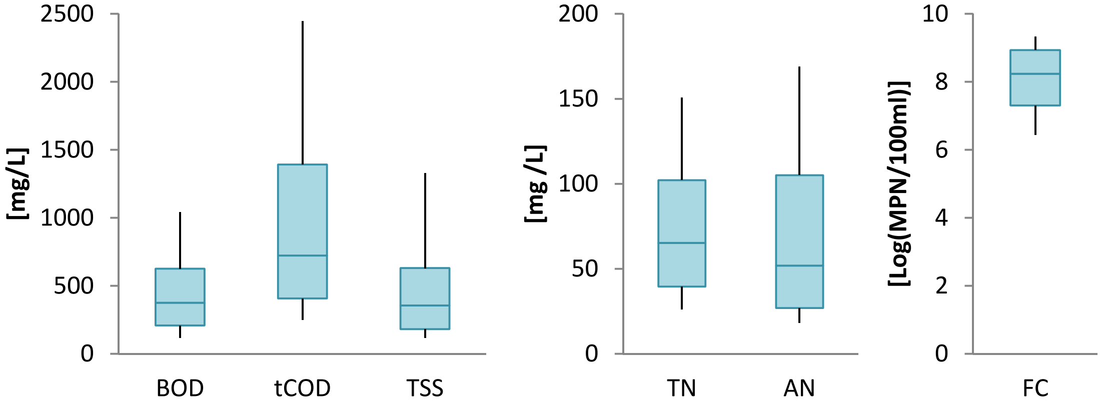


Figure 37: Box plots (0.1, 0.25, 0.5, 0.75 and 0.9 percentiles) of inflow wastewater characteristics from 40 sampled SSS systems (three rounds of 24 h composite sampling).

Figure 38 shows the influent characteristics grouped by context. Wastewater from institutions and from middle- to high-income residential blocks seems to have lower and less variable influent concentrations for all the relevant parameters. On the other hand, low-income residential units and public toilets usually have significantly more concentrated wastewater than middle- to high-income communities, probably due to the lower water consumption in these contexts (pour-flush toilets and/or no greywater). Municipal wastewater tends to have lower organics and solids content but very high and variable nitrogen content, which could be due to infiltration from surrounding farmlands as these systems were constructed away from housing settlements in agricultural areas.

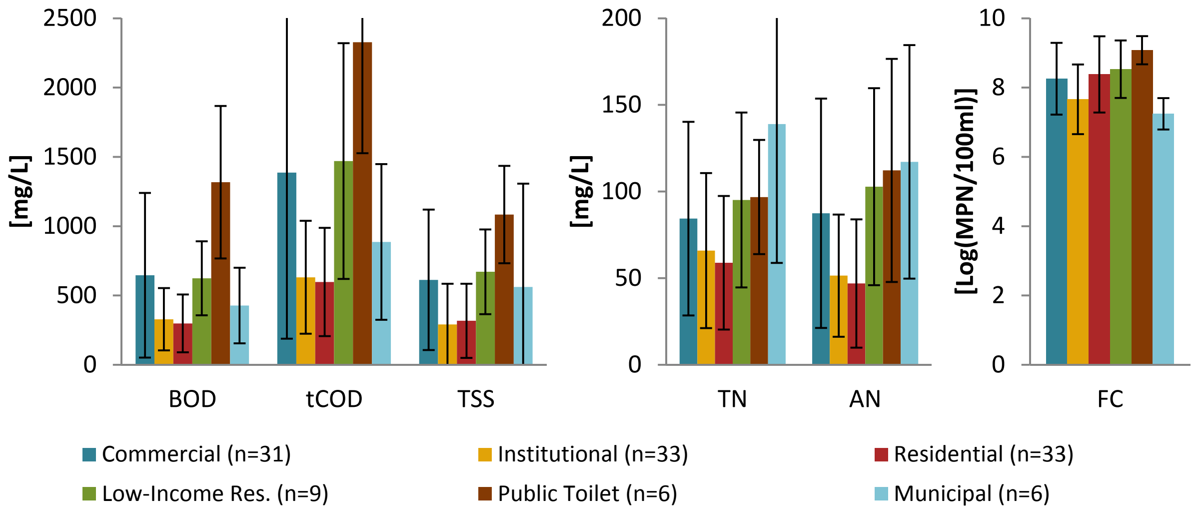


Figure 38: Influent concentration per application context (average ± standard deviation), from 40 sampled SSS systems (three rounds of 24 h composite sampling).

The feed BOD and TSS concentrations of the individual systems are shown in Figure 39. Two ABR-based systems process very highly concentrated wastewater, one operating in a commercial (ABR-based-2), the other in an institutions context (ABR-based-9). Other systems treating relatively highly concentrated wastewater are SBR-1 (residential), MBBR-6 (commercial), ABR-based-4 and 5 (both public toilet systems), ABR-based-8 (commercial) and ABR-based-10 and 11 (both low-income residential systems).

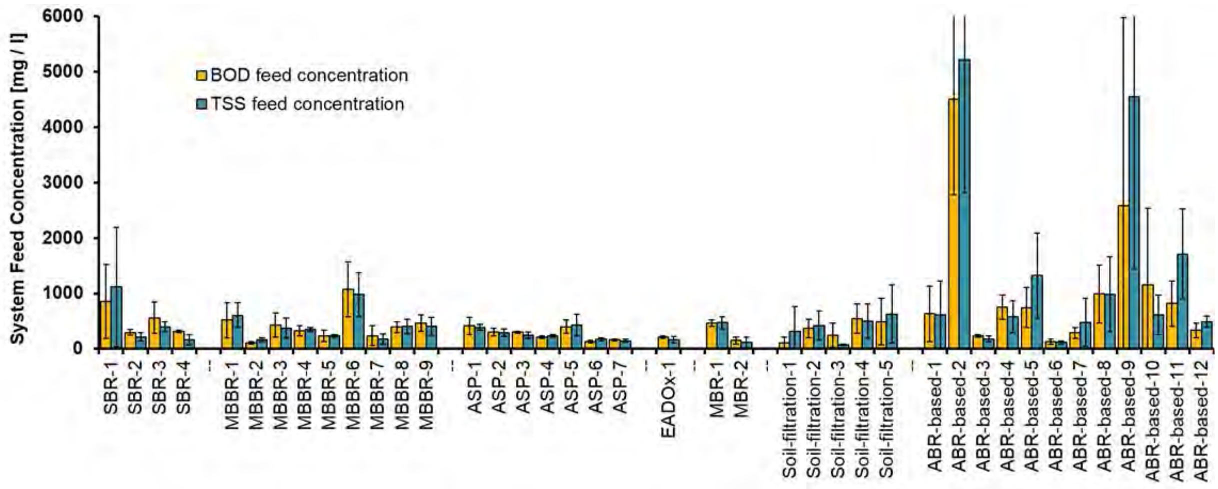


Figure 39: Average BOD and TSS system feed concentrations as measured during three rounds of 24 h flow-proportional composite sampling, error bars indicate standard deviations.

Volumetric flow was estimated by measuring the time for a 20 litre bucket to fill (see section 2.3.3). This was done one to three times every two hours during 24 hours. A total of three campaigns were done at each system, therefore producing three estimates of daily wastewater flow per site. Figure 40 presents the average of these three daily flows. The error bars indicate the standard deviation across the three estimates.

One has to keep in mind that wastewater flows produced by small communities are highly variable. Flows may significantly change from one minute to the next, and variation of average hourly flows across days is considerable. The accuracy of this flow measurement method is, therefore, expected to be low and to not allow for hydraulic system load estimations.

However, the data is presented here to showcase its high variability. Figure 40 also includes system design hydraulic loads to indicate their range across the investigated systems.

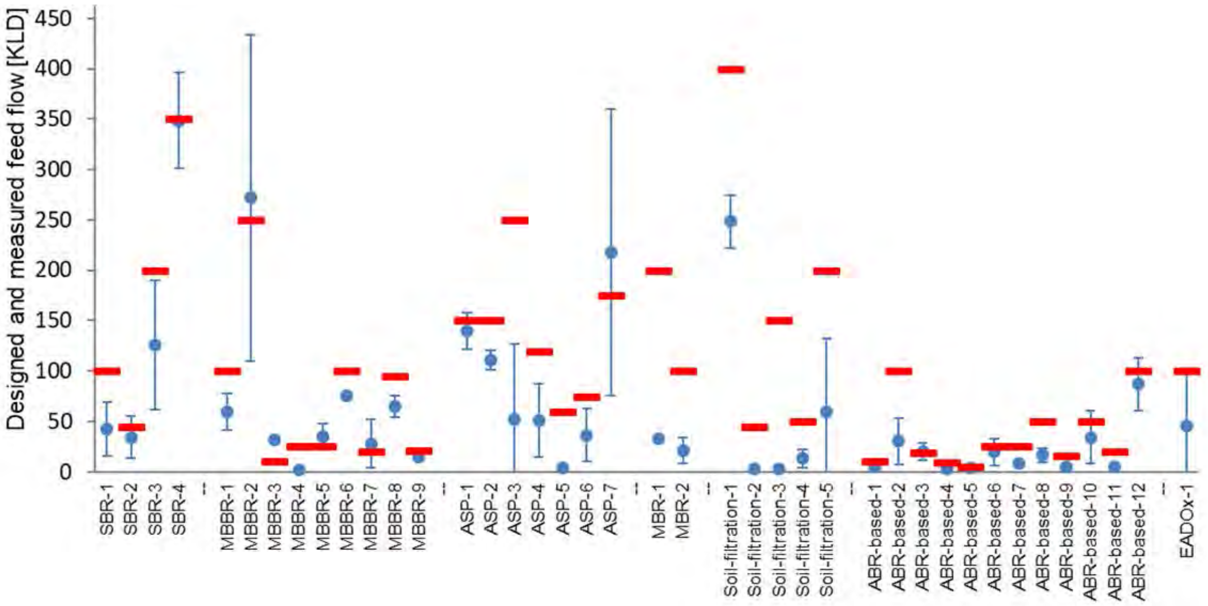


Figure 40: Average daily inlet flows at the 40 sampled systems as estimated during the three rounds of 24 h flow-proportional sampling. Error bars indicate standard deviation, red bars indicate design hydraulic loads.

3.3.2 Overall performance of systems

Organics and suspended solids removal efficiency and effluent quality

This section analyses the treatment performance of organic pollutants as well as total suspended solids. The three relevant parameters for SSS system effluent discharge in India as per CPCB standards are BOD, COD and TSS (see Table 3).

The results for BOD, COD and TSS removal efficiencies and effluent quality are presented in the following three figures.

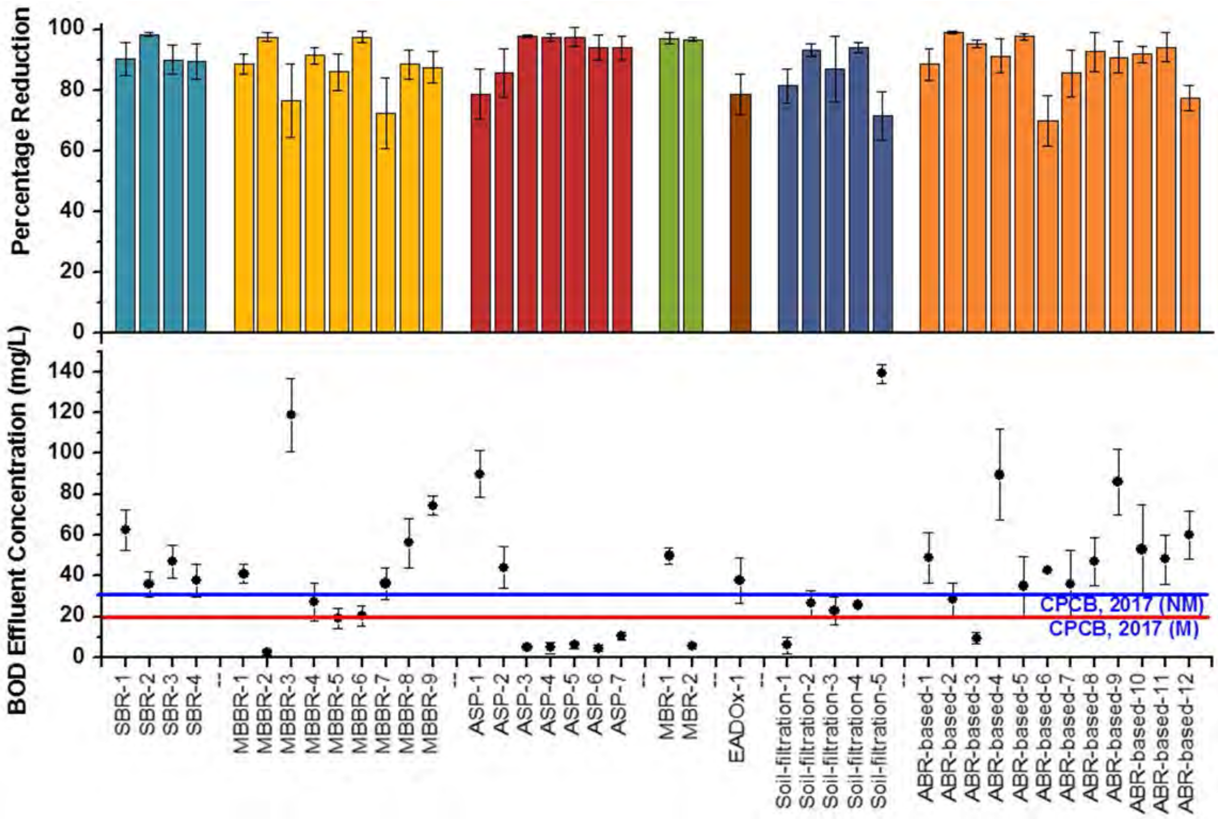


Figure 41: Average (three rounds of 24 h composite sampling ± std. dev.) BOD removal efficiency and treated water quality (M: Metro; NM: Non-Metro).

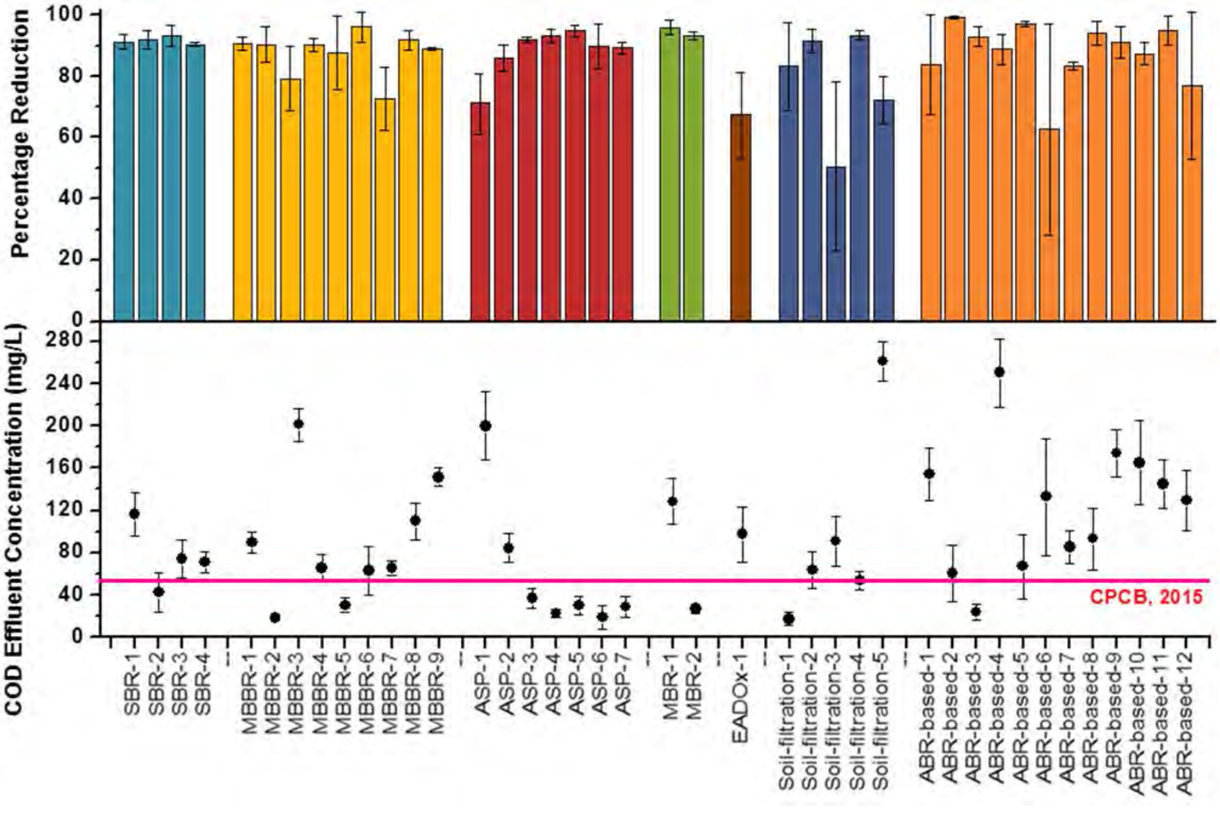


Figure 42: Average (three rounds of 24 h composite sampling ± std. dev.) COD removal efficiency and treated water quality (M: Metro; NM: Non-Metro).

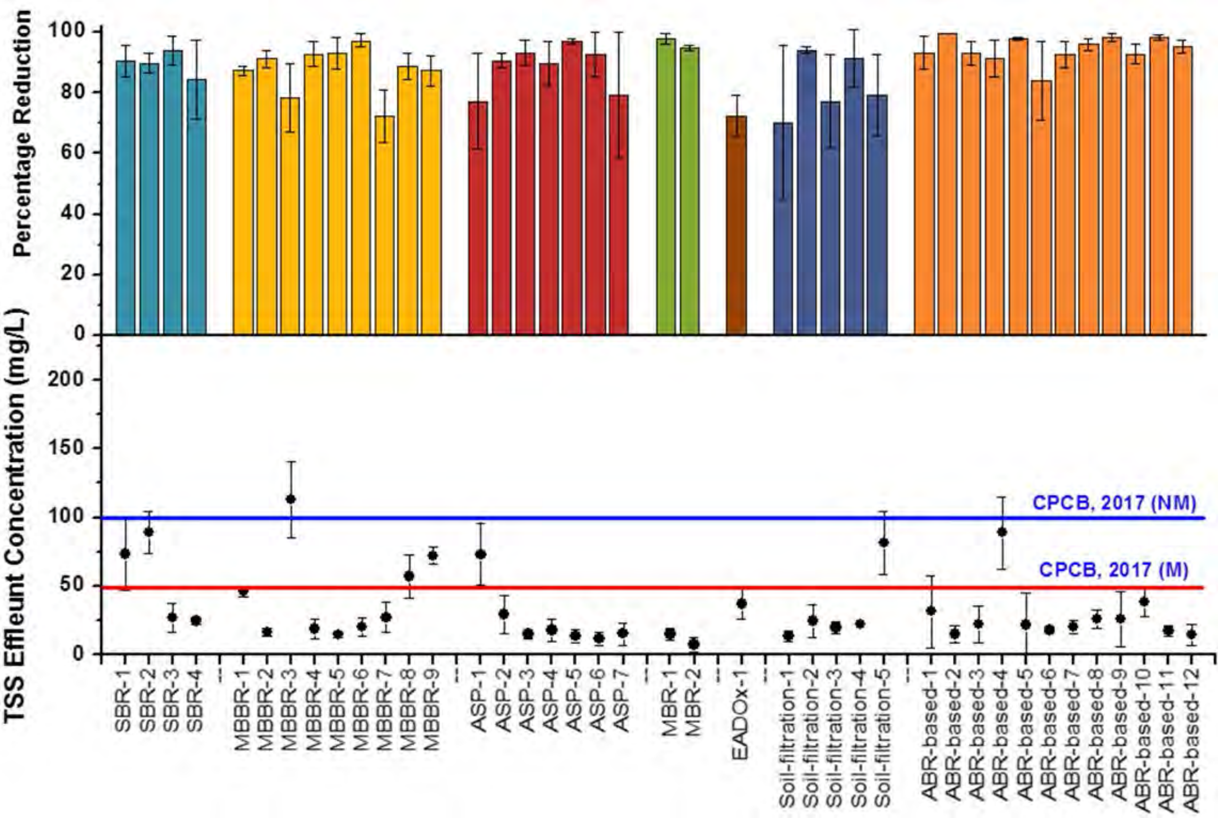


Figure 43: Average (three rounds of 24 h composite sampling ± std. dev.) TSS removal efficiency and treated water quality (M: Metro; NM: Non-Metro).

The analysis of the results for treatment of organics and suspended solids shows that most technologies can achieve a BOD removal rate of about 95% (90% for total COD; 95% for TSS) and that a majority of the systems analysed was achieving BOD, COD and TSS removal rates of about 90%. All technology families contain systems of very high and low treatment efficiency. This variability within technology families highlights the fact that the performance of a system does not primarily depend on the technology itself but on a multitude of different parameters such as actual load, correct design, O&M, management and others.

Concerning the compliance with standards, systems from all technologies can achieve the CPCB 2017 limits for organics and suspended solids effluent quality. When operated correctly, the aerated systems should have less difficulties to reach these standards than anaerobic systems. ASP/EA are, in this regard, the systems which appear to most consistently reach effluent concentrations below 20 mg BOD/L. The other aerated systems, although reportedly able to produce similar effluent qualities, exhibit more variable results. ABR-based systems show a tendency to reach slightly higher BOD levels (around 30 to 60 mg/L), but two systems still achieve BOD concentrations below 30 mg/L as per the relaxed 2017 standard for non-metro cities. Very high concentrations of organics and suspended solids were observed at the inlet of some ABR-based systems (especially ABR-based-2 and 9, but also 1, 4, 5, 8, 10 and 11; see Figure 39), showing that these systems were able to cope quite well with very high organic loads. They even present similar effluent concentrations than systems receiving much lower organic loads. It is also interesting to note that nearly all the systems achieve the new standards for TSS effluent quality.

