ADVANCING SEWAGE TREATMENT IN INDIA

CHALLENGES, TECHNOLOGY CHOICES, AND SUSTAINABLE STRATEGIES

by

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DEDICATION

This dissertation is dedicated to the pursuit of excellence in achieving the Doctorate in Business Administration (DBA). With deep love and gratitude, I dedicate this work to my late grandmother, Mrs. Prema Joshi, whose blessings and legacy continue to inspire me, and to my beloved wife, Deepika M, for her unwavering support, patience, and encouragement throughout this journey. To my father, Madan Joshi, your wisdom, guidance, and belief in me have been my steadfast source of strength. To my precious daughter, Shanaya Joshi, your smiles and boundless love have been the light that kept me motivated every step of the way. I also express my heartfelt thanks to my extended family and cherished loved ones, whose unwavering belief in me has been my pillar of strength.

ABSTRACT

ADVANCING SEWAGE TREATMENT IN INDIA
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India faces a growing water crisis exacerbated by rapid urbanization, industrialization, and population growth, leading to increased sewage generation and widespread water pollution. This dissertation investigates the challenges, technology choices, and sustainable strategies for advancing sewage treatment in India, aiming to provide actionable insights for technology applicability, stakeholders opinions considering the views from businesses, policymakers, and investors.

Through a mixed-methods approach, including a case study analysis of Padmini VNA Mechatronics Ltd., a TESEI (Technological, Economic, Social, Environmental, and Institutional) analytical framework is developed to assess the complexities of the Indian sewage treatment sector. The mixed method approach follows this way; I first did the literature review on the current status of sewage treatment in India to have a holistic understanding of the wastewater and its treatment in India which gave the insights on technology, policies, how each state and union territories is performing in these aspects along with the exploration of various challenges. Second, I did the case study design

considering the sewage treatment plant as base along with technology expansion considering reverse osmosis and ultra filtration units to see how they will perform. In this step, I procured the data from vendors accordingly the life cycle assessments and techno-economic assessments were done briefly. Once, the modelling is done, in the third step, I have explored the various sustainable strategies possible and formulated questions on it to verify whether the wastewater community is interested in this or not. In the fourth step, considering the outcomes from literature review especially the technology options and challenges, case study outcomes with technology additions, and validated expert groups opinion on sustainable strategies a TESEI matrix of challenges is constructed and validated by conducted a survey.

Overall, the findings reveal significant gaps in treatment capacity, operational inefficiencies, and limited adoption of advanced and sustainable technologies. Key challenges include aging infrastructure, resource expenditure constraints, corruption, and low public willingness to pay. The research highlights the potential of advanced tertiary treatment systems, resource recovery, and circular economy principles to enhance water quality, reduce environmental impacts, and create economic opportunities. Future research propositions focus on evaluating the performance of existing STPs, promoting decentralized treatment systems, and developing integrated models for sustainable water management in India.

ACKNOWLEDGEMENTS

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A special acknowledgment goes to Padmini VNA Company and my wonderful teammates Ullasa, Vivek, Pradeep, and Ms. Viveka Bhandari, SK Pandey, PS Bisht, Sc Pandey, and Kabir Bhandari. Your guidance, collaboration, and support have been invaluable in shaping this accomplishment.

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NOMENCLATURE

STP	Sewage treatment plant
UF	Ultra filtration
RO	Reverse osmosis
LPH	Litre per hour
UASB	Upflow Anaerobic sludge pond
SBR	Sequencing batch reactor
MBB	Moving bed bioreactor
WSP	Waste stabilization pond
ASP	Activated sludge process
PVNA	Padmini VNA (PVNA) Mechatronics Ltd.
O&M	Operation and maintenance
CapEx	Capital expenditure
OpEx	Operational expenditure
LCA	Life cycle assessment
TEA	Techno-economic assessment
TESEI	Technological, Economic, Social, Environmental, and Institutional

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CHAPTER 1

INTRODUCTION

The exponential growth in industrialization, urbanization, and global population has created unprecedented environmental externalities, significantly impacting the sustainability of our planet's resources. Water, the essence of life, is a fundamental resource that sustains all forms of life on Earth. Its significance as a precious commodity cannot be overstated, as it plays a vital role in the survival and well-being of various species across the planet. As such, the responsible management and conservation of water resources are paramount to ensuring a sustainable future for all.