The CPCB discharge standards for BOD changed from 10 mg/L in 2015 (draft standard) to 20 mg/L for metro-cities and 30 mg/L for non-metro-cities. The COD discharge standard, however, has not been revised. BOD and COD concentrations are usually quite strongly correlated. For example, in the 4S study, the concentration of BOD and COD had a coefficient of correlation of 0.96 at inlet and 0.91 at the outlet of the treatment systems. One cannot expect a system achieving 30 mg/L BOD to achieve the same COD concentration as a system achieving 10 mg/L BOD. To have a better idea of the relationship between BOD and COD, Table 9 below shows the BOD to COD ratio of the treated effluent as measured during the 4S sampling campaign. The mean BOD/COD ratio from the whole dataset was 0.42 and 0.38 for the cases that best treated the BOD (BOD removal >90%), which is usually considered to represent a moderately biodegradable effluent. Such ratio could be used as basis to set meaningful COD and BOD discharge standards.

Table 9: BOD/COD ratio for treated effluent from the full dataset (3 x 40 = 120 rounds of sampling) and for the systems that achieve a BOD removal rate over 90%.

Treated effluent BOD/COD ratio	Mean	Std. Dev.	Range
Full dataset (n=120)	0.42	0.17	0.08-0.81
BOD removal rate >90% (n=75)	0.38	0.17	0.08-0.78

Nutrient removal efficiency and effluent quality

This section analyses the treatment performance concerning nutrients. The relevant nutrient parameters for SSS systems effluent discharge in India as per CPCB standards are ammoniacal nitrogen (AN) and total nitrogen (TN) (see Table 3). There are no thresholds for phosphorus at the time of the preparation of this report.

The results for AN and TN removal efficiencies and effluent quality are presented in the following two figures.

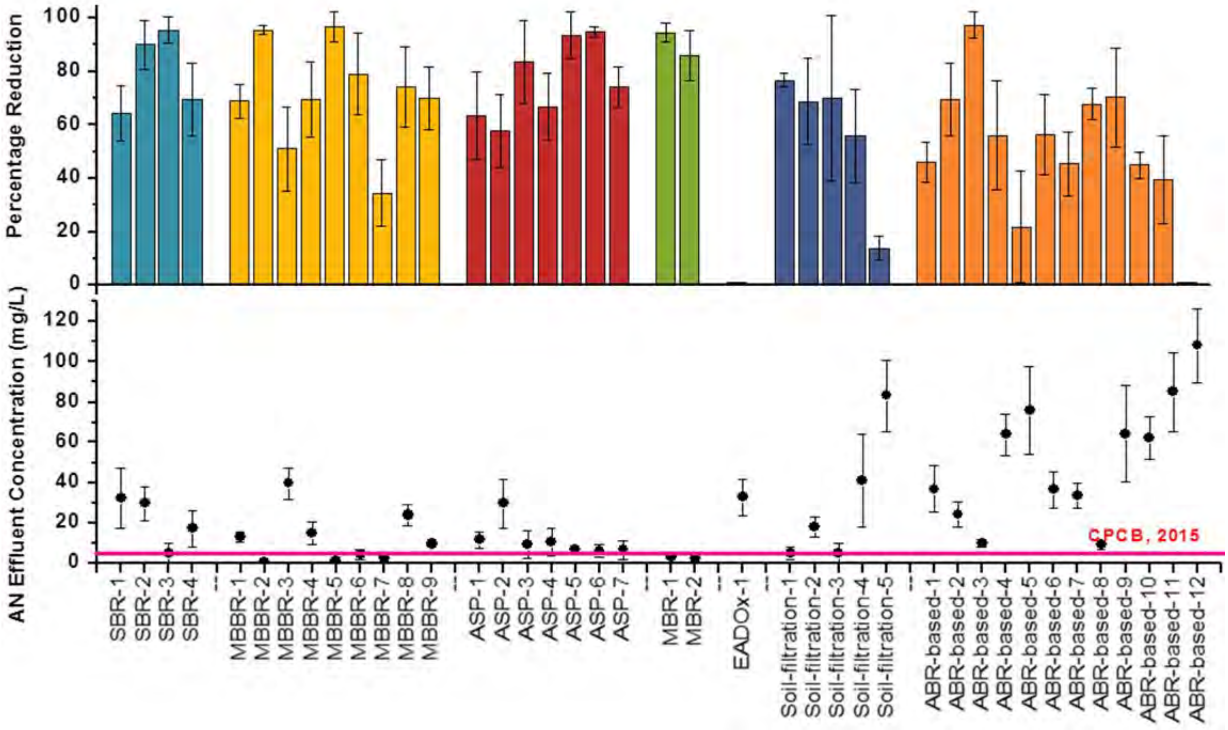


Figure 44: Average (three rounds of 24 h composite sampling ± std. dev.) ammoniacal nitrogen removal efficiency and treated water quality.

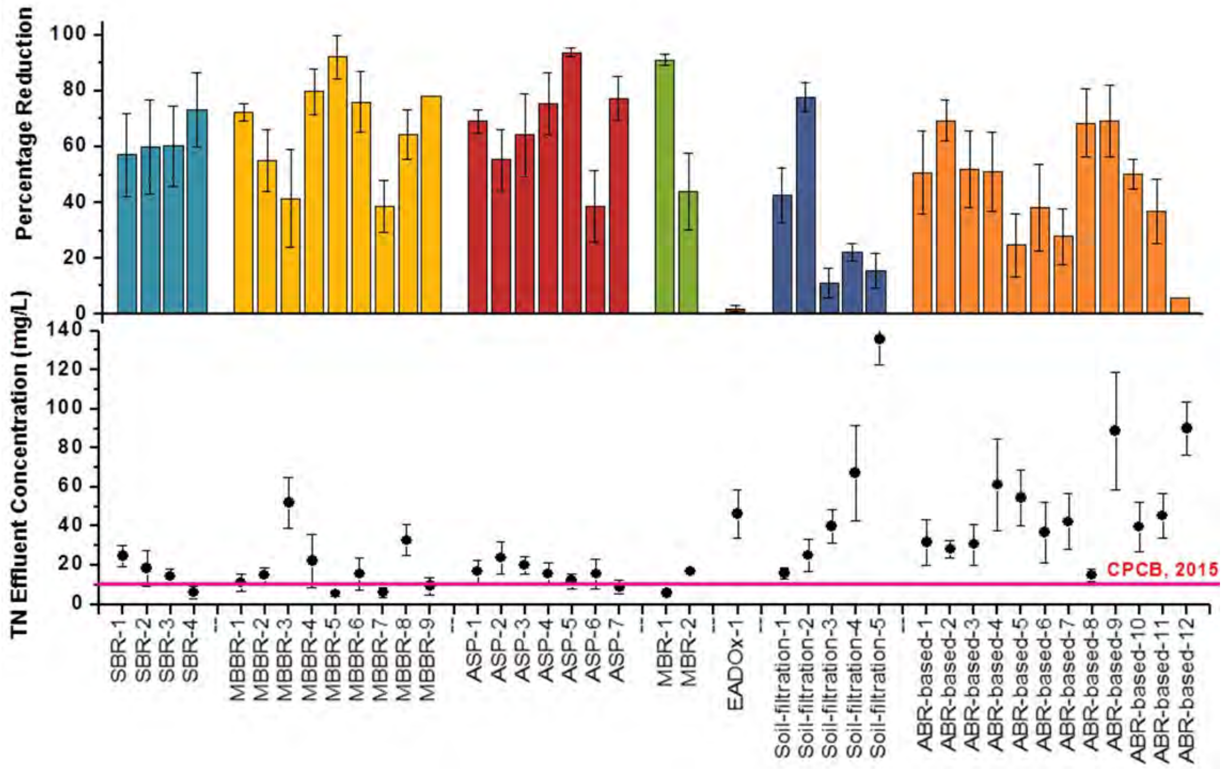


Figure 45: Average (three rounds of 24 h composite sampling ± std. dev.) total nitrogen removal efficiency and treated water quality.

Both results for ammoniacal and total nitrogen removal rates present lower removal efficiencies as well as a higher variability than the removal rates for organics and suspended solids, and this inside each technology family as well as between sampling rounds of single systems (high standard deviation, see also Figure 46 and analysis below). Having in mind this high variability, the ABR-based systems in general seem to have a slightly lower performance in removing ammoniacal and total nitrogen than the other systems. One exception is the system ABR-based-3, equipped with a vertical-flow constructed wetland as aerobic step, which apparently significantly nitrifies the ammoniacal nitrogen (see Figure 44).

The aerobic technology families seem to slightly perform better in terms of removal rate and effluent quality of ammoniacal nitrogen – although also here, treatment efficiencies vary strongly and often discharge regulations are not met. None of the investigated systems is designed with a denitrification step, with the consequence that TN standards are almost never met. High TN concentrations are generally linked to high effluent ammonium concentrations.

Concerning the CPCB 2015 discharge standards for nitrogen, only three systems (MBBR-5, MBBR-7, MBR-1) were able to consistently (i.e. throughout the three rounds of sampling) reach the levels of both standards. For the rest of the systems, the variability of influent concentration as well as operational parameters are greatly influencing the effluent levels of nitrogen in the effluent. The ABR-based systems show higher concentrations of ammoniacal nitrogen than the other technology families. The most plausible explanation for this is missing or insufficient nitrification in the case of the ABR-based systems. Also, the wastewater treated by most of the investigated soil filtration and ABR-based systems tended to be significantly more concentrated than most other systems (see section 3.3.1).

Total phosphorus (TP) is another relevant nutrient water quality parameter. The TP reduction rate and effluent quality showed trends that were very similar to those of nitrogen. As TP is not subject to the Indian standards at the time this report is prepared, the detailed results are not included here.

Removal performance comparison of organics, TSS and nitrogen

Figure 46 compares removal performances of BOD, COD, TSS, TN and AN.

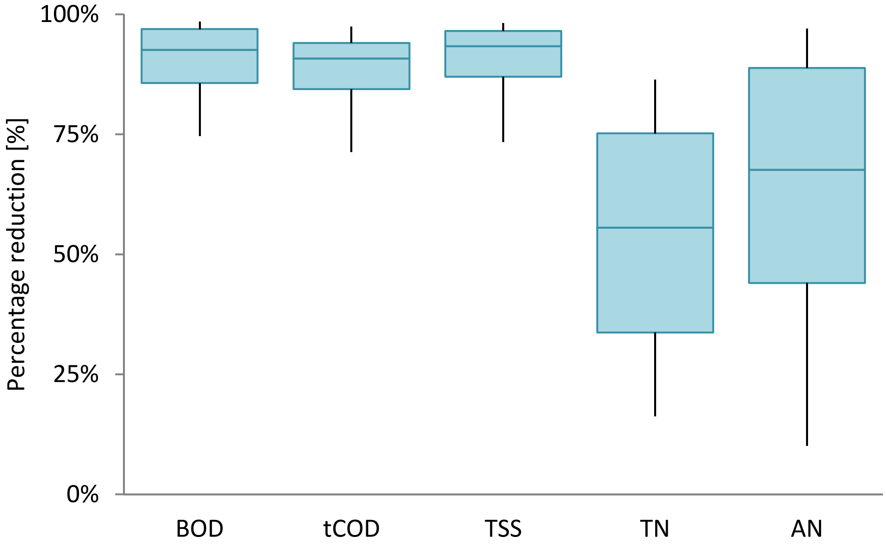


Figure 46: Box plots of removal rates for organics, TSS and nitrogen parameters based on all rounds of sampling of the 40 systems assessed (0.1, 0.25, 0.5, 0.75 and 0.9 percentiles).

It clearly shows that organics and solids are consistently better removed than nitrogen. The removal efficiencies of organic pollutants and suspended solids are more stable through time and between systems and technologies than the removal efficiency of nutrients. Regardless of the effluent quality, the analysed systems are stable in ensuring a constant organics and solids removal performance and weak in ensuring a consistent nutrient treatment performance.

Faecal coliform removal

This section analyses the treatment performance of microbial pollutants. The relevant parameter for SSS systems effluent discharge in India as per CPCB standards is faecal coliforms (FC) (see Table 3).

The FC concentration reduction results (Figure 47) show a high variability of efficiencies between systems as well as for single systems in between rounds of sampling. The mean log reduction values of the assessed systems vary between 0 log (no reduction) to 6 log (number of FC divided by 1’000’000). The variation of performance between systems and within technology families was expected as FC reduction is not only influenced by primary and secondary treatment stages but also and mainly by the presence and good operation of post-treatment stages, particularly disinfection steps (see section 3.3.3 below). The high variation of treatment performance in between rounds of sampling indicate a lack of control over the FC treatment process.

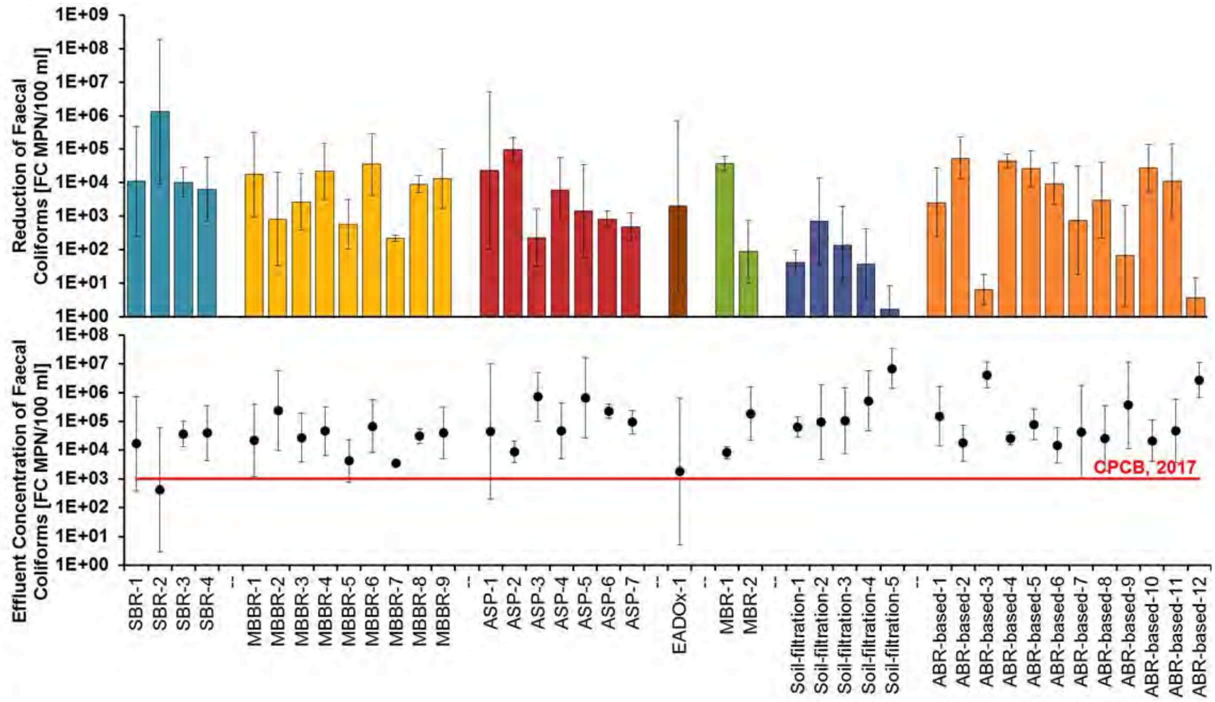


Figure 47: Average (three rounds of 24 h composite sampling ± std. dev.) faecal coliforms concentration reduction and treated water quality.

Concerning the CPCB discharge standards, they are systematically not met by all of the assessed systems with the only exception of one system which met the standard during two out of three rounds of sampling. Out of the 120 rounds of sampling conducted (three rounds times 40 plants), only four effluent composite samples (from three different plants) achieved the 1’000 MPN/100 ml required by the CPCB 2017 standard. The same amplitude of variation as the one found in the reduction results can be observed in the effluent FC concentration results.

The findings highlight that the treatment processes targeting microbial pollutants reduction are either not implemented or not operated correctly and, finally, not sufficient to achieve the required standard. These issues are further investigated in the following section.

3.3.3 Microbial removal performance in post-treatment units

The efficiency and challenges of the installed disinfection units are analysed in this section. All operational disinfection steps were chlorination units (one non-functioning UV disinfection unit was also present). Figure 48 below presents the FC concentration reduction achieved in the post-treatment units[6] of the STPs, grouped by systems with and systems without a disinfection unit. Additionally, for the units with disinfection treatment, the effluent BOD levels are also displayed as it is an important parameter influencing the disinfection process, especially chlorination.

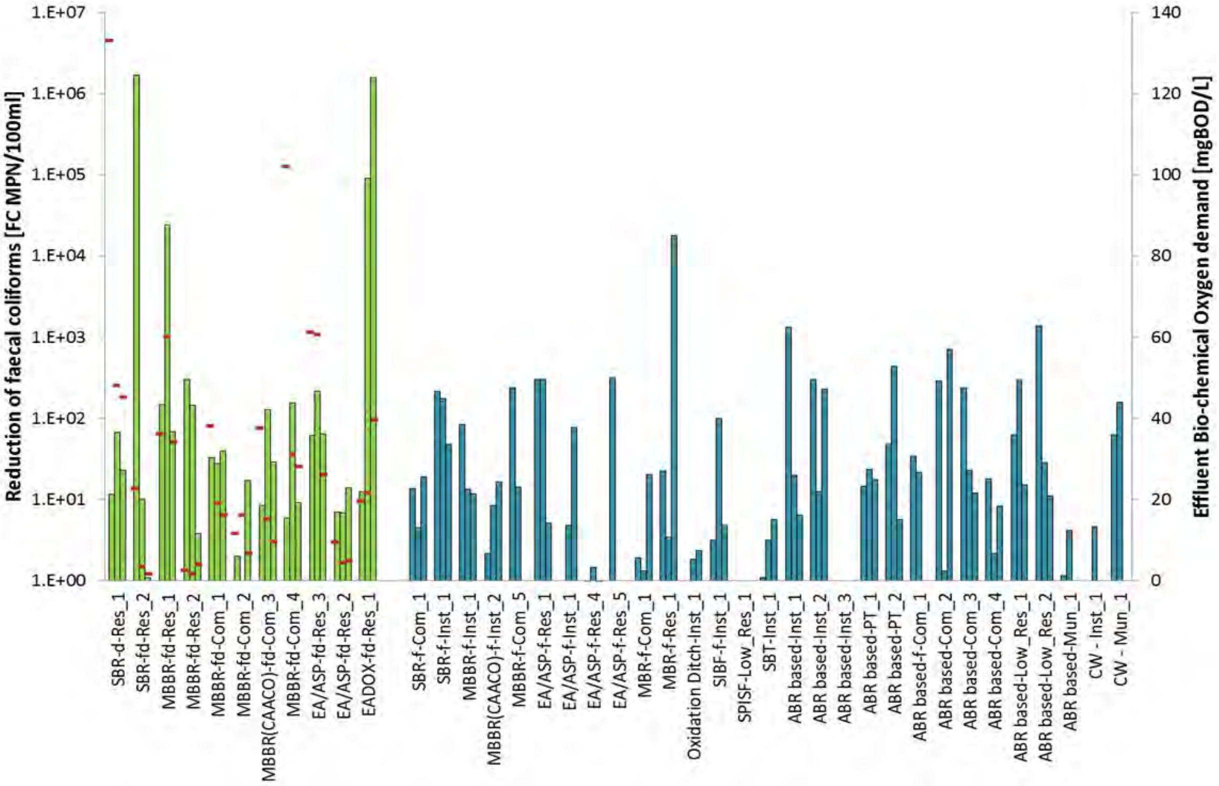


Figure 48: Reduction of faecal coliforms in post-treatment stages, shown for all sampling rounds (three per system); on the left (green) are the units with operational disinfection steps, on the right (blue) those without. The BOD effluent concentration is shown in red for systems with disinfection equipment (right axis value).

The following important observations can be made from this figure:

- Potential to reach high microbial reduction: 4 to 6 log FC reduction by the post-treatment including disinfection (pressure sand filtration + activated carbon filtration + chlorination) was observed in three different systems (SBR-fd-Res_1, MBBR-fd-Res_1 and EADOX-fd-Res_1). This shows that a good microbial reduction is possible.
- No constancy in reduction efficiency: none of the studied systems was able to reach constant high FC reduction efficiency throughout the sampling rounds. Only the systems with poor FC removal (1 to 2 log reduction) presented a constant efficiency.
- No significant difference between systems with and without chlorination unit: apart from the four samples (out of 33 with disinfection) where reduction efficiency was on the higher end, the comparison of the results of the systems equipped with disinfection units (11) with the ones without (19) does not show any significant difference in the FC reduction. This can be due to the influence of three main factors:

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[6] See Table 1 for details of the post-treatment stages present in each system.

- Inappropriate pre-disinfection water quality: high levels of BOD, nitrite and TSS have the potential to strongly affect the disinfection power of chlorine by reacting with the chlorine (they can consume free chlorine and produce potentially toxic chlorinated compounds) and by shielding of embedded bacteria (TSS) (U.S. EPA, 1999).
- Poor design of chlorination units, e.g. inappropriate contact chambers or mixing mechanisms. A proper and quick mixing is required to enhance disinfection.
- Faulty operation of chlorination units, such as uncontrolled dosage of chlorine solutions (too diluted), or direct pouring of chlorine into the final collection tank, which neither allows for a good mixing, nor for an appropriate contact time.

Overall, the poor performance of the disinfection process is striking for all systems. Apart from public health risks resulting from incomplete disinfection, the over-dosage of chlorine combined with high levels of organic carbon still present in the pre-disinfection water can lead to hazardous and carcinogenic compounds very harmful to aquatic and non-aquatic organisms. A high level of knowledge and very close care of the disinfection units is therefore required to ensure a safe and appropriate disinfection process.

3.3.4 Effect of inflow concentration on treatment efficiency

Treatment efficiency can be impacted by fluctuation or strength of inflow concentrations. This section investigates such potential relationship within the available dataset. Figure 49 presents system BOD feed concentrations as well as BOD removal data (COD, TSS and nutrient datasets show similar trends).

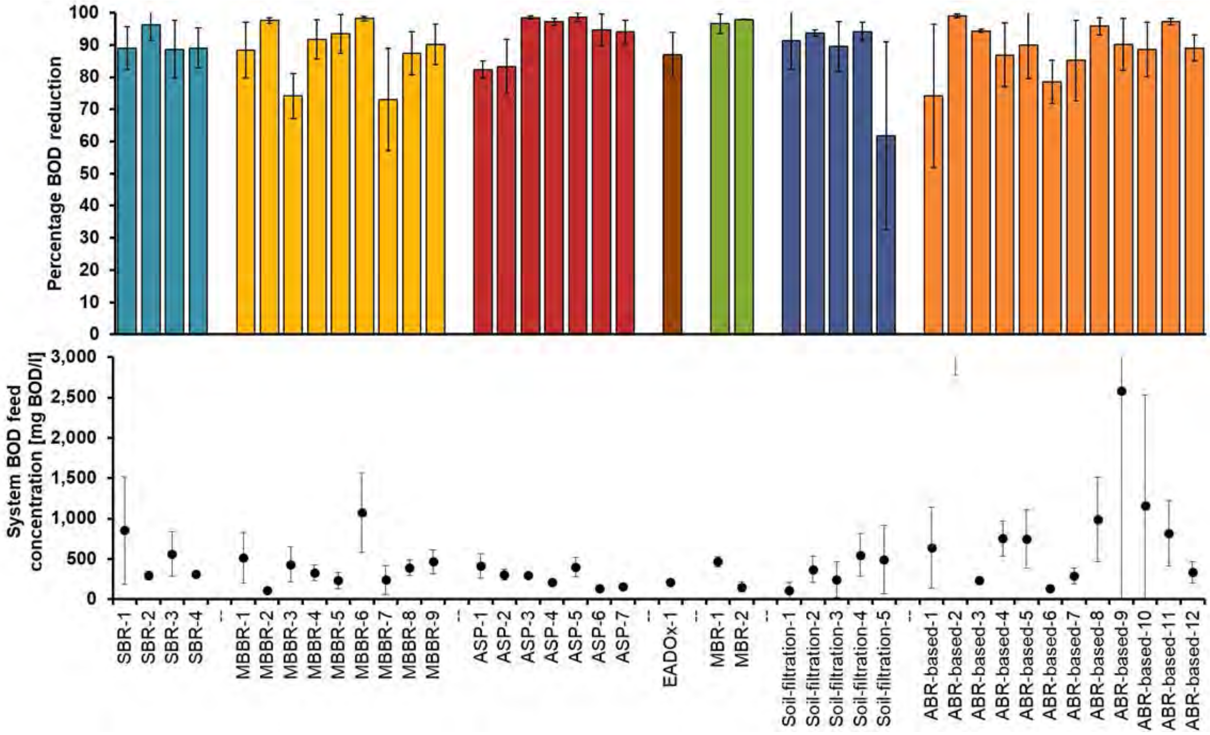

Figure 49: Average system BOD feed concentrations and removal efficiencies, error bars indicate standard deviations.

The error bars on the lower graph indicate that many systems experience considerable changes in feed concentrations over time (see also section 3.3.1 on inflow characteristics). Operation of SBR, MBBR, soil filtration and especially ABR-based systems (of which some treat very concentrated feed flows), however, seem to not be directly affected by these fluctuations. This supports the claim of these systems' robustness. Measured feed concentrations of ASP, EADOx and MBR systems vary too little – across as well as at single systems – to make any claim concerning this aspect.

However, the fact that technology, feed concentration and its variation are not the only factors which influence treatment efficiency of a system (see section 3.4.2) limit the claims which can be drawn from this dataset alone.

3.3.5 Effect of hydraulic system load on treatment efficiency

The treatment efficiency of wastewater treatment systems is directly influenced by the hydraulic load. The long-term hydraulic load as well as short-period flow peaks affect such important parameters as growth, activity and washout of the treatment-inducing microorganisms as well as their contact time with pollutants.

The assessment of system operation therefore requires knowledge on how much wastewater is treated by a system compared to what it was designed for. Information on two indicators for hydraulic system load were recorded during this study: flow data and loading estimates through field observation. The applied flow measurement method is described in section 2.3.3. Observations on system load were made by the investigation team (4S field staff), head of local management body and the system operator who had to choose one of the following response options: "underloaded", "normally loaded", overloaded", "unknown". All responses for one system were merged using the following logic:

- If no contradiction: merge the estimations
- If contradiction between estimations: choose worst scenario
    - i.e. "overloaded" or "underloaded" preferred over "normally loaded"
    - If contradiction between "overloaded" and "underloaded", prefer the answer from the investigation team

The also investigated ratio of actual to design user number is not applicable for many of the systems operating under commercial and institutional contexts and can therefore not be used as indicator for system load.

The challenges linked to the available flow data are discussed in section 3.3.1. It was concluded that this data could not directly be used to infer hydraulic system loads. The attempt to further consolidate the flow data by comparing it with the available loading estimates based on field observations was not fruitful as shown in Figure 50. Parameter responses for the same systems are not consistent with each other and even show strong contradictions in certain cases. Therefore, the effect of hydraulic system load on treatment efficiency could not be studied properly based on the available data. More precise flow data would be needed.

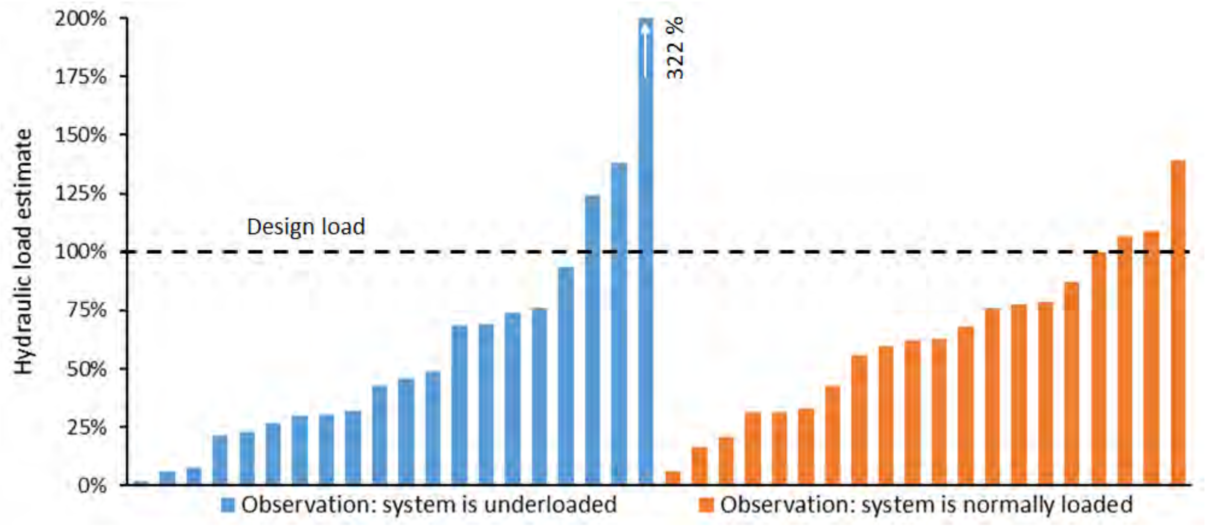

Figure 50: Hydraulic load estimates (ratio of average daily feed flow to design feed flow, see section 3.3.1) of systems reported by field staff to be underloaded (left) and normally loaded (right). None of the sampled systems were reported to be overloaded.

Technical options for measuring flow at SSS systems

Precise flow measurements at SSS systems are challenging due to corrosive and biofilm forming wastewater constituents, large flow fluctuations with very low flows at night and the large number, exposure and potential remoteness of required installations. Factors which need to be considered when selecting applicable technologies include measurement accuracy, costs, range of measurable flow rates, head loss, maintenance requirements, availability of spare parts, robustness towards particulate matter, safety of installation against vandalism and theft, power supply needs and data retrieval.

Table 10 summarizes information on selected technologies typically used for wastewater flow measurements. Mechanical flow meters cannot be used for wastewater, even if (pre-)treated, due to frequent blockages and resulting high maintenance.

Table 10: Selection of wastewater flow measurement technologies.

Flow measurement technology	Characteristics	Costs
V-notch with water height measurement	Open channel measurement, cannot block, measures flow rates ranging from 1.3 l/s (4.7 m^3/h) to 124 l/s (440 m^3/h), head measurement typically done with ultrasonic sensor, certain head loss	Medium
Venturi canal with water height measurement	Open channel measurement, cannot block, measures flow rates ranging from 10 l/s (36 m^3/h) to 5’000 l/s, head measurement typically done with ultrasonic sensor, certain head loss	Medium
Magnetic flow meters	Can be sized for large range of flows, no danger of blockages, no head loss	High
Ultrasonic (sonar) flow meters	Can be sized for large range of flows, no danger of blockages, no head loss, requires particle free, treated wastewater	High

A viable alternative to direct measurement can be to infer wastewater production from water consumption. This, however, is only advisable in the case of low probability of pipe breakages and if the fraction of water actually discharged to the system as wastewater can be estimated with a large enough degree of confidence. The disadvantage of this method is the low time resolution which would in most cases probably not enable the assessment of short-period peak flows.

At the time this report is written, no technological solution has been reported which satisfyingly addresses the challenges listed above.

3.3.6 Relationship between observed system status and measured effluent quality

Observations made in the field during wastewater sample collection can be helpful in providing explanations for the measured treatment performance of systems. Today, the performance of SSS systems is normally assessed based on the analysis of wastewater grab samples, which is costly and subject to very high uncertainties. Grab samples are not sufficient to get a reliable picture of a system's performance – extensive sampling campaigns would be needed, but this is laborious and expensive. Qualitative observations have the potential to complement measurements by providing additional valuable information on a system's health. They may even be useful to roughly predict the performance of a system. This section looks at the relationship between qualitative and quantitative assessments and explores how field observations could be integrated into the current sampling-based monitoring framework.

Table 11 below exemplarily presents such information for a selected number of systems where sampling campaigns were carried out (see Appendix 5 for a table presenting this information for the complete set of sampled systems).

The table includes the trained field staff's general impression of the system status, as well as potential issues and other system status observations made during the 24 h sampling rounds. The judgment on system status (*good*, *moderate* or *bad*) reflects a general (subjective) overall impression obtained by the field staff during the sampling visits, mainly based on operational parameters (e.g. level of sludge accumulation in clarifiers, status of filter media, health of plants in constructed wetlands, operational status and operating pattern of aerators and pumps, etc.), observed quality of wastewater (effluent odour, colour, Mixed Liquor Suspended Solids (MLSS), etc.) and uncommon events in the recent past of the system (based on discussions with the operator and manager of the plant).

The system status judgements exemplarily used here are not very accurate. Instead, sampling data could also be complemented with an assessment of specific sustainability parameters that are important for the functioning of the system on the longer term (such as trained operators and managers, well maintained documentation, financial stability, etc.). This would help having a more holistic understanding of each system and identifying systems that should be more closely controlled in the future. Such an approach is explored in section 3.4.

Table 11 further compares these observations with the measured effluent BOD concentration and removal efficiency. For comparison purposes, the BOD measurements were also categorised as *good*, *moderate* or *bad*, like the system status judgement: assuming that all systems can achieve the CPCB 2017 BOD standard for metro cities (20 mg/L, see Table 3) if properly operated and maintained, BOD values below 22 mg/L (threshold + 10%) were considered *good*. BOD values above 33 mg/L (not adhering to the BOD standard for non-metro cities of 30 mg/L + 10%) were considered *bad*, and everything in between *moderate*.

Table 11: Selected examples of field staff assessment of general system status compared with BOD effluent concentration (24 h composite samples) and removal efficiency. The green, yellow and red cell colours visualise the judgement good, moderate or bad, respectively.

System ID & sampling round N°		General system status	System status / issue description	Effluent BOD [mg/L]	BOD removal
MBBR-6	1	Moderate	Sludge accumulation in the clarifier	40	95%
	2	Good	Sludge had been removed	8	99%
	3	Good	-	14	98%
ASP-2	1	Moderate	Aeration was intermittent; Odour problems	44	89%
	2	Good	Good and continuous airflow; filters materials had been cleaned; Odour problems	24	91%
	3	Moderate	Filters were clogged; Odour problems	65	77%
ABR-based-5	1	Moderate	Sludge accumulation in settler	38	98%
	2	Moderate	Plants[1] in PGF were trimmed; sludge had been removed	53	97%
	3	Good	Plants were healthy in PGF and no sludge accumulation	14	98%
ABR-based-11	1	Moderate	No plants in PGF	101	89%
	2	Good	Healthy plants in PGF	10	98%
	3	Moderate	Sludge accumulation in settler	32	96%
SBR-2	1	Bad	Kerosene had been poured into the treatment plant a week before the assessment.	98	38%
	2	Good	STP was repaired and functioning well	4	99%
	3	Good	-	6	98%
EADOx-1	1	Good	-	13	90%
	2	Moderate	The collection tank had been cleaned; The effluent is whitish because of high amount of chlorine added; The EC plates are corroded and old; In the morning the inlet was submerged in wastewater	28	87%
	3	Bad	The treated water is quite turbid, smelly and frothy. In the morning the inlet was submerged in wastewater	72	60%
SBR-3	1	Good	Well maintained MLSS	52	87%
	2	Good	Cleaned filters	37	95%
	3	Good	Well maintained MLSS and cleaned filter	52	88%

[1] The influence of plants on PGF efficiency is very controversial. Therefore, plant observations have a limited usefulness for system status judgements. They may be used, however, to infer information on system maintenance.

When there is a change in the status of a system, very often, this change is reflected in the BOD effluent quality. Aspects like sludge accumulation or clogging of a filter have an important impact on treatment effectiveness. When issues occur with one of these aspects, the system does not work as it should and it seems that there are good chances that the effluent quality will not be satisfactory. However, it is important to keep in mind that events like changes in the influent characteristics or in the treatment system itself may only be reflected in the effluent quality with a certain delay, depending on the type and severity of the event.

It is also important to note that observations can only tell if a system is not functioning as it should, but they are not reliable in predicting that a system is reaching good treatment performance. For example, the last system in Table 11 (SBR-3) had good system status judgements during all three rounds of sampling. However, the BOD effluent quality was always significantly above the threshold of the discharge standard. There are other factors that cannot be easily observed that are influencing the treatment performance of the systems. This is explored further in section 3.4.

In order to understand more precisely what can be concluded from observations, and how to use observations to optimize monitoring frameworks and the performance of SSS systems, the relationship between the general system status judgements and the measured effluent BOD quality was further analysed for the complete dataset. This was done by giving a score to both the status judgements and the BOD values. General system status judgements were available for a majority of the 120 sampling rounds (n=104).

Table 12 below shows how the scoring of the two compared variables was done. To understand how well the qualitative evaluation of the system status "predicts" the effluent quality, the two variables were put into a cross table (see Table 13). The table shows how many cases are in each combination of score values for the two variables. The class error is the proportion of variables that are not scoring the same (not 0:0, 0.5:0.5 or 1:1) per line. It represents the proportion of effluent quality that was not correctly "predicted" by the qualitative evaluation of the system.

Table 12: Scoring system for the two variables compared. BOD values below 22 mg/L (threshold + 10%) were considered *good*. BOD values above 33 mg/L (not adhering to the BOD standard for non-metro cities of 30 mg/L + 10%) were considered *bad*, and everything in between *moderate*.

Score	0	0.5	1
System status (evaluated by field team)	Bad	Moderate	Good
Effluent BOD [mg/L]	> 33	22-33	< 22

Table 13: Distribution of cross scores between the field staff evaluation of the system status and the effluent BOD in the 9 (3 x 3) possible outcomes (n=104).

		Effluent BOD score			
		0	0.5	1	Class error
System status score	0	20	0	0	0%
	0.5	22	8	4	76%
	1	8	8	34	32%

As such, this rough scoring system fails in providing a good prediction of the BOD effluent quality of treated wastewater based on the subjective status judgements. However, as already felt when looking at the examples shown in Table 11, there is still an interesting trend to be observed. Indeed, when the trained field staff estimated that the general system status was bad, the BOD effluent quality was insufficient in 100% of the cases. For the rest of the cases, there is no strong conclusive correlation that can be drawn. This means that qualitative observations of the system status have the potential to help spotting the worst performing systems, but not much more. If the observer assesses that the system is working properly, it does not mean that its effluent quality is satisfactory.

3.4 Conditions for sustainable SSS system performance: a cause-effect analysis

Chapter Summary

Scores of performance objectives

- The qualitative assessment of wastewater treatment effectiveness shows that no major flaws in the treatment sequence (i.e. all treatment components operational) as well as in effluent appearance were observed in 69% of the visited systems; 18% scored *insufficient*.
- Only 47% of the systems scored *good* for the PO adequate loading; 17% scored *insufficient*.
- Active water reuse scored well, with 90% of the systems designed for reuse actually practicing reuse. However, this does not consider the actual amount of water reused.
- 67% of the studied systems do not foresee nutrient recovery in their designs. Of those which are designed for nutrient recovery, 74% scored *good* and only 6% scored *insufficient*.
- Only 6% of the assessed systems are designed for energy recovery (namely biogas). 11% of them scored good, 61% *insufficient*.
- As already identified in section 3.2, solids management (sludge, solid waste and scum) is a real issue for a majority of the systems. 29% of the systems scored *good*, 63% *insufficient*.

Scores of critical success factors

- Only five out of 14 CSF achieved relatively good scores (*Quality of Design, Quality of Implementation, Availability of Energy and Chemicals, Human Resources Management,* and *O&M Cost Recovery*).
- The low-income residential and public toilet contexts scored particularly low in some CSF.
- The crucial system startup and handover phase in which ownership and/or responsibility are transferred from the designer/builder to the management entity was found to be frequently neglected.
- O&M personnel and management entities are often not sufficiently informed about the functioning of SSS systems and the requirements for good performance.
- Operators are often not clearly instructed and supervised.
- Clear responsibility for organising spare parts, as well as for planning and budgeting scheduled maintenance services, is frequently lacking.
- The documentation of O&M activities and financial flows is a considerable weakness in many systems.
- User behaviour and user satisfaction both indicate that social aspects are often not sufficiently considered.

Cause-effect analysis: investigating the potential interlinkages between the fulfilment of critical success factors and the performance outcome

- The different statistical methods applied did not yield any significant correlation of the CSF and the PO. With the present model and dataset it was not possible to confirm that the 14 CSF are actually exerting a critical influence on the PO scores, highlighting the high complexity of this cause-effect framework.
- A larger, longer-term dataset as well as refining the scoring of both CSF and PO would help to better understand and measure the influence of the CSF on performance.

This section presents the results of the analysis of the conditions for system performance (see section 2.4 for the approach, methods and terminology used). First, the performance objectives (PO) and critical success factors (CSF) are scored, analysed and discussed separately. Then, the complex relationship between the CSF and PO is analysed and discussed.

This part of the analysis is based on the entire available dataset (309 systems, 279 in India and 30 in Nepal).

3.4.1 Scores of performance objectives

Table 14 summarizes the performance objectives (PO) used in the analysis (see section 2.4.1 and 2.4.3 for details). All POs are scored based on the qualitative dataset collected during the basic assessment phase of the project (see section 2.2), except for the quantitative assessment of wastewater treatment (PO 1.3-1.5), which is based on the results from the sampling campaign (see section 3.3) and available for 40 systems only.

Table 14: Overview of performance objectives of SSS systems.

1. Wastewater Treatment: Qualitative Assessment (n=309)
PO 1.1: Treatment Effectiveness
PO 1.2: Adequate Loading
1. Wastewater Treatment: Quantitative Assessment (n=40)
PO 1.3: Effluent Organic and TSS Quality
PO 1.4: Effluent Nutrient Quality
PO 1.5: Effluent Microbial Quality

2. Resource Recovery (n=309)
PO 2.1: Active Water Reuse
PO 2.2: Active Nutrient Recovery
PO 2.3: Active Energy Recovery

3. Solids Management (n=309)
PO 3: Appropriate Management of Solids

The following subsection A) provides an overview of the PO scores for the 40 sampled systems, and subsection B) analyses the scores for the full dataset (n=309).

A) System performance scores of the 40 sampled systems

Figure 51 shows all PO scores for the 40 sampled systems (the resource recovery POs are discussed below in B). PO 1.3-1.5 are scored based on the compliance of the measured effluent quality with the CPCB 2017 standards for metro cities (see section 2.4.3), whereas the others are based on basic assessment data.

Note: The datasets on which the quantitative PO (in-depth assessment) and qualitative PO (basic assessment) are based were not taken on the same date. Between both assessments, a potential time lag ranging from a few weeks up to one year can exist. The situation of the system might have changed in the meantime, which would lead to a mismatch between both scores.

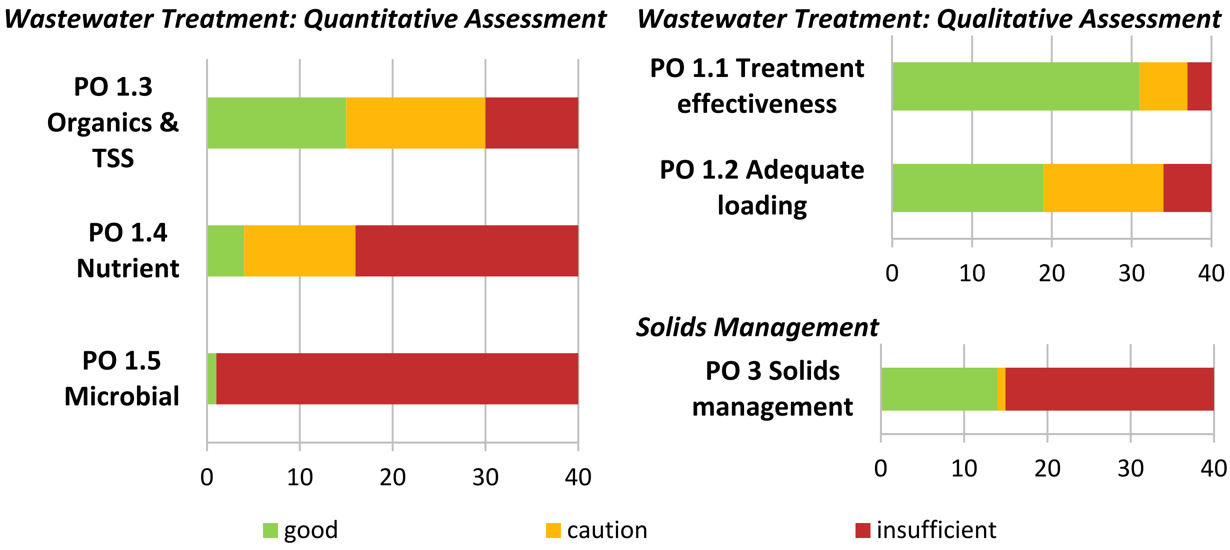

Figure 51: PO scores for the 40 sampled systems: quantitative and qualitativ assessment of wastewater treatment effctiveness, adequate loading and appropriate management of solids.