1.1. India's Water Crisis

India is currently facing an unparalleled water crisis, impacting a significant portion of its populace. Current statistics reveal that over 500 million individuals are struggling with acute water scarcity, see *Figure 1.1.* This situation is intensified by the swift decline of groundwater reserves, a critical component of the nation's water resources. The agricultural sector, a vital pillar of India's economic stability, is particularly susceptible to these water-related challenges. Given that a majority of the country's agricultural practices depend on rainfall, the rising incidence of droughts presents a grave danger to the economic well-being of farmers and the stability of the nation's food supply (NITI Aayog, 2018). Furthermore, water quality is a pressing issue. Research indicates that a considerable proportion of India's water sources are polluted, leading to substantial public health problems and a significant number of deaths annually due to waterborne illnesses. The water crisis has also ignited disputes between states, with several major conflicts remaining unresolved. This underscores the limitations of the current national water management systems and organizations. Without prompt and decisive intervention, future prospects appear bleak.

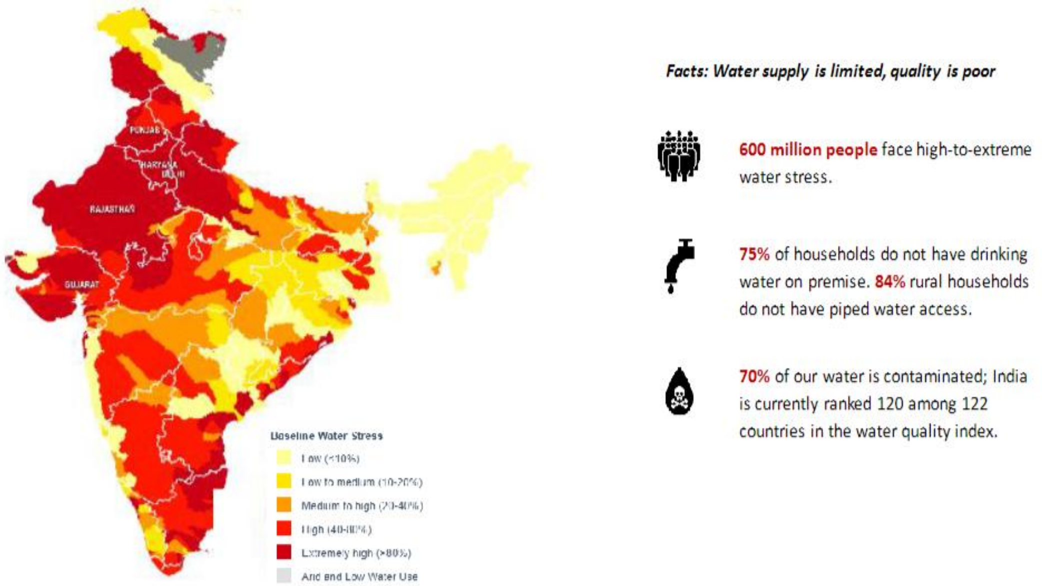


***Figure 1.1**. Baseline water stress in India. (Source: Composite Water Management Index report June 2018 NITI Aayog)*

The projected surge in India's water demand as per (ASSOCHAM, EY, UN-Water; 2010), as illustrated in *Figure 1.2.*, underscores the critical need for advancements in sewage treatment and water reuse. The *Figure 1.2.*, illustrates India's water demand in 2010 with projections for 2025 and 2050, broken down by sector (irrigation, drinking water, industry, energy, and others), measured in billion cubic meters. In 2010, irrigation accounted for the largest share of water demand at 688 billion cubic meters, followed by drinking water (56), others (52), industry (12) and energy (5). Projections for 2025 indicate a rise in demand across all sectors, with irrigation reaching 910 billion cubic meters. By 2050, the total water demand is expected to further increase, with irrigation projected to reach 1,072 billion cubic meters, highlighting the critical need for efficient water management strategies in the coming years.

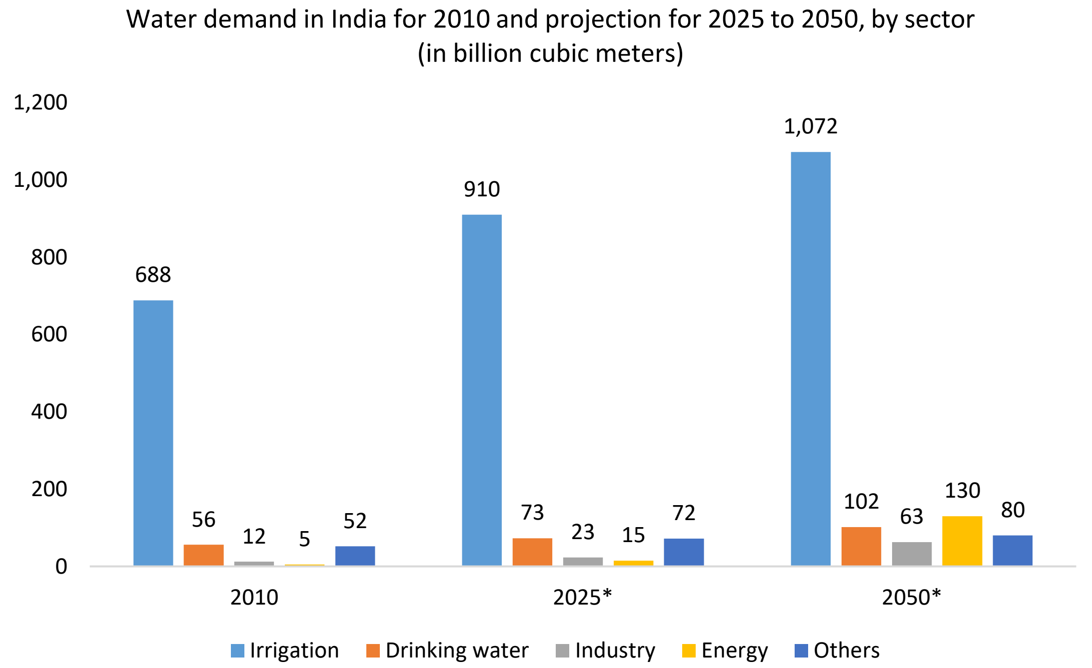


Figure 1.2. *Water demand in India in 2010-2050 by sector. Note: the * mark indicates projections. (Source: India; ASSOCHAM; EY; UN-Water; 2010)*

To put it simple, irrigation, the dominant consumer will be placing immense strain on already scarce freshwater resources. While irrigation demands attention, the industrial and energy sectors exhibit the most significant percentage increases, highlighting the growing water footprint of India's economic development. This escalating demand, coupled with increasing urbanization reflected in the rise in drinking water needs, necessitates a paradigm shift towards integrated water management strategies. Effective sewage treatment and water recycling can play a pivotal role in mitigating this crisis by augmenting water supply, reducing reliance on freshwater sources, and minimizing the environmental impact of wastewater discharge. Also, forecasts as per Composite Water Management Index report published in June 2018 by NITI Aayog suggest that by 2030, India's water requirements may far exceed its available supply, potentially resulting in severe water shortages for a large segment of the population, see *Figure 1.3.*