Wastewater treatment: quantitative assessment

The scores of the quantitative wastewater treatment assessment show a mixed fulfilment of the organics and solids effluent quality PO (BOD; COD; TSS), a poor fulfilment of the nutrient effluent quality PO (AN, TN) and a nearly total non-fulfilment of the microbial effluent quality PO (FC), regardless of the presence or absence of disinfection treatment. This is in accordance with the findings from the treatment performance analysis (same dataset used, see section 3.3 for more details).

Wastewater treatment: qualitative assessment

Treatment Effectiveness scores relatively well for most of the 40 systems. This shows that no major flaws in the treatment sequence (i.e. all treatment components operational) as well as in effluent appearance were observed. This includes pH, turbidity, colour, odour of treated effluent as well as presence/absence of froth in the effluent. Seemingly, the selected systems were mostly functioning well at the time of assessment.

Adequate Loading shows a slightly worse score, i.e. inadequacy of current vs. designed loading. Unplanned intrusion of storm water or additional connection of wastewater are further reasons for low scoring systems. Inadequate loading can lead to a decrease in the treatment quality of the wastewater. Due to the many factors influencing the loading PO (e.g. occupancy rates, unplanned connections), no significant influence of the age of a system (since start of operation) was observed (correlation coefficient: -0.14), although being a central parameter in a system’s load increase throughout its life time (see section 3.2.3).

Appropriate Management of Solids received the worst scores of all qualitative PO, confirming the findings from the basic assessment (see sections 3.2.7 and 0). This PO is strongly influenced by the very low (30-40%) occurrence of treatment of removed sludge (correlation coefficient: 0.91). The primary goal of a wastewater treatment system cannot be achieved if there is no sound management of solids, especially sludge, but also solid wastes and scum. The poor score of this PO highlights a high potential of environmental pollution and public health risks.

Scoring quality and limitations:

The quality and availability of the information was variable when scoring the different PO. In order to correctly interpret the meaning of their score it is important to understand what it means for the precision of the scores. The time variability of the PO score is also evaluated for each PO to understand whether the score displayed is covering the full lifetime of the system or a single snapshot of the moment of the site visit. These two evaluations help to put the scores of the different PO into context and to get a better understanding of their meaning.

Treatment Effectiveness

- Precision of scoring: **good**
  The data collected is of good and trustworthy quality as it is mainly based on direct observation from trained field staffs. Yet, accuracy is lower than sampling data. This relationship will be discussed in next section.
- Time variability of PO: **high**
  As noted earlier this PO is a one-time assessment of the treatment effectiveness and as such potentially subject to variations through time.

Adequate Loading

- Precision of scoring: **medium**
  The lack of accessibility to design details as well as the lack of documentation on flow measurements for each assessed system are decreasing the precision of this PO. Yet, sufficient information were collected to estimate the load at the moment of assessment as compared to the initial design. The information was collected from primary sources and double checked between the two interviewees (operator and manager) as well as based on direct observation by trained field staff.
- Time variability of PO: **medium**
  The loading PO is a variable that potentially evolves significantly during the lifetime of a system but that has low probability to vary at the shorter term, provided that the system was correctly designed with equalization infrastructure. As seen in section 3.2.3, due to higher probability of idle capacity the younger systems will have a tendency of being more underloaded, whereas older system will tend to reach and even exceed the design capacity.

Appropriate Management of Solids

- Precision of scoring: **good**
  The information was collected from primary sources and double checked between the two interviewees (operator and manager) as well as based on direct observation from trained field staffs.
- Time variability of PO: **low**
  This PO is mainly bound to the availability of sludge treatment options which is less likely to evolve rapidly.

Altogether, the 40 sampled sites appear to be well-working systems with no ostensible sign of poor wastewater treatment effectiveness standing out from the qualitative assessment. Nonetheless, the results show some very worrying statistics. Very poor solids management, nutrient and microbial effluent quality were observed which would require important and rapid interventions in order to improve the situation.

B) System performance scores of all 309 assessed systems

This section analyses the PO fulfilment for all the 309 systems visited during the basic assessment. Figure 52 shows the scores of all PO, including the three PO for resource recovery (2.1-2.3). In the analysis of the findings from site visits (see section 3.2.5), reuse of treated wastewater was highlighted as an important objective for most systems, while nutrient and energy recovery were only targeted in fewer systems. This is reflected here in a high occurrence of the score *not applicable* (nap) for these two recovery options, as only few of the visited systems were actually designed for it.

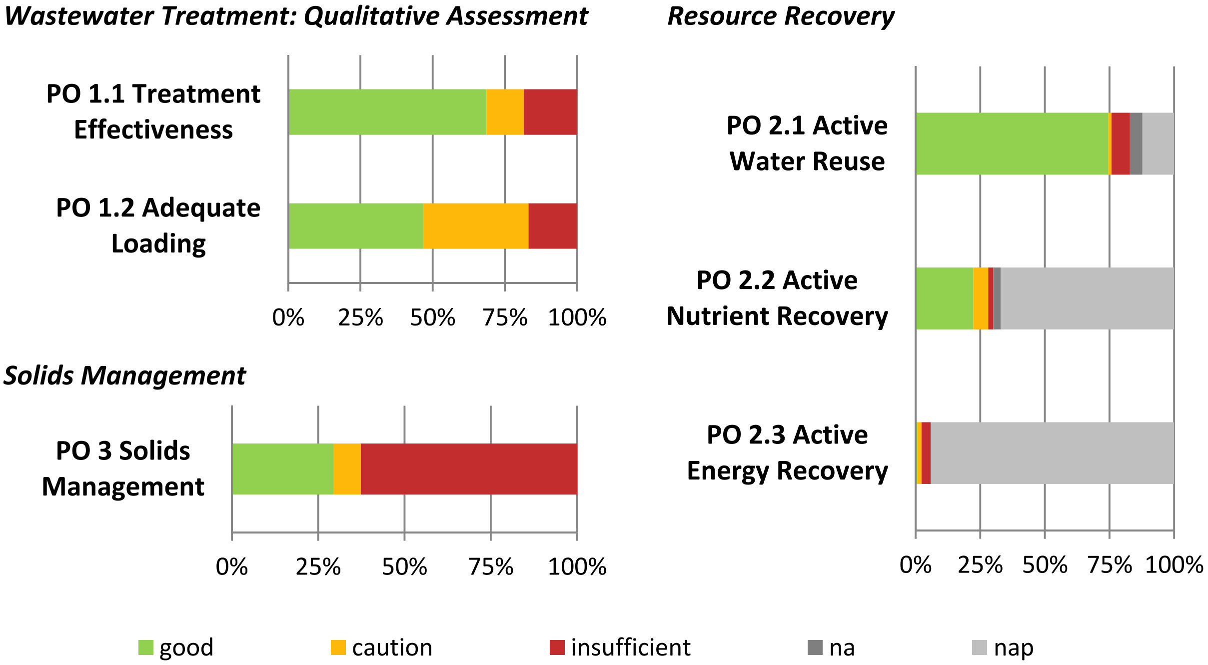

Figure 52: PO scores for all the assessed systems (na = not available, nap = not applicable) (n=309).

The results from the overall dataset for the three PO *Treatment Effectiveness*, *Adequate Loading* and *Appropriate Management of Solids* showed similar trends as the 40 sampled systems. As expected, the scores were slightly worse for the complete dataset because the 40 systems for sampling were chosen among seemingly ‘better’ systems.

Active Water Reuse: As already seen in the results from the basic assessment site visits, water reuse is a predominant aspect of SSS systems. Most of them were designed to reuse treated wastewater and, among those, most are actually reusing it, at least partially. Water reuse policies developed along with the new regulations for SSS have been at least partially successful. Due to lack of detailed information, the overall percentage of treated wastewater that is reused is not captured by this assessment. Based on observations from the field visits, full reuse of the treated wastewater from SSS systems is often not possible. The reclaimed treated water is commonly used for toilet flushing and gardening but a significant amount, typically in the range of 25-70%, (Drangert and Sharatchandra, 2017; Evans, AEV; Varma, S; Krishnamurthy, 2014; Kodavasal, 2011b; Shankar and Yathish, 2013), unfortunately cannot be reused due to a lack of local reuse opportunities.

Active Nutrient Recovery: The majority of the systems were not designed to address nutrient recovery. This PO presently correlates to some extent (coefficient 0.78) with the PO *Appropriate Management of Solids*, as most of the systems that are not designed for nutrient recovery (on-site sludge treatment and reuse infrastructure) are often not scoring well for *Appropriate Management of Solids* (and vice-versa) due to the lack of off-site treatment opportunities.

Active Energy Recovery: Energy recovery was found to be part of the design in only very few systems (18) and a majority (11) of them were scored as insufficient. These systems possess an anaerobic digester unit to produce biogas; most of them were operational but in half of the installations the biogas produced was not used. Consequently, only 2 out of 18 systems did not have any issue (score good) and were using the produced biogas, whereas 5 (out of the 18) experienced some issues but were still using the biogas (score caution). This performance highlights a poor care of these systems, possibly due to improper O&M, which can originate in a lack of financial means, knowledge or interest in the system.

Scoring quality and limitations:

Scoring quality and limitations of PO *Treatment Effectiveness*, *Adequate Loading* and *Appropriate Management of Solids* were already discussed in the previous subsection A) above.

Resource recovery PO

- Precision of scoring: good
  The information was collected from primary sources and double checked between the two interviewees (operator and manager) as well as based on direct observation from trained field staffs. As discussed above, the ratio of reused (treated) wastewater vs. total volume of wastewater was not assessed.
- Time variability of CSF: low
  The three PO did not vary too much over time expect in the case of major unexpected system breakdowns.

3.4.2 Scores of critical success factors

The following section describes the scores of the CSF (see sections 2.4.2 and 2.4.3 for details). The CSF indicate the potential of long-term sustainability of the system and cover the five performance enabling realms of SSS systems (Planning, Design and Implementation, O&M, Management and Monitoring, Socio-Cultural Aspects and Finance). Vice versa, they also reflect all possible causes for failure of a system (i.e. poor fulfilment of PO). CSF scores are subject to temporal variations, i.e. the CSF fulfilment can improve or deteriorate over time (all except the CSF under Planning, Design and Implementation). Hence, the scores shown here generally represent a snapshot at the time of the data collection visit.

All non-operational systems visited during the basic assessment (19; 7% of total number of visited systems) are excluded, since the link to the daily operation of the systems could not be made and datasets were incomplete. The scores for each CSF (insufficient, caution and good) for the 290 (309 assessed system minus 19 non-operational ones) analysed systems are presented in Figure 54.

Figure 53: Basic assessment data collection at an SSS system (Photo: Kiran Patil G.S.).

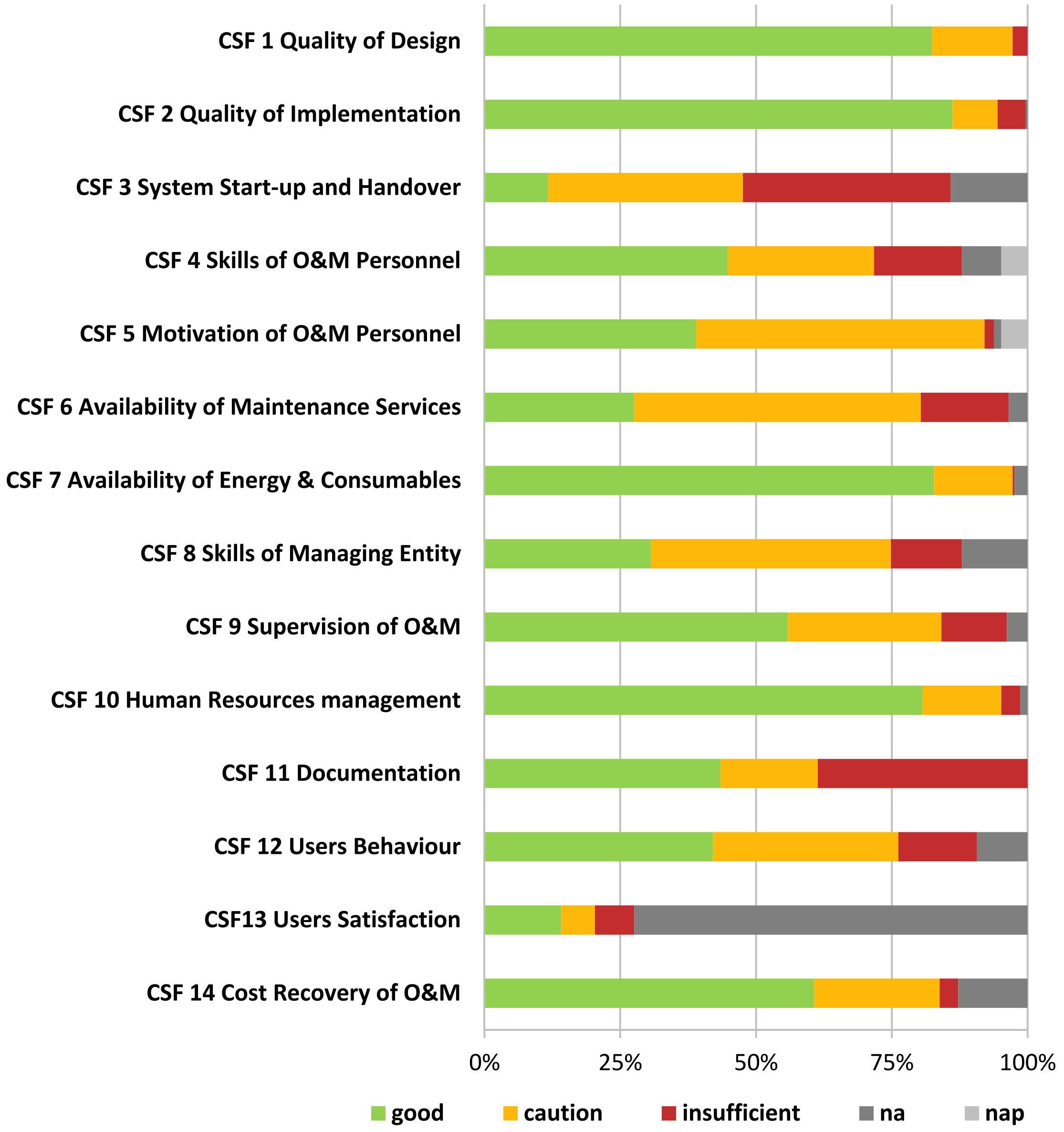

Figure 54: CSF scores for all the operational assessed systems (na = not available, nap = not applicable) (n=290).

Overall, the results roughly indicate a relatively good fulfilment of the following five CSF: *Quality of Design*, *Quality of Implementation*, *Availability of Energy and Chemicals*, *Human Resources Management*, and *O&M Cost Recovery*). The remaining CSF are predominantly rated with ‘caution’ to ‘insufficient’ (*System Startup and Handover*, *Skills* and *Motivation of Personnel*, *Accessibility of Maintenance Services*, *Skills of Management Entity*, *Supervision of O&M Activities, Documentation, User Behaviour and User Satisfaction*).

The following five subsections discuss the findings in more detail for each of the five performance enabling realms.

Planning, Design and Implementation

Figure 55 shows the scores of CSF 1-3 for all systems.

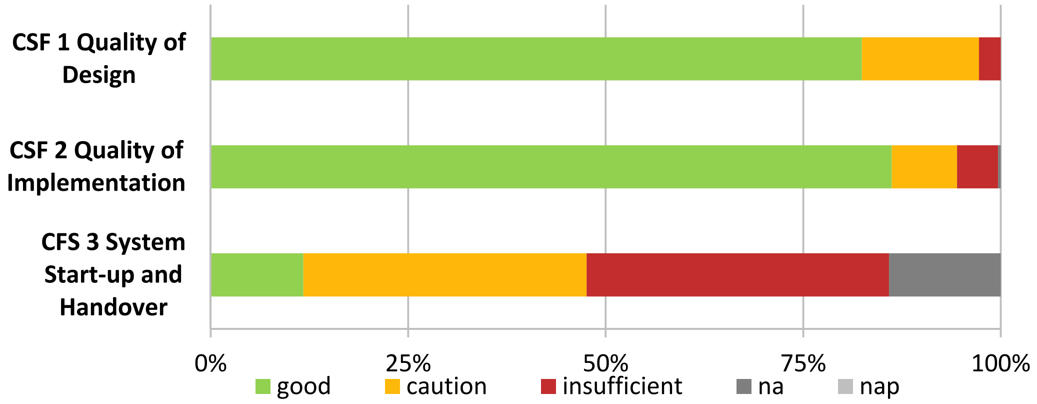

Figure 55: Scores of the CSF covering the performance enabling realm 'Planning, Design and Implementation' (na = not available, nap = not applicable) (n=290).

Quality of Design and *Quality of Implementation* scored high which means that at the time of the assessment, there were only few obvious design mistakes or construction quality issues in the assessed systems.

System Startup and Handover scored caution and insufficient for 75% of systems, showing the general lack of involvement and support after handover by design and construction companies. System documentation, such as design reports, flow sheets and drawings is very often missing. The handover phase is crucial for knowledge transfer and can lead to failure of the system.

Scoring quality and limitations:

- Time variability of CSF: low
  All three CSF are bound in time and thus not subject to variation in time.

Quality of Design and *Quality of Implementation*

- Precision of scoring: low
  It was not possible to get design assumptions, construction material details and quality of components used for the 309 systems. Furthermore, the data was often collected from secondary sources (i.e. current operator and manager which were not always in place since the beginning of operation). This leads to a quite coarse estimation of the quality of design and implementation. This also means that the precision of these CSF scores might be subject to variation in time (e.g. more accurate data about design for younger systems but a better assessment of construction quality after the system has gone through some years of operation).

System Startup and Handover

- Precision of scoring: medium - high
  The quality of startup and handover of the system can be quite straightforward to assess; yet, there is the possibility that information has been lost over time and when managers change (insufficient transfer of knowledge). Thus, the potential of information loss is increasing with time.

Operation and Maintenance

Figure 56 shows the scores of CSF 4-7 for all systems.

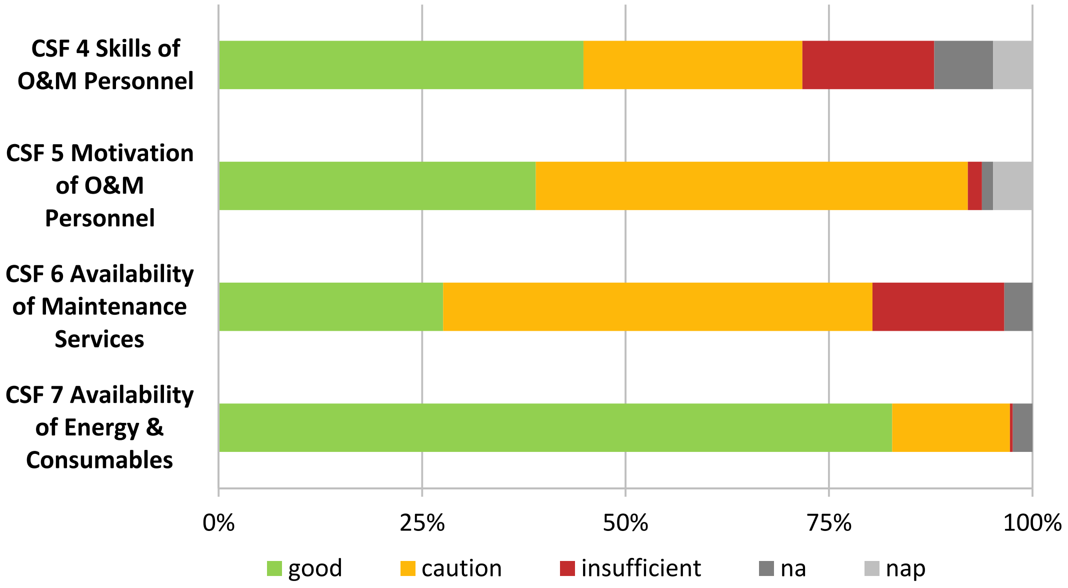

Figure 56: Scores of the CSF covering the performance enabling realm 'Operation and Maintenance' (na = not available, nap = not applicable) (n=290).

The CSF under O&M overall scored rather unsatisfactorily, with 3 out of 4 CSF scoring insufficient or caution in more than 50% of the cases. Specifically, these results highlight the lack of the operators' proper training, system knowledge and ability to detect and solve the systems' technical problems.

The motivation scores were impacted by the medium satisfaction of the operators with their job, the generally poor appearance of the system's surrounding area and the medium reliability of the operator from the managers' point of view.

The weaknesses regarding the accessibility of maintenance services (in up to 70% of systems) were mainly due to unclear responsibilities and difficulties encountered when maintenance works were required (i.e. manager or operator reported that maintenance was or has been a major issue in the present or past).

Energy and chemicals provision seems to be quite well assured due to a high coverage of power backup and presence of consumables on-site when needed.

Overall, insufficient operation and, therefore, the risk of failure, drastically increases without skilled O&M personnel or access to maintenance services. Improper skills of O&M personnel means that the operator might know how to run the plant, mechanically turn on and off the pumps etc., but as soon as something goes wrong, he will fail to identify it and even more to have the correct reaction in order to fix the issue. If maintenance is not organized, planned or available, when a component of the system fails, it will not be replaced and can lead to plant failure.

Scoring quality and limitations:

- Precision of scoring: good
  The four CSF were quite precisely scored as both the current operator and manager were interviewed. The information was collected from primary sources and double checked between the two interviewees and observation on-site by trained field staffs.

The *Accessibility of Maintenance Services* score accuracy might vary over time and be more precise for older systems. As such, the actual availability of the maintenance services can be measured only if maintenance works were previously required.

Skills of Personnel and *Motivation of Personnel*

- Time variability of CSF: **medium**
  These CSF describe the current status of the O&M personnel of the system. The score does not take into account how was the situation from the start of the system till the interview took place. These CSF are subject to changes through time with turnover of manager and operators or if further trainings are taking place.

Accessibility of Maintenance Services

- Time variability of CSF: low
  The availability of maintenance services are at first site not prone to drastic changes in time, but is still bound to a good management and costs planning.

Availability of Energy and Chemicals

- Time variability of CSF: low
  The energy availability should not be subject to changes except for unexpected breakdowns. The consumables on the other hand may be subject to quick variations and are bond to the skills to the operator and manager of the system.

Management and Monitoring

Figure 57 shows the scores of CSF 8-11 for all systems.

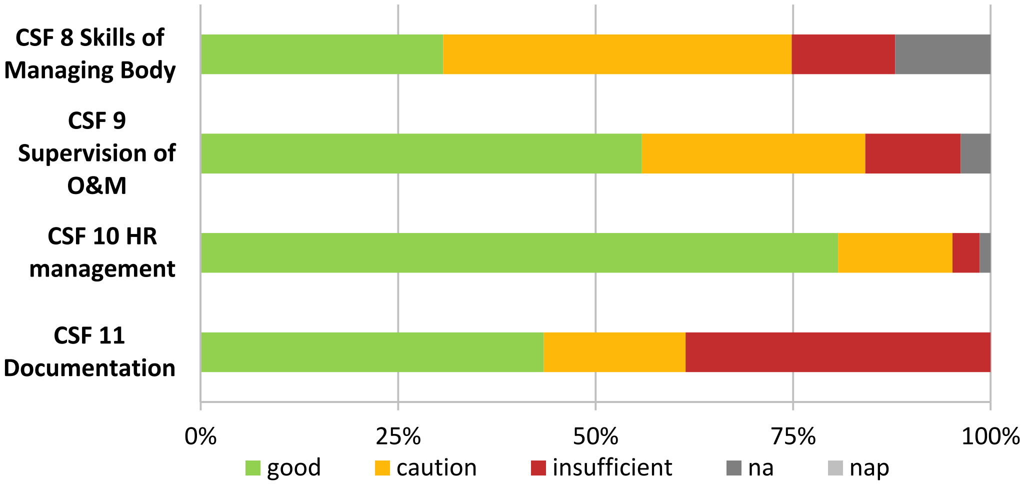

Figure 57: Scores of the CSF covering the performance enabling realm 'Management and Monitoring' (na = not available, nap = not applicable) (n=290).

The managing body was often found to have a medium to poor level of skills and knowledge, i.e. a low level of training on financial aspects and/or technical knowledge, as well as low understanding of the reasons behind a system's good or bad performance. The *Supervision of O&M Activities* overall scored better (i.e. with a bit more than 50% of *good* scoring systems) but was pulled down in a considerable number of systems by a low frequency of effluent quality and performance supervision as well as the low provision of training for the operator and poor monitoring of operator presence and work. Figure 60 below shows how CSF 8 and 9 score differently in the various application contexts.

Lack of systematic and comprehensive collection and storage of data about finances, presence and work of operator as well as other O&M tasks were the major factors that impaired the CSF *Documentation*.

The good score of *Human Resources Management* reflects the fact that usually there is O&M personnel assigned to adequately look after the plant 24/7, that staff is remunerated with adequate salary and that they did not complain about the management entity.

Overall, these results show an insufficient situation. The lack of management knowledge or proper documentation about finances and O&M can strongly impact the long-term performance of systems. It was observed that very often the manager in charge of the SSS system was not fully aware of all the aspects he/she should be aware of and that the SSS systems management duty was often only a small part of his/her overall duties.

Scoring quality and limitations:

- Precision of scoring: **good**
  As for the O&M realm, the CSF covering the management and monitoring realm were quite precisely scored with information from primary sources (manager and operator).
- Time variability of CSF: **medium**
  The CSF are subject to time variability with the turnover of management entity personnel. All these four CSF might have been fulfilled differently in the past and scores depend on the interviewees. The CSF *Documentation* might be more robust through time and includes legacy from previous management units' decisions.

Socio-Cultural Aspects

Figure 58 shows the scores of CSF 12 and 13 for all systems.

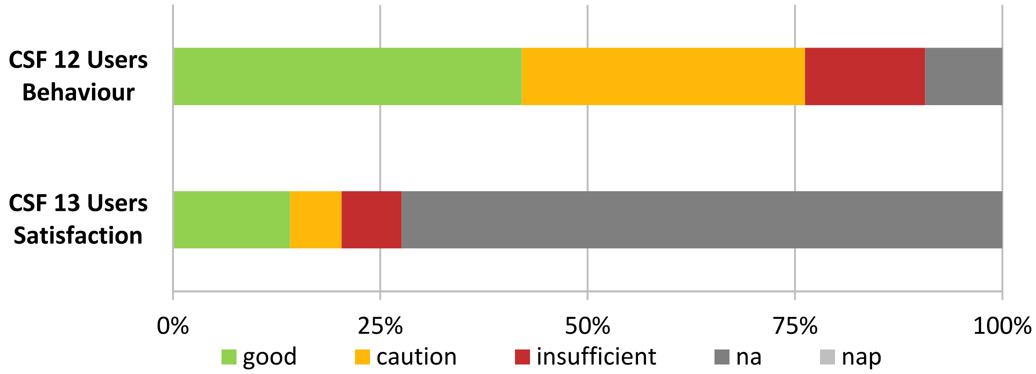

Figure 58: Scores of the CSF covering the performance enabling realm 'Socio-Cultural Aspects' (na = not available, nap = not applicable) (n=290).

The CSF *User Behaviour* yielded quite mixed scores with variable compliance of users to instructions on how to use the system (e.g. what not to discharge in the sewer). This kind of behaviour can induce blockage or clogging of the sewers and/or the treatment plant, impact on the treatment and create nuisance which will negatively influence the satisfaction of users. The awareness of users about the sanitation system they are benefiting from is crucial for good operation. On the other hand, there were usually no major issues with the wastewater fee collection (when relevant).

Concerning *User Satisfaction*, data was collected only for residential systems as the users of commercial or institutional treatment systems usually don't even know about the systems' existence. They are often temporary users and could not express a long-term satisfaction, resulting in a high proportion of scores *not available* ('na'). Users were frequently complaining about the nuisances provoked by the plant but were welcoming the reuse of the treated wastewater as well as treated sludge (when relevant), which led to an overall mixed satisfaction of users.

Scoring quality and limitations:

- Time variability of CSF: **medium**
  The validity in time of the CSF is medium as they are covering past and present challenges but are bound to single individuals (users, operators and manager) which are subject to change. Potential changes of the CSF score through time can be assumed.

User Behaviour

- Precision of scoring: **good**
  The evaluation of adequate user behaviour is overall good as information were provided by the operator, manager and user whenever it was possible and this cross-assessment should ensure a strong confidence in the scoring.

User Satisfaction

- Precision of scoring: **medium**
  Even if the scoring of the satisfaction of the users might be straightforward, the scores presented here are the result of interviews with one to three users which may be weak and not representing the average opinion of all the users.

Finance

Figure 59 shows the scores of CSF 14 for all systems.

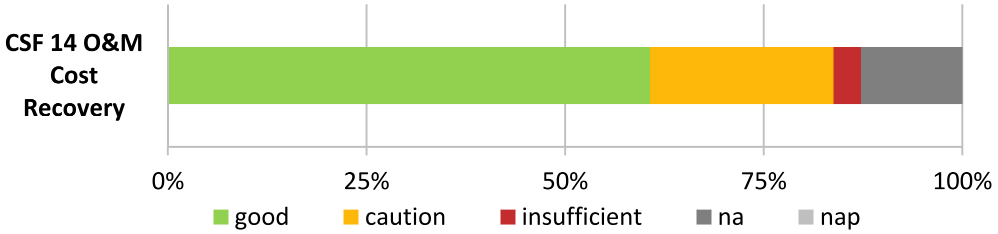

Figure 59: Scores of the CSF covering the performance enabling realm 'Finance' (na = not available, nap = not applicable) (n=290).

It seems that overall the cost recovery of O&M expenses was not a major challenge in over 60% of the treatment plants. This is also in alignment with the finding that managers hardly state high operating costs as a main disadvantage of SSS systems (see Figure 30 on p. 54). But the scoring of the CSF highlighted a total absence of planning of expenditures in 80% of the systems. This increases the risk of financial dry-out in case of future major maintenance works. Further, it was observed that owners and resident welfare associations sometimes put a lot of pressure on managers and operators to lower the O&M costs of the STP, which can drastically hamper correct operation and eventually affect the treatment performance of the system. A strong variation of the CSF scores distribution can also be observed between the different contexts of application (see Figure 60 in the following section).

Scoring quality and limitations:

- Precision of scoring: **medium**
  Even though detailed financial data on costs and revenues was impossible to gather, the qualitative assessment of the *O&M Cost Recovery* level was well covered with information from the primary source (i.e. manager). On the other hand, the pressure to lower O&M costs (leading to the financial non-coverage of the full required O&M costs) was only partially integrated in the evaluation of the cost coverage of O&M activities.

- Time variability of CSF: **medium**
  The income generated should not be subject to high variability. However, sudden requirements of high financial inputs for maintenance works (especially if expenses are not planned correctly) can arise which could negatively influence the score of the CSF.

Context implications on CSF scores

It is possible that the specific conditions in certain contexts facilitate or hinder the fulfilment of the different CSF. This was verified by separately analysing how the scores differ in the various application contexts of SSS systems. The biggest inter-contextual differences of scores were found for CSF 4, 8, 9 and 14. Figure 60 displays the category-specific scores for these CSF.

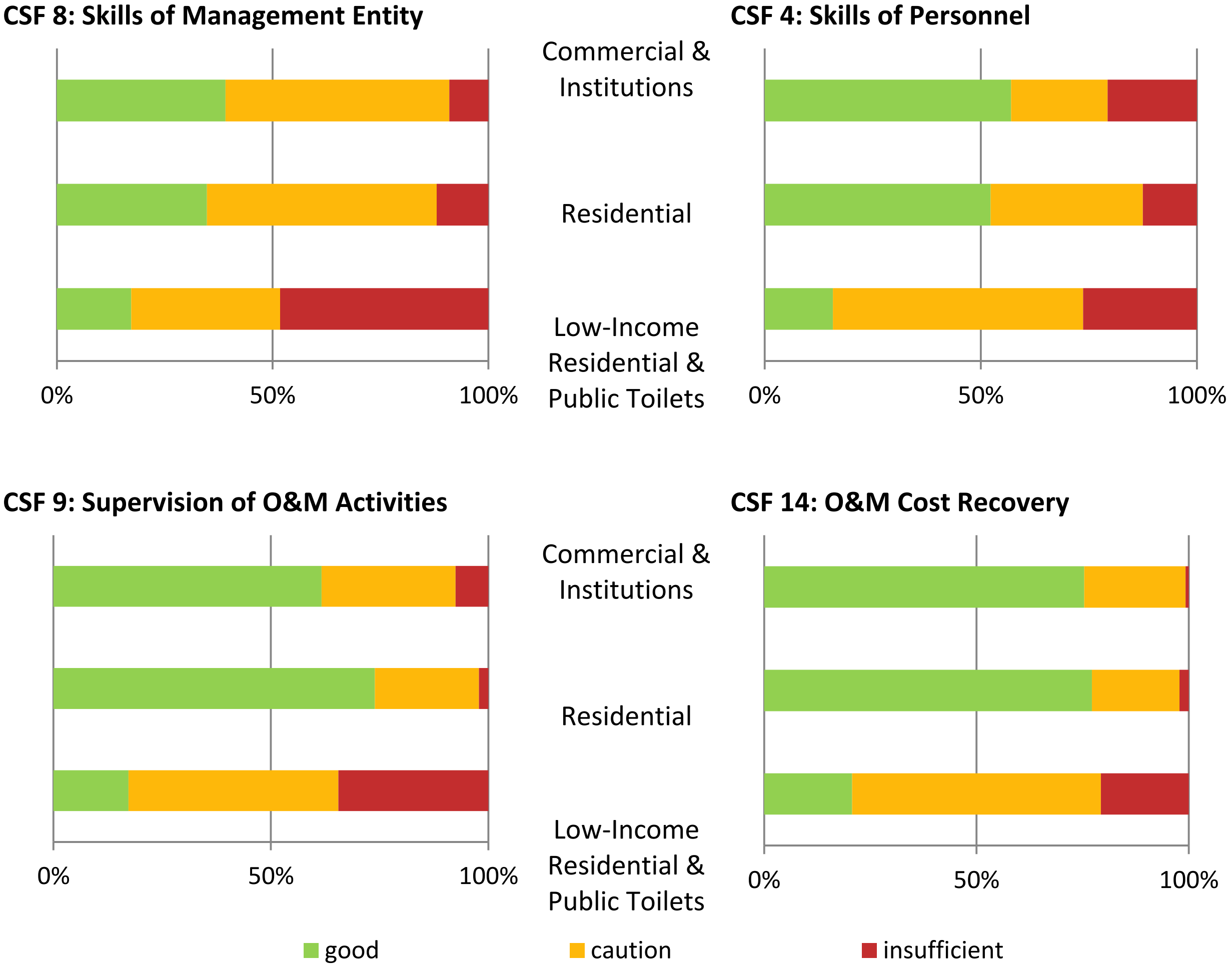

Figure 60: Scores of four CSF in different contexts of application: Commercial & Institutions (n=133), (High- and middle-income) Residential (n=92), Low-Income Residential & Public Toilets (n=29). Municipal is not shown due to an insufficient number of cases.

The systems from the category *Low-Income Residential and Public Toilets* scored significantly lower in CSF 4, 8, 9 and 14. The poor scores in *O&M Cost Recovery* shows that they frequently don't have financial stability to properly manage, operate and especially maintain the system, eventually leading to system failure. Also, the same systems scored lower in *Supervision of O&M Activities*, likely due to optional monthly effluent testing whereas this was usually mandatory for the systems present in other contexts. As seen in section 3.2.5, systems in the low-income and public toilet context often don't practice water reuse, which makes it easier to forget about the system and its O&M. Further, O&M responsibility is often with the local government, an NGO or CBO (see section 3.2.11). This indicates a more distant management scheme which can also lead to weaker supervision. Finally, the skills of both managers and operators scored low in lower-income residential systems. Even if the systems implemented in this context require less supervision and knowledge (e.g. filtration- or ABR-based systems), the absence of skills increases the risk of poor performance and eventually failure of the system.

Technology implications on CSF scores

It is possible that the technology used in a small-scale sanitation system facilitates or hinders the fulfilment of certain CSF. This was verified by separately analysing how the scores differ for the various SSS technologies. The most relevant technology impact on the CSF scores is found in CSF 6 *Accessibility of Maintenance Services*. Figure 61 displays the technology-specific scores for this CSF.

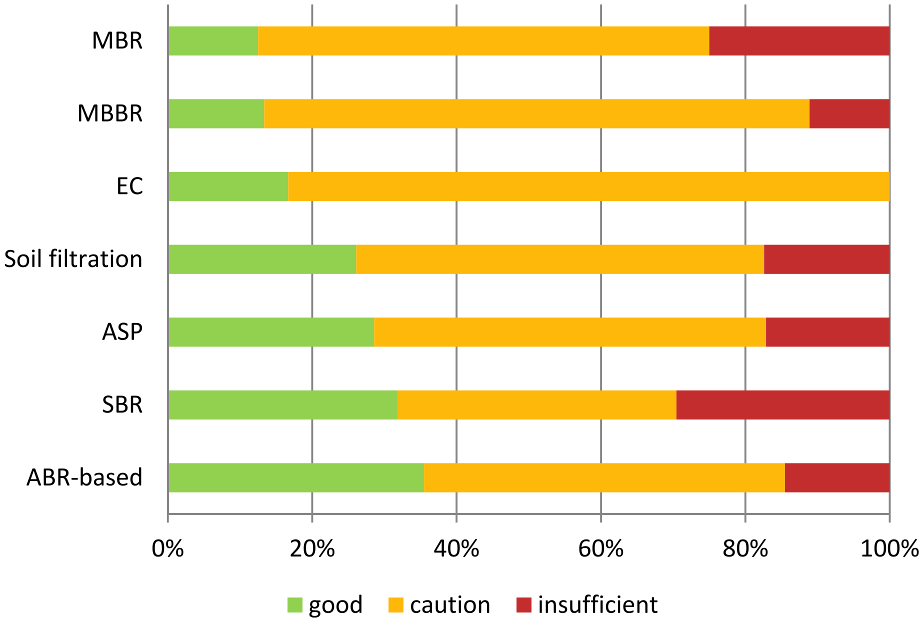

Figure 61: Scores of the CSF *Accessibility of Maintenance Services* across 7 technology families (MBR: n=8, MBBR: n=45, EC: n=6, Soil filtration: n=23, ASP: n=70, SBR: n=44, ABR-based: n=62).

The most complex (MBR, MBBR) and uncommon systems (Electrocoagulation, EC) that require more complex (and possibly also more expensive) maintenance tend to score worse than the more conventional or simple systems such as ASP, SBR and ABR-based technologies. This shows that the planning for maintenance investments and actual maintenance work is a critical factor.

3.4.3 Cause-effect analysis: investigating the potential interlinkages between the fulfilment of critical success factors and the performance outcome

This section aims to better understand which factors influence the performance of small-scale sanitation systems, and what the underlying reasons are if a system does not perform well. For this purpose, the effect of the critical success factors (CSF) on the performance objectives (PO) is analysed.

The analysis is done for PO 1.1 (*Treatment Effectiveness*), PO 1.2 (*Adequate Loading*), PO 2.2 (*Active Nutrient Recovery*) and PO 3 (*Appropriate Management of Solids*). The quantitative PO (PO 1.3-1.5) as well as PO 2.3 (*Energy Recovery*) do not have a sufficient number of cases (40 sampled sites and 18 sites with energy recovery infrastructure, respectively) to build a statistically meaningful model. PO 2.1 (*Water Reuse*) scored nearly 90% *good* and thus lacks sufficient variation. PO 1.3-1.5, PO 2.3 and PO 2.1 are therefore not included in this analysis. Independent variables are all the CSF. Next to these, three control variables were assumed to potentially play a role in explaining performance: presence/absence of grease traps for pre-treatment, presence/absence of screen for pre-treatment, and age of the system. They were integrated in the analysis.

Presentation of results

The results of the Random Forest (RF) analysis for all Performance Objectives report a very low accuracy in prediction. As such, the CSF together fail to predict performance.

Two examples are presented here: PO 3 *Solid Waste Management* and PO 1.1 *Treatment Effectiveness*.

Analysis of PO 3: the model includes PO 3 as the dependent variable and the CSF as independent variables. RF analysis can only deal with complete cases (i.e. all CSF and PO were successfully scored). Hence, as CSF 13 User Satisfaction was scored based on user interview data which was only available for a relatively small number of systems (residential ones only), CSF 13 was excluded as an independent variable for this analysis in order to increase the number of data points. After removing incomplete cases (i.e. at least one of the CSF was not scored due to lack of data points), 33.3% of the systems have a score of *good* for PO 3. 7.6% of the systems have a score of *caution*. The remaining 59% of systems are scored *insufficient*. The total number of systems that fulfil the above criteria for analysis is 210.

The Out-Of-Bag (OOB) error (measurement of the prediction error of RF model) of the calculated RF analysis is 38.1%. This means that the model predicted 61.9% (or 130 out of 210 cases) correctly. This a very low value, which becomes more evident when looking at the confusion matrix. A confusion matrix is a cross table showing predicted versus real values (see Table 15).

Table 15: Confusion matrix between real scores of PO 3 *Active Management of Solids* and the predicted scores by the Random Forest model (n=210). Bold table entries highlight correct predictions.

		Predicted PO 3 Scores		
		Insufficient	Caution	Good
Real PO 3 Scores	Insufficient	**93**	0	31
	Caution	9	**0**	7
	Good	32	1	**37**

The model predicted 75 cases as *good*, one case as *caution* and 134 as *insufficient*. Looking at individual classes, the confusion matrix shows that especially *good* and *caution* couldn't be predicted very well. The accuracy in prediction is mainly achieved by predicting the majority class (*insufficient*) correctly. Hence, the RF Analysis is comparable to the simplest model which would be predicting only for the majority class. Overall, it can classify 5 cases more correctly as the simple model (all *insufficient*). The data does not contain the needed information to make a better prediction.

Analysis of PO 1.1 (see Table 16): the accuracy of the RF Analysis increases but is subject to be a case of "false accuracy". The OOB error is only 19.52%. But the RF model correctly predicted *good* (i.e. the majority class) 80% of the time. A simple model, only predicting *good*, would achieve 80% accuracy and consequently an error rate of 20%. A better measure here is the "balanced accuracy" as it takes the individual class errors into account. The balanced accuracy of the RF model is only 57%. This low accuracy is the result of a class error of 100% for *insufficient* and 85% for *caution*. There is nothing in the data that would suggest a bad performance.

Table 16: Confusion matrix between real scores of PO 1.1 *Treatment Effectiveness* and the predicted scores by the Random Forest model (n=210). Bold table entries highlight correct predictions.

		Predicted PO 1.1 Scores		
		Insufficient	Caution	Good
Real PO 1.1 Scores	Insufficient	**0**	0	22
	Caution	0	**3**	17
	Good	0	2	**166**

Aggregated PO *System Performance*: Although their explanatory power is very weak, cross tables for the aggregated PO *System Performance* (POagg, the average of PO 1.1, 1.2, 2 and 3) are presented in the following.

Table 17 shows the frequency distribution for the aggregated PO. Most systems have been scored *caution* (60%). One third of the systems have been scored *good*. The remaining 7%, i.e. 19 out of 286 cases, are scored *insufficient*.

Table 17: Distribution of scores for the aggregated PO *System Performance* (POagg) between *good*, *caution* and *insufficient* (n=286).

POagg	n	Proportion	Cumulated n
Insufficient	**19**	**6.6%**	**19**
Caution	**172**	**60.1%**	**191**
Good	**95**	**33.2%**	**286**

Table 18 shows the cross table for the aggregated PO and CSF 4 *Skills of Personnel*. CSF 4 has consistently been the most important throughout the models. The percentages included are raw percentages showing the frequency of the PO scores for a single CSF score. Looking at the individual frequencies first, CSF 4 has been scored *good* most of the time. The cross table suggests a slight positive effect of the CSF 4 score on the aggregated performance. The number of good performance scores is highest when the CSF is scored *good*. An *insufficient* PO is more likely with an *insufficient* score of the CSF. *Caution* is most likely when the CSF is scored *insufficient*. But the cross table also already shows a certain amount of randomness. The PO is scored 48 % *good* when the CSF is scored *good*. It is scored 19% *good* when the CSF is *insufficient*. Hence, this CSF is not confirmed as critical for success by this analysis.

Table 18: Cross table of scores between CSF 4 *Skills of Personnel* and POagg *System Performance*.

		POagg *System Performance*		
		Insufficient	Caution	Good
CSF 4 *Skills of Personnel*	Insufficient	**12.8%**	68.1%	19.1%
	Caution	8.9%	**66.7%**	24.4%
	Good	1.0%	51.0%	**48.0%**

By definition the CSF should be critical for a performance. If the values of the CSF do not lead to a good prediction, the CSF cannot be considered critical for predicting the performance. The same results are achieved when analysing the other Performance Objectives. Hence, with the present model and dataset it is not possible to confirm that the CSF are actually critical for performance.

Methods tried to improve the quality of the model

Up- and down-sampling

The data is highly unbalanced. For example, PO 1.1 has been scored *good* in 80% of the cases (9.5% *caution* and 10.5% *insufficient*). Unfortunately, Random Forest does not handle unbalanced data very well.

To cope with unbalanced data, one can use up- or down-sampling. Up-sampling replicates cases from the minority class, down-sampling reduces cases in the majority class. The RF model is trained on the balanced data and tested on the whole dataset / test dataset. Another possibility would be to use weights to modify the cost of a misclassification, but this wasn't applied (same goal as up-/downsampling).

After applying down-sampling to PO 1.1 (i.e. by reducing the number of *good* scores), the OOB error is even higher with 37.62% than when using the original dataset (OOB error of 20.95%). So down-sampling does not increase but decreases accuracy.

When applying up-sampling, the variable needs to be binary (i.e. they require change of classes from *insufficient*, *caution*, good to *insufficient/caution*, *good*). The RF model is then trained on this dataset and used to predict values in the test dataset (OOB error cannot be used any more. It usually is a good estimate of the error calculated from test data).

Upon up-sampling, PO 1.1 has a frequency distribution of 48.1% *good* and 51.9% *insufficient/caution*. The data is balanced. Running the RF model then predicts the values in the test dataset, indicating 25 out of 74 cases have been wrongly predicted. This equals 33.8%, which is again worse than the accuracy of the model run with the original dataset (if compared to the original OOB error of 20.95%). This means that up-sampling also does not increase but decreases accuracy.

Binary POs, weighted averages and logistic regression

A RF analysis with transformed binary PO 1.1 and all data without up- or down-sampling reports an OOB error of 20.95%. It only classifies 5 cases as *insufficient/caution* correctly, while classifying 37 as *good* that are actually *insufficient/caution*. Hence, the model with the binary PO does not provide better insights.

The ordinal data with three ordered categories (*insufficient*, *caution*, *good*) can also be analysed by applying an ordered logistic regression. The so-called "Maximum Likelihood Estimations" in a logistic regression generally require a huge amount of data. It was not possible to calculate an ordered logistic regression due to the small sample size of some combinations of PO and CSF. Again, a logistic regression with the transformed binary PO didn't yield any improvement in prediction.

Finally, instead of using the POs and CSFs classified into three categories, the weighted averages that were the basis for classification were used. To analyse this proportional data, a so-called "Generalized Linear Model" with a logit link function was used. However, the explained variance remained to be very low.

Potential reasons for failure to predict performance

The results suggest a very low predictive power of the CSF on PO. However, in theory and in practice, there is strong evidence that all these variables (i.e. O&M, management, finance, etc.) have a critical influence on the performance of a treatment plant and its success or failure. The potential reasons why the model developed here failed in finding strong relationships between the CSF and the system performance, are:

- Unbalanced data

  As explained above, the data is most of the time unbalanced with an over-representation of *good* over *insufficient* and *caution* cases for most of the CSF and PO. Random Forest is known to be fairly sensitive to unbalanced datasets. Attempts to balance the data by up- and down-sampling were not successful in improving the sensitivity, which suggests that the low predicting power of the model is not only due to the unbalanced dataset but also due to missing diversity in the dataset. This confirms the earlier doubts about the bias of the data (see section 2.2.3 and 3.2.1). This implies that the data used for the analysis mainly covers the best cases and that there is an under- or non-representation of worst cases. This is the result of three main factors:

  - The exclusion of the non-operational systems from the cause-effect analysis framework.
    Most of the CSF from non-operational systems could not be scored because the manager and/or operators in charge before the failure were not present anymore. The reasons for system failure were not fully covered also as the questionnaires were primarily designed to cover the current and not past system status.
  - With the complete cases requirement (only the systems with each CSF scored were selected), data is lost and proportionally more from the non-good cases.
  - Biased access to systems for assessment: as explained earlier, some methods to get access to systems (i.e. through private companies) were subject to bias (see 2.2.3). This led to an over-representation of well-working systems over underperforming ones.

  The fact that the data is unbalanced might have heavily impacted the model, by excluding relevant cases. Also, some CSF may have a big influence on these cases and less on the better functional systems clouding the issue.

- Measurement or accuracy errors

  As presented in the CSF scores section (see section 3.4.2), the scoring accuracy might vary over time and/or between the different CSF. This can be due to:

  - Data quality hampering precision of scoring
    The quality of the data collected was sometimes difficult to assess and some data might be inaccurate. Training, validation procedure and triangulation of answers have been used to avoid and correct these potential errors (see sections 2.2.4 and 2.2.5), but mistakes might have prevailed and often it is not possible to say if the answer of the interviewee is actually true or not.
  - Mismatch between the analysis framework and the questionnaire data
    The analysis framework having been built after the data collection phase, the questionnaire data sometimes couldn’t describe exactly the wanted CSF. Each CSF and PO was described as precisely as possible but due to variable data availability some CSF might be scored more precisely than others (e.g. *Quality of Design* or *Quality of Implementation* were more difficult to score than *Skills of Personnel*).
  - Too many independent variables
    Overall, the scoring might still be quite good but for a model to integrate 13 independent variables (CSF) in order to predict the outcome of nine different dependent variables (PO) is extremely challenging. The noise in the scoring accuracy might have amplified by the high number of variables to include in the model.

- Finally, the ordinal "traffic light" scale (*insufficient*, *caution*, *good*) might have been too simple to correctly represent the complexity of each CSF. Information might have been lost in the process.

o Mismatch between the long-term influence of CSF and the snap-shot description of PO

In theory, CSF are influencing the performance on the long term. A change in the score of a CSF might not have a direct, immediate influence on the performance. The questionnaire was designed for assessing the present status of the CSF and less for its history, and possible "legacy" effects from previously better or worse CSF status were difficult to take into account. On the other hand, the PO scores are a one-time assessment (or "snap-shot") of the performance of the system. There might be a mismatch between the current CSF and PO at the time of assessment. Finally, the influence of a CSF over time, might vary with high or lower importance for younger or older systems.

o Lack of data points

There were often quite low numbers (low n) of cases in minority classes. Especially when splitting the dataset or using the up-sampling mechanism. With a low n, the possibility of randomness increases. A single case can make a huge difference and robust relationships are harder to find, especially when effects are weak.

Potential improvement measures for the cause-effect analysis

Looking at the different potential reasons for the failure to confirm the influence of the critical success factors on SSS systems performance, it is possible to suggest improvement measures. Due to lack of time these improvements were not implemented in the present project but could be used if one wants to further analyse the cause-effect relationship of sanitation system performance. Potential improvement measures include:

o Narrow down the varying factors

Selecting one city, one specific age of system or one specific context might help in reducing the uncontrolled external variations influencing the cause-effect relationship. Reducing the varying variable would bring the situation closer to "lab" setting which might help in measuring the effect of specific variables (i.e. O&M, management, etc.).

o Increase data balance

Strictly including totally and partially failed systems, along with apparently well-working systems, would help in having a more balanced dataset and would, thus, provide a better understanding of success and failure influencing factors.

o Increase number of data points

Having a bigger number of systems would help being able to have more statistically significant results. This could be achieved if a larger-scale monitoring system was to be put in place, such as an online data platform for small-scale sanitation systems, see 4S Project Report Vol. II on governance (Chandragiri et al., 2020).

o Long-term monitoring

Instead of a snap-shot picture of the CSF and PO scores of a system, a longer-term monitoring (also potentially facilitated by an online data platform) would allow to have a better understanding of the relationship between the fulfilment of CSF and the performance of systems.

- Optimise the model

  Having fewer independent variables would simplify the model and provide better chances to get significant results. But on the other hand, a too simple model might not provide insights with an added value. A trade-off between a too complex model that cannot extract any significant relationship (i.e. as the present model) and a too simple model that results in obvious findings (e.g. concluding that O&M is an issue) should be found.

- More precise data

  A more precise dataset with a questionnaire that is tailored to the cause-effect analysis framework would help improve the scoring. This could also shorten the questionnaire and help keeping the attention of the interviewee focused during the whole interview.

This study shows that it is extremely complex and difficult to build robust and reliable cause-effect analysis frameworks. It is clear, however, that careful problem-structuring and systematic and on-going data collection are helpful and needed to further improve the understanding of the numerous factors that influence SSS system performance. 4S can be seen as a first step in this process.

Figure 62: Measuring the flow at an SSTP (Photo: Nadège de Chambrier).

4 Conclusions and Recommendations

4.1 Conclusions

Key Conclusions

- There has been a considerable, private sector driven scale-up of SSS in India's urban areas since 2006. The lack of comprehensive system databases highlights the difficulties PCBs are facing with their limited human and financial resources to do a rigorous follow-up of large numbers of privately owned and operated systems.
- The major challenges facing SSS systems are:
    - Neglected startup and handover phase
    - Underloading during first years of operation, leading to performance issues, high per capita operating cost and possibly late discovery of underdimensioned systems
    - Intermittent operation of SSTPs to save cost, which can affect the biological treatment process
    - Lack of technical knowledge of managers and operators
    - Insufficient supervision of O&M activities
    - Lacking documentation of O&M activities and financial flows
    - Poor anticipation of maintenance works
    - Limited opportunities for reusing the total amount of treated water, and
    - Unsafe sludge management
- Systems implemented in lower-income residential settlements are a lot more sensitive and poorly scoring in many of the critical success factors.
- Conclusions on performance:
    - Well-operated SSS systems are found to be able to achieve quite stringent standards in terms of organic constituents and suspended solids, but they are not designed for nutrient removal and are not currently able to reach corresponding water quality requirements.
    - The standard for faecal coliforms is consistently not met in nearly all analysed systems, no matter whether or not a chlorination step is used for disinfection.
    - SSS systems are exposed to generally higher feed fluctuations than larger systems, and they often treat higher concentrated wastewater. This can lead to higher effluent concentrations than in large systems (even if the removal rate is the same).
    - Next to the treated water quality, adequate loading, resource recovery and solids management are important indicators of a fully functional SSS system. The consideration of these performance objectives can be useful for a holistic perspective of performance.
- With the data, models and methods used, it was not possible to statistically correlate the fulfilment of critical success factors with the fulfilment of performance objectives. While this highlights the complexity of the cause-effect relationships, it is likely that the non-fulfilment of certain factors does not lead to poor performance immediately, but with a delay.
- Many a sustainability issue of SSS systems and related failure risks cannot be identified even by the most precise sampling results. On the other hand, observations and qualitative data will never be able to fully predict the actual treatment performance of a plant. By combining both quantitative and qualitative information on performance and the factors that affect it, a mixed monitoring approach has a lot of potential.

4.1.1 The small-scale sanitation landscape in India

The landscape study reveals that SSS has seen a **considerable scale-up in urban India since 2006**. This development, which is mainly a result of environmental protection and urban water reuse policies, has been **realised primarily by the private sector, with hundreds of companies now operating in this field**. However, there is currently **no licensing or accreditation of vendors**, consultants etc. A **very diverse range of wastewater treatment technologies are used**, from the conventional ones to interesting innovations, making it difficult to keep the overview of what is the best for which application. Conventional activated sludge processes along with SBR and MBBR systems are among the most widespread options.

To date, research on small-scale sanitation has mostly focused on the scientific analysis of specific technologies or case-studies. There has been **almost no research** on how SSS can best complement conventional wastewater management approaches, and what it takes to successfully implement and manage SSS and water reuse systems at scale. Consequently, there is currently a **lack of information and guidance material, such as procedures for appropriate technology choice, or design standards**. Since SSS has been implemented through private sector efforts, it is also **not yet in the solutions portfolio considered by planning departments, and most of the knowledge is with private actors** (Chandragiri et al., 2020).

As the previous SSS scale-up has been led by the private sector, there are **no comprehensive databases of SSS systems** neither at city, nor at state or national level. Accordingly, it is impossible for the regulator to know how much wastewater is being treated to what level by SSS systems, and for planning authorities to consider these existing assets in the preparation of water supply and sewerage plans.

Despite its growing relevance, **there is still a relatively small number of systems implemented, considering the size of the country and potential market**. With increasing water scarcities, the importance of SSS and water reuse systems will only increase, providing a **tremendous opportunity for the private sector**. At the same time, the enabling conditions and structures are yet to be created to **transform this into an institutionalised, well-managed process**. This is further described in the 4S Project Report Vol. II on governance (Chandragiri et al., 2020).

4.1.2 Basic assessment of SSS systems

From the inspection visits and interviews at 279 systems in India one could conclude that only a small number of systems actually fail completely, i.e. are not operational at all. However, it has to be considered that it was a major challenge to get access to systems for data collection, as study participation was on a voluntary basis. Accordingly, it has to be assumed that there is a considerably higher proportion of well-functioning systems among those that were accessible than those which weren’t, and that the dataset holds a bias towards the good examples. On the other hand, the advantage of voluntary study participation over forced participation (e.g. through Pollution Control Boards who have the right to inspect systems) is that interview answers are likely to be more authentic and honest, as participants did not have to fear sanctions.

Despite the non-representative, unbalanced database, several important conclusions can be drawn:

- **Context:** SSS systems are built in various contexts, including commercial, institutional and residential settings, and even public toilets. These contexts imply different incentives, designs, management schemes and enabling environments, all of them influencing performance and causing different characteristic challenges.
- **Design and implementation**: detailed design information was not available in most cases, making it difficult to identify design flaws (e.g. inadequate capacity) during inspection visits. It is clear, however, that STPs built with low quality equipment or workmanship are more

likely to fail, as components have a lower life expectancy and robustness (see 4S Project Report Vol. III on finance (Rajan et al., 2020)).

- **Operation and run time:** many systems are actually working properly with all parts operational. However, the actual operational pattern is still unclear even when most of the interviewees said that they were running the plant 24/7. Observations during in-depth assessments showed that most plants were not running 24 h without either a full stop or only partial functioning during night time. Given the potentially high O&M costs, it is likely that owners try to save staff and energy cost by turning off systems at non-peak hours (see 4S Project Report Vol. III on finance (Rajan et al., 2020)). A biological treatment process based on aerobic microorganisms cannot perform properly without sufficient and regular aeration. If STPs are not operated 24 h, the consequence is that the sensitive biology suffers or dies off, reducing performance, or even that untreated sewage is released during those hours. Most mechanised systems require 24 h supervision by operators (normally working in three shifts). However, there are also systems and designs which are fully automated or minimally mechanised and only need little attention by caretakers.
- **Capacity of managers and operators:** a potential lack of knowledge and expertise in operating and managing SSS systems was observed. This might be the cause of technical issues (smell, poor performance) or financial mismanagement, which both together or separately could eventually pose a risk of system failure. No training programs are available for STP operators and no certifications are needed to become a professional operator. Unskilled and untrained workers therefore find themselves in this role, leading to widely varied standards of operations, low job perception and pay scales, absenteeism and attrition – which discourages better quality operators and causes O&M mistakes. To meet the needs of price-sensitive customers, O&M companies also recruit unskilled workers and put them to work after minimal training (Rajan et al., 2020). While such operators can often manage the day-to-day tasks of running the STP, preventive maintenance may not be properly undertaken or they may miss signals of underperformance or future problems with the STP.
- **Water reuse:** the analysis of the water reuse practices highlights the positive impact of the water reuse policies which entered into force over the last decade in the wake of increasing water stress. Reuse appears to be quite well established: reclaimed water from SSS systems is commonly used for toilet flushing and gardening, which can reduce the freshwater consumption of a building or campus by 30% or more. However, it was observed that 100% of on-site water reuse is normally not realistic, and straightforward opportunities for the off-site reuse of excess treated water are often also limited. This calls for innovative solutions for this precious resource. Specific information about how much of the treated wastewater is actually reused is currently missing and would be required to understand the volume of treated wastewater available for other reuse purposes in the surrounding areas of the SSS systems.
- **Sludge management:** a majority of the systems studied do not safely treat and dispose of the solids they produce. Off-site sludge treatment or disposal options are also not normally available, making sludge management a major issue. Owing to a lack of alternatives, sludge is often disposed of in nearby drains, water bodies or land. This compromises the overall goal of the SSS systems and potentially neutralises their benefits.

The most concerning issues observed were the lack of capacity of operators and managers together with the pressure for cost saving from owners as well as the very high amount of sludge that is produced, not treated and unsafely disposed of. Some key actions in these fields (see section 4.2) would probably have a high impact on long-term treatment performance and sustainability of the SSS systems.

4.1.3 Performance of SSS systems

The performance analysis shows that for the **organics and solids** effluent quality levels (BOD, COD, TSS), **any technology if combined with the right post-treatment units and operated correctly has the potential to achieve quite stringent discharge standards**, such as the CPCB 2017 standards.

The rest of the parameters subject to the CPCB discharge standards, however, are systematically not met by the assessed SSS systems. The **nutrient levels are not reached**, and it appears that partial nutrient removal is more a side-effect of the treatment of organic pollutants, and not a goal by itself in the assessed SSS systems. This is no surprise since almost all **systems are not designed for nutrient removal** (e.g. lack of treatment stage for denitrification).

The microbial effluent quality requirement is consistently not met in almost all analysed systems. Systems with disinfection steps (chlorination in most cases) do not ensure a better microbial removal rate and effluent quality than systems that do not disinfect. This indicates both too high organic concentrations before disinfection, as well as a poor design and/or wrong operation of the installed disinfection infrastructure, which inevitably also leads to the production of harmful chlorination by-products.

These conclusions from the detailed sampling campaign at 35 STPs in India highlight **significant discrepancies between the performance of SSS systems under field conditions and the limits stipulated in the current discharge standards**.

Due to the **absence of flow meters at most SSS systems**, it was not possible to make reliable comparisons of the actual loading with the design loading of plants. However, the findings from the basic assessment, the sampling campaign and from discussions with stakeholders (apartment owners, STP designers) indicate that **systems are commonly underloaded during their first years of operation**. Especially in the residential context, but also in commercial properties, it can take 4-5 years (or even more according to the basic assessment findings) to completely occupy a new building. This can result in the following **problems**:

- Underloaded systems may not be able to run at full technical performance.
- Systems may be expensive to operate (high cost on a per household basis), which might increase the risk that operators are under pressure to cut costs, e.g. by switching off the plant at night.
- Potential underdimensioning would only become apparent years after construction, leading to poor performance when the building is fully occupied. It is important to avoid that this delay is not misused during the design and implementation phase. Facing client pressure to cut costs, STP designers may otherwise build systems that have a lower capacity than what is required, or small margins to handle shocks.

Investigations confirm the previously reported intrinsically **high variations of raw wastewater characteristic from small communities**, depending on contextual factors and temporal patterns (e.g. seasonal and diurnal variations). SSS systems are therefore exposed to generally higher feed fluctuations than larger systems. **In many cases, small-scale systems also treat higher concentrated wastewaters (e.g. in situations where water is scarce, which can increase with climate change). This can lead to higher effluent concentrations than in large systems, even if the efficiency (removal rate) is the same.** This highlights the importance of:

- a good understanding of the specific local wastewater characteristics when designing SSS systems
- robustness of system operation to large range of feed concentrations and
- adequate effluent standards that do not discourage investments in communities with low water consumption

Besides efficient wastewater treatment, SSS systems may also have other objectives. Therefore, it can be useful to take a **broader, more holistic perspective of performance**, as described in sections 2.4.1 and 3.4.1. Next to the treated water quality, aspects like **adequate loading, resource recovery (water and potentially nutrients and energy) and solids management** are important indicators of a fully functional SSS system.

4.1.4 Conditions for sustainable SSS system performance

The analysis of the **critical success factors**, i.e. factors that can influence a system's successful long-term performance, highlights some areas of concern where SSS systems clearly don't score well. Accordingly, actions taken in these fields have the potential to drastically improve the sustainability of SSS systems in India:

i. **System startup and handover:** the period in which ownership and/or responsibility are transferred from the designer/builder to the management entity was found to be crucial. Proper knowledge transfer and support from designers and implementers during this process is important to lay the foundation of long lasting and robust SSS systems. A good handover is particularly critical in the residential context because it can take years until a so-called resident welfare association is formed which will eventually be responsible for the system. A well-organised startup phase can also help to minimise the issues around initial underloading (see section 4.1.3.).

ii. **Skills and knowledge of operation and maintenance (O&M) personnel and management entities:** as already described in section 4.1.2, operators and managers are often not sufficiently informed about the functioning of SSS systems and the requirements for good performance. Troubleshooting skills are, therefore, generally weak.

iii. **Supervision of O&M activities:** operators are often not clearly instructed and supervised. This can result in unclear or neglected responsibility and lack of information exchange.

iv. **Documentation of O&M activities and financial flows:** the absence of systematic documentation and archiving of information leads to the loss of knowledge and lack of understanding of the systems' performance and history. Such data is crucial for decision-making.

v. **Anticipation of maintenance works:** clear responsibility for organising spare parts, as well as for planning and budgeting scheduled maintenance services, is lacking. As a consequence, funds may not be earmarked or available for capital maintenance, leading to substantial risks of lasting system failures. This is confirmed by a basic assessment finding: the number one reason for non-operational systems are unrepaired damages (see Figure 23, p. 52).

Systems implemented in lower-income residential settlements are a lot more sensitive and poorly scoring in many of the CSF. This is in alignment with a finding from the basic assessment data collection visits, where a large proportion of the systems found non-operational were also in the low-income category. A better handover of the systems from implementation partners to the end users/communities as well as training programs for managers and operators seem most appropriate and promising in order to improve the situation.

The **correlation of the CSF and the PO** was analysed with different statistical methods in order to understand the cause-effect relationship between them. It was not yet possible to demonstrate that the 14 CSF are critical influencing factors for the PO scores, highlighting the high complexity of this cause-effect framework. The **limitations and differences in precision of scoring** between the different CSF, as well as the changing validity and accuracy of scores over time show the complexity of the task to assess the sustainability of SSS systems. It is also likely that the **non-fulfilment of certain factors does not lead to poor performance immediately, but with a delay**. A larger, longer-term dataset (e.g. from an SSS online monitoring platform) as well as refining the scoring of both CSF and PO would help to better understand and measure the influence of the CSF on performance.

4.1.5 Implications for monitoring

Performance assessment of SSTPs is normally done by analysing different water quality parameters in wastewater grab samples, and by comparing the measured concentrations with the applicable discharge standards. As confirmed by the study results, **grab samples will never be able to give a representative picture of an SSTP's performance**, as they cannot capture the large fluctuations typically occurring in small systems and carry high uncertainties. The analysis of 24 h flow-proportional composite samples (as done in this study) can overcome some of these limitations and provide a better picture by evening out diurnal fluctuations. However, it involves time-consuming and expensive work which is not practicable for the routine assessment of thousands of SSTPs. Online performance monitoring is also not an option for the coming years yet, as sensor technology is expensive, high-maintenance and technically mature for few parameters only.

Many a sustainability issue of SSS systems and related failure risks cannot be identified even by the most precise sampling results. The 4S Project tried to point out other complementary ways to assess performance and critical success factors, using descriptive data. An advantage of such an approach is that data collection can be quick and inexpensive (e.g. through inspection checklists and concise questionnaires). Certain quantitative descriptive data points could also be monitored online or through data loggers more easily than performance parameters (e.g. electricity consumption, pump operation). Automatic, continuous flow measurement is an important and not yet implemented support for system monitoring. At the time this report is written, no technological solution has been reported which satisfyingly addresses the challenges linked to precise flow measurement.

As confirmed in sections 3.3.6 and 3.4.3, observations and qualitative data (e.g. from surveys and inspections) will never be able to fully predict the actual treatment performance of a plant. The accuracy of such predictions is too low and cannot include all influencing factors compared to sampling methods which will always be more precise. **Qualitative surveys and inspections can obviously not replace sampling campaigns. However, a good set of complementary monitoring data has the potential to**

- provide additional information to back up and supplement unreliable grab samples,
- minimise the frequency of sampling and reduce the monitoring cost,
- help identify and prioritise the most problematic SSS systems with the lowest performance and potentially highest environmental impact (e.g. by checking the status and run-time of plant components, the presence of qualified staff etc.),
- provide datasets for further scientific analyses of cause-effect relationships and to support the constant optimisation of the SSS sector.

The approach used here would have to be carefully refined and scientifically validated.

Having been a **relatively unmanaged process until now**, it is evident that there are major challenges coming along with the scale-up of SSS. The tremendous benefits that SSS offers in terms of public health, environmental protection and water reuse can be harnessed by **taking control of the process**, and by implementing targeted measures both at the sanitation system level and at the governance level. The findings of the 4S Project confirm the enormous opportunity that SSS presents for the Indian water and wastewater sectors.

4.2 Recommendations

Through the 4S Project a profound understanding of the current status, challenges and opportunities of the Indian SSS sector could be gained. Building on the evidence from this study, targeted measures can directly or indirectly contribute to improved performance of SSS systems in India. Based on the analyses described in this report, a number of key recommendations are proposed (see Table 19). These recommendations are explained in the following sub-sections.

Table 19: Overview of key recommendations derived from the 4S performance analysis.

	Sanitation System Level Measures	Governance Level Measures
Planning, Design and Implementation	☞ Consider life cycle cost in technology choice ☞ Consider contextual factors in design decisions ☞ Ensure correct design of disinfection units ☞ Promote more automation ☞ Implement modular and standardised designs ☞ Implement appropriate on-site sludge management equipment ☞ Provide user-friendly handbooks	☞ Licence vendors ☞ Prepare informed choice materials and design guides ☞ Create incentives for sustainable SSS systems ☞ Standardise procedure for approval of technology choice and design ☞ Standardise procedure for handover of plants ☞ Plan & implement semi-centralised sludge management facilities
Operation and Maintenance	☞ Train operators ☞ Ensure correct operation of disinfection units	☞ Create mandatory operator training programs ☞ License operators
Management and Monitoring	☞ Train managers ☞ Provide backstopping engineer for each system ☞ Establish performance-based contracts between owners and operators	☞ Adapt water quality standards for SSS systems ☞ Create online database for SSS system management ☞ Support development of centralised management structures ☞ Develop market for treated water ☞ Develop holistic and problem-oriented monitoring approach ☞ Make documentation of O&M activities and financial details mandatory ☞ Create and incentivise manager training programs

4.2.1 Recommendations for the planning, design and implementation of SSS systems

Sanitation System Level Measures

- **Consider life cycle cost in technology choice.** In order to ensure long-term cost recovery, the operation and maintenance cost should correspond to the ability and willingness to pay of the end-users. More information on life cycle cost is provided in the 4S Project Report Vol. III on finance (Rajan et al., 2020).
- **Consider contextual factors in design decisions.** Context-specific challenges should be considered and addressed in the design. For instance, when designing a treatment system for low-income residential and public toilet contexts, high organic loading should be taken into account. Depending on the end-use or disposal of the treated water, systems may also need to be designed for nutrient removal.
- **Ensure correct design of disinfection units.** Disinfection steps should be adapted to the reuse or disposal application. Optimising disinfection to minimise health risks associated with treated water may require further scientific accompaniment.
- **Promote more automation.** Some companies already implement SSTPs that only require a short daily check by a caretaker or engineer instead of 24/7 operator presence. In view of the current shortage of skilled O&M personnel, this allows for high-quality expert supervision of multiple plants by one trained expert who understands the processes and can compare performance to other references to make optimisations. Automation to improve performance (keyword advanced process control) or for data logging on operational parameters is also increasingly available and affordable.
- **Implement modular and standardised designs.** A valid concern of developers and residents is that when there are few occupants, running the entire system can become very expensive on a per household basis. Further, components may get spoilt from underuse for several years. The variation of load throughout the lifetime of a system may affect a system's treatment performance. Such challenges could be mitigated by stepwise, modular implementation of SSS systems. It would provide cost saving opportunities as well as a better robustness of the treatment plant itself. Some of the advantages of modular systems are:
  - Scalability
  - Flexibility in operation
  - Cost-effectiveness

  Modular designs also offer the opportunity of standardisation. Some of the advantages of standardised components are:
  - Economy of numbers through mass production
  - Facilitates training of operators and centralised management of decentralised systems
  - Quality control
- **Implement appropriate on-site sludge management equipment** to address the current issue of untreated sludge being dumped in the environment. Alternatively, semi-centralised sludge management facilities should be provided (see below under governance level measures).
- **Provide user-friendly handbooks** as guidance and reference material for plant owners and operators.

Governance Level Measures

- **Licence vendors** and other players who design, install and operate SSTPs.
- **Prepare informed choice materials and design guides** to address the current lack of design standards, technical specifications and guidelines in the SSS sector:
    - **Technology factsheets:** The selection of the technology should take place based on a holistic multi-criteria consideration of all relevant implications. A technology decision guide with factsheets of all major technology families would provide helpful guidance. Factsheets should include the following technology-specific information in a nutshell:
        - Technology description
        - Advantages and disadvantages
        - Typical performance data
        - Engineering and design considerations
        - Considerations for planning, implementation, startup and handover
        - Information on O&M and management requirements and tasks
        - Financial considerations (capital cost, O&M cost)
        - Social considerations (user behaviour and acceptance)
        - Recommended applications
        - Appropriateness checklist
    - **CPHEEO manual on sewerage and sewage treatment systems** (CPHEEO, 2013)**:** in the engineering manual (Part A), the chapters on decentralised sanitation (Chapter 9) and reuse (Chapter 7) should be updated based on state-of-the-art knowledge. The manuals on O&M (Part B) and Management (Part C) are excellent resources that should be operationalized for SSS systems.
    - In 2011 the Karnataka State Pollution Control Board published an "**STP Guide**" with the aim to provide private players and managers with a reference for design and O&M of plants, and KSPCB officials with a guidance for design approval, inspections and checking (Kodavasal, 2011a). Besides useful general considerations for SSTPs, the guide includes comprehensive technical details of activated sludge plants (extended aeration design), along with an engineering checklist and an operational checklist. Similar references are needed for all key SSS technology families, considering the SSS specificities and the wide variety of technologies now on the market.
- **Create incentives for sustainable SSS systems.** Well-designed and operated SSTPs should benefit from lower development charges, property taxes or water rates as they save substantial money and work for the government. Such benefits could be granted to SSS systems which prove that they fulfil the key requirements for long-term performance, or critical success factors. More specific recommendations are provided in the 4S Project Report Vol. III on finance (Rajan et al., 2020).
- **Standardise procedure for approval of technology choice and design.** Today, developers, STP designers and consultants do not have to account for the technologies they choose and systems they compile (the supplier of equipment is often held responsible). There should be clear checklists for design approvals, including safety and operability aspects. Government officers authorising systems need to be equipped to critically examine design proposals (trainings, checklists).
- **Standardise procedure for handover of plants.** A clear, standardised procedure for the handover of plants from technology providers to end-users and long-term owners of systems is required. Systematic transfer of information, with minimum requirements of technology-specific design details, user-friendly and comprehensive O&M handbooks etc. should take place to ensure proper operation after designers and builders are no longer involved. STP installers should take up O&M responsibilities for a certain time, e.g. 5 years (build-operate modalities).

☞ **Plan & implement semi-centralised sludge management facilities.** The issue of solids management should be addressed strategically by providing well-placed off-site treatment systems that can handle the produced sludge from the surrounding SSS systems. Any newly planned infrastructure for the treatment of faecal sludge, septage or sewage sludge should account for capacity to receive the sludge from existing and future SSS systems nearby.

4.2.2 Recommendations for the operation and maintenance of SSS systems

Sanitation System Level Measures

☞ **Train operators** not merely in day-to-day operation, but also in doing preventive maintenance, understanding the treatment process and making performance judgements, and troubleshooting (including what to do in case of underperformance).

☞ **Ensure correct operation of disinfection units** to minimise health risks associated with treated water. This also requires the corresponding operator training.

Governance Level Measures

☞ **Create mandatory operator training programs**, adapted to technology, design and context-specific O&M requirements. Operators should be certified upon successful completion of trainings.

☞ **License operators.** Only accredited operators should be authorised to operate SSS systems. Through the introduction of licenses, operators would become part of the regulatory system and get more responsibilities.

4.2.3 Recommendations for the management and monitoring of SSS systems

Sanitation System Level Measures

☞ **Train managers.** Managers should be carefully instructed by the STP designers upon system handover, particularly on the system’s functioning, performance monitoring and optimisation, as well as O&M and other requirements for good system performance. General manager training programs should also be developed (see below under governance level measures).

☞ **Provide backstopping engineer for each system** to support O&M personnel and SSTP management entities in problem-solving and taking performance-related decisions. Trained experts who understand the wastewater treatment processes can supervise multiple plants, compare performance to other references and make optimisations. Backstopping engineers should ideally be deployed by the company who designed the system for at least five years, or otherwise by professional, licensed O&M service providers.

☞ **Establish performance-based contracts between owners and operators.** Performance-focused contracting which links performance to payments may improve the efficiency and increase the life expectancy of SSS systems. Using a strong system of checks, the quality of the O&M service and performance are regularly assessed. The monitoring framework should include a clear list of operational and performance parameters, including the O&M tasks that need to be fulfilled, staff presence, run-time, energy usage, effluent quality and quantity, safe sludge management etc. As performance-based contracting is a new concept in the SSS sector, it first needs to be tested in the field. The proposal of performance-based contracts is described in more detail in Briefing Note 19 of the 4S Synthesis Report (Ulrich et al., 2020).

Governance Level Measures

- **Adapt water quality standards for SSS systems.**
  - Good effluent quality regarding **organic constituents and suspended solids** can be achieved by combining measures to ensure proper O&M of systems with an efficient monitoring framework. The relaxed 2017 CPCB standards on BOD and TSS are technically achievable by all types of technologies assessed if operated and maintained correctly. To be meaningful, the COD standard should be revised based on the standard for BOD and a defined BOD/COD ratio (e.g. 0.3 or 0.4), as explained in section 3.3.2.
  - It is not realistic to expect compliance with stringent **nutrient standards** from most existing systems. If current standards for nitrogen parameters are to be fulfilled, treatment systems must account for this in their process design. While this could be implemented for newly planned systems in the higher capacity size range, it will be necessary to lower the bar for existing and smaller systems. A pragmatic trade-off has to be found between the level of treatment, energy consumption, cost and other factors, considering the capabilities of available technologies. Nutrient removal requirements depend on the type of reuse. For example, if the treated water is discharged into a water body, nutrient removal is essential.
  - Concerning **microbial effluent quality**, standards should be adapted to the reuse or disposal application. Reuse-specific microbial standards are required to ensure a safe reuse of the treated wastewater.
  - Future SSS regulation should take into account intrinsically high variations of raw wastewater characteristics from small communities, and that small-scale systems may treat higher concentrated wastewaters (e.g. in situations where water is scarce, which can increase with climate change). This can lead to higher effluent concentrations than in large systems, even if the efficiency (removal rate) is the same. Whilst effluent standards have to be aligned with the specific reuse or disposal requirements, they should not discourage investments in communities with low water consumption and challenging wastewater characteristics.
  - The issue of discharge standards is discussed in more detail in the 4S Project Report Vol. II on governance (Chandragiri et al., 2020) and in Briefing Note 16 of the 4S Synthesis Report (Ulrich et al., 2020).
- **Create online database for SSS system management.** A collated, unified database would foster coordination and harmonisation between agencies, standardise data collection, allow for automated analyses and facilitate SSS progress monitoring and water reuse planning at national, state and city levels. The proposal of an online data platform for SSS systems is described in more detail in the 4S Project Report Vol. II on governance (Chandragiri et al., 2020) and in Briefing Note 15 of the 4S Synthesis Report (Ulrich et al., 2020).
- **Support development of centralised management structures**, namely the creation of dedicated expert units for small-scale sanitation management at state and city levels. This would allow to oversee the growing number of SSS systems. Such units could be empowered to administer the online database, develop capacity-building programmes for SSS practitioners and devise optimisation strategies based on data analysis. The proposal of SSS expert units is described in more detail in the 4S Project Report Vol. II on governance (Chandragiri et al., 2020) and in Briefing Note 15 of the 4S Synthesis Report (Ulrich et al., 2020).
- **Develop market for treated water.** Local markets can be created whereby owners of SSTPs can sell excess water to other users including municipality (for landscaping and road washing), farmers, construction and industry. Thereby, it is important to quantify how much of the treated wastewater is actually reused, and how much is available for other reuse purposes in the surrounding areas of the SSS systems. The idea of an Uber-like service to link producers of treated water with potential users is described in more detail in the 4S Project Report Vol. II on governance (Chandragiri et al., 2020).

☞ **Develop holistic and problem-oriented monitoring approach.**

- The analysis of wastewater grab samples for monitoring should be complemented with further quantitative and qualitative parameters. This would have multiple benefits as described in section 4.1.5.
- Holistic monitoring of the performance beyond grab sampling: next to the treated water quality, aspects like adequate loading, resource recovery (water and potentially nutrients and energy) and solids management are important indicators of a fully functional SSS system. Their inclusion in performance assessments will facilitate to monitor and address the corresponding challenges as described in this report, especially those around underloading, water reuse and sludge management.
  - The installation of separate electricity meters for STPs should be mandatory.
  - Concerned authorities should monitor market developments in the fields of wastewater flow telemetry and regularly reassess the feasibility of making it mandatory to install flow meters at new systems.
- Monitoring the fulfilment of the conditions for performance (critical success factors) will provide a more holistic understanding of each system and help to pinpoint sustainability risks. If institutionalised, such monitoring can also be used to constantly assess the impact of measures taken to improve the SSS sector, or to reward owners of model SSTPs with property tax rebates etc.
- Collection of qualitative monitoring data should be facilitated with simplified questionnaires and checklists, considering the specific conditions, requirements and challenges of different application contexts and technologies.
- A monitoring tool should be developed which can visualise an SSS system's current fulfilment of all critical success factors and performance objectives at a glance, for instance with scorecards (see Figure 63 for an example). This would not only be of use for monitoring agencies but also for system owners. It would raise awareness of all the relevant aspects of a sanitation system, beyond the effluent quality of the STP itself.

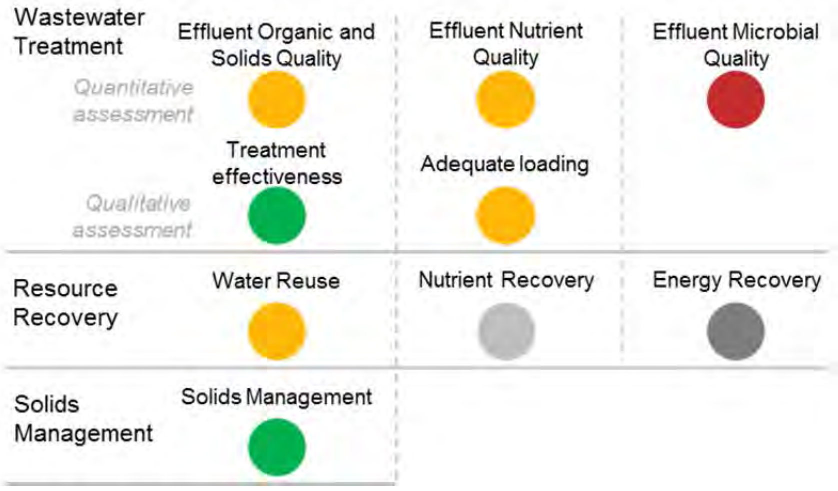

Figure 63: Sample system performance scorecard showing how the fulfilment of different performance objectives could be visualised (green = good; orange = caution; red = insufficient; dark grey = not available; light grey = not applicable).

- It is too ambitious to expect effluent compliance from all existing "legacy systems" in the short term. A staged approach is therefore needed, focusing on a) impactful and easy to achieve steps ("small wins"), and b) the prioritised refurbishment of the most problematic plants. As a first step, existing systems need to be classified according to their status and need for action (condition and operational readiness of infrastructure components and equipment, adequate system loading, safety and health risks, aesthetics, design weaknesses and ability to achieve treatment performance). The gradual step-by-step improvement of existing plants will eventually also result in considerable freshwater savings.

- ☞ **Make documentation of O&M activities and financial details mandatory**. This would allow traceability of the systems' operation and upkeep. Analysis of such information should also become part of the monitoring procedures. In the long term, online logbooks should be established for all systems.
- ☞ **Create and incentivise manager training programs.** Training for the personnel of management entities should also be made available, promoted and incentivised. Financial management (life cycle cost planning) of the SSTP is one of the key training needs identified. Trainings should also highlight the importance of proper supervision and documentation of O&M activities, as well as the anticipation of maintenance works. Such trainings could be developed by the proposed SSS expert units (see above).

Figure 64: Planted gravel filter for wastewater polishing (Photo: Milan Basil Kurian).

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Appendices

Appendix 1: Procedure for data validation and pre-processing

Methodology of data validation

Due to different issues during the design and implementation of the questionnaires survey, an improvement of the dataset quality was found to be necessary. The main objectives were to:

- Complete the missing information due to:
    - Design errors in the skip logic of the questionnaires
    - Mistakes or oversight in the questionnaires filling procedure
    - Issues during the uploading of the questionnaires online
- Adapt the dataset to fit the constraints of statistical analysis:
    - Categorize the text answers in the relevant format of multiple choices questions
    - Create new categories when required
    - Homogenize the text answers that cannot be categorized
    - Format the question and answer codes
- Merge the different versions of the questionnaires implemented

A procedure for validation and consolidation of the database was established and the following steps were implemented:

1. Automatic formatting of the dataset

The first step was to identify the tasks that could be done automatically by running the data through a C script. Two main tasks were identified: The reformatting of the data and the differentiation between the manual (by the interviewer) and the automatic (by the software based on previous answers) skip of questions. The code (written in C language) was built based on the questionnaire definition files provided by kobo toolbox.

2. Validation of each project using validation templates

The second step was to scan manually each questionnaires filled during the survey in order to identify mistakes, contradictions (intra and inter-questionnaires), missing information or uncommon answers. This was done by transposing the answers into validation templates. Based on field experience with the questionnaire, the flaws to be rectified and the missing information were identified and a validation procedure was established. The "validator" had first to identify the missing and uncommon information for a specific project and then ask the field team members who visited the site for precisions and complementary information. Then the validator had to complete the dataset with the available information he/she gathered and look for potential categorization and homogenization to implement. This procedure was gradually improved as the process went along and changes to be made were consciously documented and updated in spreadsheets available to all the validators. The corrections were duly recorded in the validation templates for each projects.

3. Consolidation of the validation

After the detailed validation process, the questionnaires of all the sites were merged back together. All the steps implemented during the validation process were checked, question by question, by scanning through the answers provided in the overall validated dataset. The goals of this step were to ensure the homogeneity of the validation procedure implementation as well as correcting potential typographical errors introduced by mistake in the standards answers during the validation process. Having an overall look at all answers for each question also allowed to further categorize text answers into new standard form more fit for statistical analysis.

4. Formatting the answers and question codes to ease analysis process

In order to ease the analysis process, the question codes were adapted to fit the format variableName. The answer codes were modified to fit the format answer_code. The new variable names and answer codes were chosen as short as possible and as explicit as necessary.

5. Merging of the different versions of the questionnaires

Throughout the project different versions of the questionnaires were used. Either because of questionnaire improvement (at the beginning of the project) or because of differences of implementation contexts (between India, Nepal and Pakistan). To be able to use the dataset for statistical analysis, these different versions had to be merged together in one common format. The differences in the questions and answers of all versions were first identified. Then, the actions required (adding new column, changing answer code or variable name) to allow the merging process were decided and implemented directly in the different versions of the form. Finally all the different versions were merged together.

Limitations of validation process

The whole process of validation allowed to greatly improved and dataset quality as well as to prepare it for statistical analysis. But it has also some clear limitations, the first of which would be time. The process is extremely time intensive and this could be avoided by dedicating more time to the questionnaire design and implementation steps as well as to adequate training of data collection team. Another limitation of the validation process is the categorization of the text answers into existing answers options can only be done to a certain point without losing potentially important information or without knowing exactly how these answers will be used during the different analysis processes. For some of the project sites, it was also not possible to gather the missing information from the field team members as they had left the organization at the time of validation of the data. In these cases, if the missing information was too important, the projects had to be removed from the dataset. Finally, the process of validation is done mainly by persons and this increase the risk of introducing new mistakes into the dataset or of losing relevant information. In order to reduce this risk and to be able to trace back all the changes, all the modification should be well documented.

Appendix 2: Analysis plan – laboratory parameters

No. of samples taken to lab				**Analyses (1: single, 2: duplicate)**								
Plastic bottle	**Glass bottle**	**Sample ID**	**Description**	**BOD [mg/L]**	**COD [mg/L]**	**sCOD [mg/L]**	**TSS [mg/L]**	**TP [mg/L]**	**TN [mg/L]**	**AN [mg/L]**	**FC [MPN/100 mL]**	**O&G [mg/L]**
1		Comp_u_1-in	System inlet composite: flow-proportional compositing of u_1-in_1 to u_1-in_12	2	2	2	2	2	2	2	2	
1		Comp_u_n-out	System outlet composite: flow-proportional compositing of u_n-out_1 to u_n-out_12	2	2	2	2	2	2	2	2	
	1	u_1-in_8	System inlet grab 8.00 h									1
1	1	u_n-out_8	System outlet grab 8.00 h		2	2	2					1
	1	u_1-in_14	System inlet grab 14.00 h									1
1	1	u_n-out_14	System outlet grab 14.00 h		2	2	2					1
1	1	u_1-in_20	System inlet grab 20.00 h	2	2	2	2	2	2	2	2	1
n-1		u_2-in_20 to u_n-in_20	Inlet grabs of all units 20.00 h	2*(n-1)	2*(n-1)	2*(n-1)	2*(n-1)	2*(n-1)	2*(n-1)	2*(n-1)	2*(n-1)	
1	1	u_n-out_20	System outlet grab 20.00 h	2	2	2	2	2	2	2	2	1
	1	u_1-in_2	System inlet grab 2.00 h									1
1	1	u_n-out_2	System outlet grab 2.00 h		2	2	2					1
n+6	8		Total:	2*(n+3)	2*(n+6)	2*(n+6)	2*(n+6)	2*(n+3)	2*(n+3)	2*(n+3)	2*(n+3)	8
Total for n = 5: 19 bottles			Total for n = 5:	16	22	22	22	16	16	16	16	8

Table annotation:

- n stands for the total number of treatment units (reactors) of an SSS system
- Samples for oil and grease analysis are collected in glass bottles (orange font)

Appendix 3: Description of critical success factors (CSF) and their development

How were the CSF developed?

The overall set of factors (as compiled by Fettback, 2017) that have a potential influence on the performance of SSS systems can be arranged in chains of effects (e.g. factors A and/or B lead to C, and C influences D etc., see Figure 65 below). Some of the identified factors are outside the system boundary, i.e. they are not specific to one SSS system, and their influence with regard to a system is often indirect and impossible to measure (e.g. supporting policies and regulations, or capacity of private players).

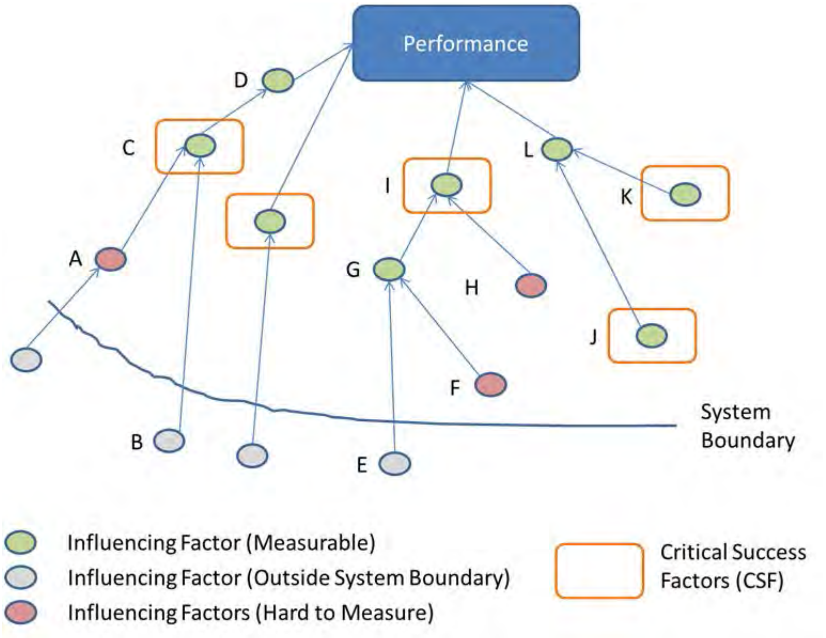

Figure 65: Illustration of the concept of Critical Success Factors.

For 4S, the aim was to obtain the main, measurable superordinate factors, and to study how well their fulfilment explains the SSS system performance. These “critical success factors”, therefore, had to fulfil the following conditions:

- They should be within the system boundaries, i.e. SSS system specific.
- They should be measurable, i.e. it should be possible to score their degree of fulfilment as *good*, *caution* or *insufficient*.
- They should be independent from each other, i.e. a CSF should not be an influencing factor for another CSF.
- The total set of CSF should sufficiently consider the totality of factors identified, i.e. CSFs should reflect the effects of the factors further down in the hierarchy well enough, and no important factor should be ignored.

In the first example shown in Figure 65, factors A and B are either outside the system boundary or hard to measure, so C is used as the CSF.

In the second example, E and F are the ones outside the system boundary or hard to measure, but G would be measurable. However, I is influenced also by H, so either both G and H should be taken as CSF, or I alone. In this case, I is the CSF because H was found not to be measurable.

In the third example, J and K lead to L, and all three are within the boundary and measurable. Here, either L could be considered as CSF, or J and K together. In this example, J and K are selected as CSF, because it increases the resolution of factors studied.

Appendix 4: PO and CSF scoring tables

This Appendix provides the scoring details of all performance objectives and critical success factors. It is a Google table that can be accessed at:

https://tinyurl.com/pocsfscoring

The table contains separate spreadsheets for each PO and CSF. For each CSF and PO the topics and related questionnaire data used are listed, along with the details how the scoring and weighting was done.

Overview of CSFs incl. topics that were scored

Table 20 below lists and describes the topics which were measured for each CSF.

Table 20: Overview of the 14 critical success factors (CSF) and the topics they cover.

Number	CSF name	Topics covered/investigated
CSF 1	Quality of Design	Adequate design for stormwater, Presence of equalization infrastructure, Adequate design for potential nuisances, Accessibility for desludging, Accessibility for sampling, Design errors
CSF 2	Quality of Implementation	Construction quality, Corrosion, Cracks or leakage, Manholes/control opening conditions, Challenges during implementation
CSF 3	System Startup and Handover	Availability of system documents, Information provided to users at start of operation, Technical issues at start of operation, Support after handover
CSF 4	Skills of Personnel	Responsibility for treatment, Background of personnel, Level of training of personnel, Personnel discovers and solves problems, Opinion of manager about skills of personnel, Knowledge about desludging and monitoring of the system, Opinion of interviewer on knowledge of personnel
CSF 5	Motivation of Personnel	Responsibility for treatment, General appearance of treatment site, Reliability of operator, Happiness of operator with his job
CSF 6	Accessibility of Maintenance Services	Maintenance and repairs responsibility clear, Spare parts responsibility clear, Emergency plan for breakdown, Major repairs responsibility clear, Operation challenges
CSF 7	Availability of Energy and Chemicals	Consumables requirement, Consumables stock on site, Responsibility for consumables clear, energy requirement, System has enough energy to run 24/7, Power and consumables are not a challenge for operation
CSF 8	Skills of Management Entity	Knowledge about small-scale sanitation systems, Level of training of management personnel, Reason for measuring treated water quality, Interviewer judgement on knowledge of manager
CSF 9	Supervision of O&M Activities	Responsibility for O&M of treatment clear, Frequency of performance assessment, Frequency effluent quality measurement, Operator has received training, Monitoring of operator, Availability of safety equipment, Responsibility for O&M of sewer clear
CSF 10	Human Resources Management	Adequate availability of O&M personnel, Salary/incentive for operator, Operator satisfied with current HR mgt., O&M responsible is replaced when needed
CSF 11	Documentation	Existence of records about O&M, Financial details recorded, Presence and work of operator recorded
CSF 12	User Behaviour	Inadequate grey water discharge, Problems with fee collection, Users follow instructions
CSF 13	User Satisfaction	User are happy with the system, Complaints from neighbours, Opinion on utilization of treated wastewater, Opinion on utilization of treated sludge in agriculture, Opinion on cost of treatment
CSF 14	O&M Cost Recovery	Enough money for adequate operator salary, Willing to pay more to improve the system, Presence of planning of expenses, Adequate household contribution, Revenue from products, Way to cover maintenance costs, Money is not a challenge for operation

Appendix 5: System status observations from the sampling campaign

Table 21: Judgement of system status and knowledge of operators and managers, along with related observations (n=37). The effluent BOD results from the sampling campaign are also shown.

System ID & sampling round N°		General system status	System status / issue description	Knowledge of operator	Knowledge of manager	Changes since previous rounds	Additional observations	Effluent BOD [mg/L]	BOD removal
SBR-1	1	Bad	No MLSS and no aeration provided	Bad	Moderate	NA	No tertiary units were there in STP. The caretaker of the apartments looks over the functioning of STP	82	92%
	2	Moderate	Aeration was provided	Bad	Moderate	Aeration was continuous		49.5	95%
	3	Moderate	MLSS was well maintained	Bad	Moderate	MLSS was maintained		56	84%
SBR-2	1	Bad	Kerosene had been poured into the treatment plant a week before	Moderate	Good	-		98	38%
	2	Good	STP was repaired and functioning well	Moderate	Good	STP was repaired and functioning well		3.9	99%
	3	Good	-	Moderate	Good	-		5.6	98%
SBR-3	1	Good	Well maintained MLSS	Good	Good	NA	The operators and managers were well knowledgeable in operating the plants	52	87%
	2	Good	Cleaned filters and membranes	Good	Good	NA		37.4	95%
	3	Good	Well maintained MLSS and cleaned filter	Good	Good	NA		52	88%

SBR-4	1	Good	Well maintained MLSS	Good	Good	NA	The operators and managers were well knowledgeable in operating the plants	23	95%
	2	Good	Well maintained MLSS and cleaned filters	Good	Good	Cow dung added for maintain MLSS		33.5	84%
	3	Moderate	Filter clogs found	Good	Good	NA		56.5	89%
MBBR-1	1	Moderate	Aeration was intermittent	Moderate	Moderate	NA	The biomass was sloughed from the carriers and was floating	35	91%
	2	Moderate	Filter materials exhausted	Moderate	Moderate	Air flow was continuous		32	90%
	3	Bad	Air flow continuous, sludge accumulation in clarifier and filters exhausted	Moderate	Moderate	Filters were not replaced		56	85%
MBBR-2	1	Good		NA	Good			0	100%
	2	Good		NA	Good			4.6	96%
	3	Good		NA	Good			3.2	97%
MBBR-3	1	Bad	No aeration provided; Filters were exhausted	Bad	Good	NA	The cost for O&M is not provided to the agency on time	135	74%
	2	Bad	Operators are reluctant and not switching on the aeration unit	Bad	Good	NA		149	73%
	3	Bad		Bad	Good	NA		40	90%
MBBR-4	1	Moderate	Less attachment of microbes in carriers	Moderate	Good	NA	Operators were stable; 1st round aeration in MBBR	33	91%

	2	Good	Good attachment of microbes seen in carriers	Moderate	Good	Microbes attachment	was intermittent	22	94%
	3	Good	Filter and MBBR working well	Moderate	Good	NA		27	89%
MBBR-5	1	Good	Proper aeration were provided and filters were working well	Moderate	Good	NA	Pre-fabricated / packaged system	19	96%
	2	Good		Moderate	Good	NA		11	95%
	3	Good		Moderate	Good	NA		27	67%
MBBR-6	1	Moderate	Sludge accumulation in clarifier	Good	Good	NA	Anaerobic followed by aerobic condition and has three filters (PSF/ACF/CAACO)	40	95%
	2	Good	NA	Good	Good	Removed sludge		7.5	99%
	3	Good	NA	Good	Good	NA		14	98%
MBBR-7	1	Moderate	Filters were clogged; no aeration provided	Moderate	Moderate	NA	The SSTP treats only the greywater. As the system is overloaded they are installing another unit FICCO	20	75%
	2	Moderate	Overloaded	Moderate	Moderate	Filters were cleaned and aeration was continuous		45.8	60%
	3	Moderate	Overloaded	Moderate	Moderate	NA		43	83%
MBBR-8	1	Bad	Sludge accumulation in chlorine tank, filter tank and filters	Moderate	Moderate	NA	Operators were replaced frequently	92.4	85%
	2	Moderate	Sludge removed; Filters were replaced	Moderate	Moderate	Sludge removed		46	87%
	3	Moderate	NA	Moderate	Moderate	NA		30	94%
MBBR-9	1	Bad	Filters were clogged	Moderate	Bad	NA	Maintenance cost was higher; so plant was shut-down during 3rd round of sampling	101	84%
	2	Moderate	Filters working fine	Moderate	Bad	Replaced media in filter		48	91%
	3	NA	NA	NA	NA	NA		NA	NA

ASP-1	1	Moderate	Sludge's accumulated in aeration tank	Moderate	Moderate	NA	Scum formation in aeration tank; Overloaded and filters get clogged frequently. Urea and diammonium phosphate (DAP) used in aeration tank.	99	77%
	2	Bad	Clogging of filters	Moderate	Moderate	Sludge's removed		47.2	88%
	3	Bad	Clogging of filters	Moderate	Moderate	NA		123.4	71%
ASP-2	1	Moderate	Aeration was intermittent	Moderate	Moderate	NA	Odour problem was an issue – complaint raised by residents	44	89%
	2	Good	Good airflow and filters materials were cleaned	Moderate	Moderate	Aeration was continuous		23.5	91%
	3	Moderate	Filters clogged	Moderate	Moderate	NA		65	77%
ASP-3	1	Moderate	2 blowers not working; Chlorine dozing pump not working, chlorination done in the final tank	NA	NA			5.5	98%
	2	Good	Chlorine dozing pump not working, chlorination done in the final tank	NA	NA	Blowers were repaired		4.6	98%
	3	Good		NA	NA	Final and inlet tank more full as they are not using so much water for gardening		9.3	97%
ASP-4	1	Good		NA	NA		The air blowers and filters are functioning	8.4	96%
	2	Good		NA	NA			5.2	98%

	3	Good		NA	NA	Power goes off frequently due to last night rain, Diesel generator was switched on for 2 h. Air blowers and filter feed pumps worked intermittently.	intermittently Some of the aeration tank water is pumped to nearby farmland in the night times without the land owner permission. Some of the aeration tank water is taken by the farmer to his farmland. Hence, it reduces the outflow.	5.2	98%
ASP-5	1	Good		NA	NA		Air blowers and pumps are functioning intermittently	12.6	94%
	2	Good		NA	NA			2	99%
	3	Good		NA	NA			3	99%
ASP-6	1	Good		NA	NA		System is running for 24 hours.	2.6	97%
	2	Good		NA	NA			9.3	86%
	3	Good		NA	NA	Around the filter unit treated water is stagnant due to leaks.		1.8	99%
ASP-7	1	Good		NA	NA	Fewer students in the campus due to vacation. Treatment system working intermittently due to less inflowing water.	Flocculation step not used since 2 years	18.8	89%
	2	Good		NA	NA			7	95%
	3	Good		NA	NA	Higher inlet flow		5.1	97%
MBR-1	1	Moderate	Membranes were damaged	Good	Good	NA	Frequent fouling seen in membranes and huge cost involved for maintenance	108	97%
	2	Good	Changed membranes	Good	Good	Replaced membranes		35	96%
	3	Good	NA	Good	Good	NA		6.5	99%
MBR-2	1	Good						6	96%
	2	Good						3.6	97%

	3	Good						6.5	97%
EADOx-1	1	Good		Moderate	Moderate			12.9	90%
	2	Moderate	The EC plates are corroded and old. In the morning the inlet was submerged in wastewater	Moderate	Moderate	The collection tank was cleaned. Effluent in whitish because of high amount of chlorine added		27.8	87%
	3	Bad	The treated water is quite turbid and smelly. In the morning the inlet was submerged in wastewater	Moderate	Moderate	More turbid and smelly treated wastewater. Outlet very frothy		72	60%
Soil-filtration-1	1	Good	Healthy plants in PGF and no sludge's	Moderate	Good	NA	Solids-free system	3.3	69%
	2	Good	Healthy plants in PGF and no sludge's	Moderate	Good	NA		11.3	77%
	3	Moderate	Plants in PGF were trimmed	Moderate	Good	NA		3.2	99%
Soil-filtration-2	1	Moderate	Sludge accumulated in filters	Bad	Moderate	NA	No specified operator for STP, the street sweeper switches on/off the pump	35.6	94%
	2	Moderate	Sludge accumulated in filters	Bad	Moderate	NA		22.4	94%
	3	Good	NA	Bad	Moderate	Removed sludge's		22	91%
Soil-filtration-3	1	Good		Bad	Good			46	78%
	2	Good		Bad	Good			21.9	84%
	3	Good		Bad	Good			0	100%

ABR-based-1	1	Moderate	Seen accumulation of sludge's in ABR	Bad	Moderate	NA	Gardener is appointed as operator, No trained operator. Large amounts of sanitary pads, shampoos and other floating items in the raw water collection tank.	75	76%
	2	Moderate	Plants in PGF not present	Bad	Moderate	Removed sludge's		41.3	92%
	3	Moderate	Again accumulation of sludge in ABR	Bad	Moderate	Planted plants in PGF		24.9	98%
ABR-based-2	1	Good	Plants in PGF were healthy; No sludge's	Good	Good	NA	Black and greywater were collected separately	33.3	99%
	2	Good	Plants trimmed; No sludge's	Good	Good	NA		26.3	99%
	3	Good	Plants in PGF were healthy; No sludge's	Good	Good	NA		25.5	100%
ABR-based-4	1	Bad	Sludge Accumulation	Bad	Moderate	No	Women self-help group operates the plant	132.5	86%
	2	Bad	No Plants in PGF	Bad	Moderate	No		90	91%
	3	Bad	Sludge accumulation + No plants + Water overflow in PGF	Bad	Moderate	No		46	97%
ABR-based-5	1	Moderate	Sludge accumulation in settler	Bad	Moderate	NA	No separate operators provided, the compost yard workers take care of the SSTPs	38	98%
	2	Moderate	Plants in PGF were trimmed	Bad	Moderate	Removed sludge's		52.5	97%
	3	Good	Plants were healthy in PGF and no sludge accumulation	Bad	Moderate	Plants in PGF were health and no sludge accumulation		14	98%
ABR-based-6	1	Moderate	Floating materials are found in settler and collection tank	Moderate	Moderate	NA	Managers and operators used to change frequently; reluctance in	37	90%

	2	Bad	Filters were clogged	Moderate	Moderate	Floating materials were not removed	implementing suggestions	48	50%
	3	NA	NA	NA	NA	NA		NA	NA
ABR-based-7	1	Bad	Sludge accumulation in settler	Moderate	Moderate	NA	Large amounts of bottles, sanitary pads, shampoos and other floating items in the raw water collection tank	72	77%
	2	Moderate	No plants in PGF	Moderate	Moderate	Sludge's were removed		13	91%
	3	Moderate	No plants in PGF	Moderate	Moderate	-		22	89%
ABR-based-8	1	Bad	Sludge accumulation and vortex not working	Moderate	Moderate	NA	Algal growth seen in polishing ponds	76	85%
	2	Moderate	Vortex 2 was clogged and operated intermittent	Moderate	Moderate	Sludge removed in ABR		39.3	97%
	3	Moderate	Vortex 2 is operated intermittently	Moderate	Moderate	Clog in vortex removed		25.5	95%
ABR-based-10	1	Bad	Sludge accumulation in settler and ABR	Bad	Moderate	NA	No separate operators; the person who sweeps the street was involved in operating the plants. STP was covered with bushes and thorns.	46	93%
	2	Bad	No plants in PGF	Bad	Moderate	Sludge's were not removed		48	89%
	3	Bad	No plants + water overflow in PGF	Bad	Moderate	Sludge's were not removed and plants were not planted in PGF		64.8	94%
ABR-based-11	1	Moderate	No plants in PGF	Bad	Moderate	NA	No separate operator	101.3	89%
	2	Good	Healthy plants in PGF	Bad	Moderate	Plants were planted in PGF		9.89	98%
	3	Moderate	Sludge accumulation in settler	Bad	Moderate	NA		32.2	96%

Small-scale sanitation (SSS) systems (also known as decentralised or distributed sanitation systems) have great potential in areas where extending trunk sewerage infrastructure is too costly or otherwise challenging, and where there is a necessity to reuse treated water. Small-scale sewage treatment plants (SSTPs) are the core component of an SSS system. By removing pollutants from sewage and greywater, they reclaim valuable water for toilet flushing, irrigation of urban gardens and other purposes. Thereby, such systems simultaneously contribute to healthy and water-secure cities.

In urban India, thousands of these small-scale wastewater treatment and reuse systems already exist. These units are mostly implemented and operated at building level by the private sector, largely as a result of various pollution abatement and water saving policies. However, they often do not achieve the desired performance and create substantial financial burdens for their owners and operators.

The research project Small-Scale Sanitation Scaling-Up (4S) was the first systematic assessment of SSS systems in South Asia. This report deals with the technology, implementation and operation of SSS in India. It presents the results from an analysis of the performance and sustainability of SSTPs and provides recommendations for professionals in the field.

Eawag (the Swiss Federal Institute of Aquatic Science and Technology) together with the Indian Institute of Technology Madras, BORDA (Germany), CDD Society and other partners implemented 4S under the auspices of the Indian Ministry of Housing and Urban Affairs. The project was conducted between 2016 and 2018 and jointly funded by the Bill & Melinda Gates Foundation (main donor) and the German Federal Ministry for Economic Cooperation and Development.

Project website: www.sandec.ch/4S

www.eawag.ch