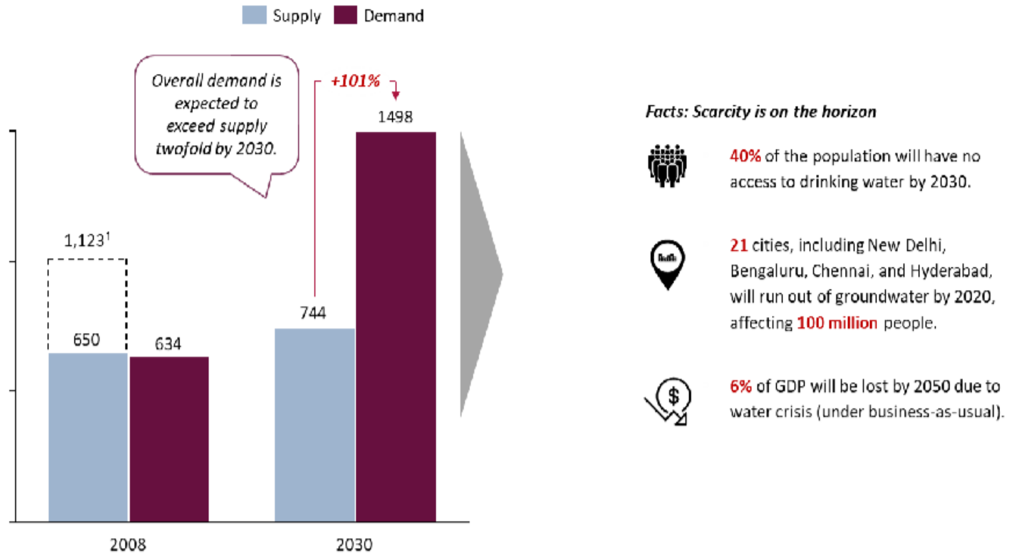


Figure 1.3. *Demand and supply of water in India. (Source: Dalberg analysis; CWC Water & Related Statistics 2013; FAO & UNICEF, Water in India 2013; McKinsey & WRG, 'Charting our water future', 2009; World Bank' Times of India)*

This impending crisis emphasizes the immediate requirement for extensive and enduring water management approaches at both the national and regional levels.

1.2. Motivation and the aim of the dissertation

Building upon this foundational understanding of water's critical role, it is essential to acknowledge that these resources, vital inputs for both economic activity and societal well-being, are increasingly threatened by escalating pollution levels. This degradation poses not only ecological risks, disrupting delicate ecosystems and endangering biodiversity, but also substantial economic and social costs. These costs manifest in various forms, including increased healthcare expenditures associated with waterborne diseases, reduced agricultural productivity due to contaminated irrigation sources, and constrained industrial output resulting from water scarcity and quality issues.

A key contributor to this escalating crisis is ineffective wastewater management. Traditional approaches, often characterized by outdated infrastructure and inadequate treatment processes, fail to adequately address the complex challenges posed by emerging pollutants, aging infrastructure, and the dynamic impacts of climate change. This necessitates a paradigm shift towards innovative, sustainable, and economically viable solutions that can optimize resource utilization and minimize environmental impact. From a business perspective, the wastewater treatment sector presents both challenges and opportunities. The increasing demand for clean water, coupled with stricter environmental regulations, is driving the need for significant investments in advanced treatment technologies and infrastructure. Companies that can develop and deploy cost-effective, scalable, and sustainable solutions are poised to capture a significant share of this growing market. However, realizing this potential requires a deep understanding of the complex interplay between technological innovation, regulatory frameworks, and market dynamics. Companies must navigate a complex landscape of competing technologies, evolving regulations, and diverse stakeholder interests. Moreover, they must develop business models that can deliver both financial returns and positive social and environmental outcomes.

India, with its rapidly expanding economy and burgeoning population, faces particularly acute challenges in the wastewater management sector. The country's existing infrastructure is often inadequate to meet the growing demand for wastewater treatment, leading to widespread pollution and significant public health risks. This situation presents both a challenge and an opportunity for businesses to develop and deploy innovative solutions that can address India's specific needs. Therefore, this dissertation seeks to address this critical gap by exploring the challenges, technology choices, and sustainable strategies for advancing sewage treatment in India. This research aims to provide actionable insights for businesses, policymakers, and investors seeking to drive sustainable growth in the water sector. To achieve this aim, the research will begin by assessing the current state of the sewage treatment sector, with a particular focus on identifying the key barriers and challenges, kind of technologies the Indian sewage treatment industry is using. Building upon this assessment, the dissertation will evaluate the potential of different business models and technological solutions for addressing India's wastewater treatment needs. This will include an analysis of the costs and benefits of treatment systems, resource recovery technologies, and public-private partnerships. The research will also examine the role of stakeholder engagement and public awareness in promoting sustainable wastewater management practices. Ultimately, this dissertation seeks to provide actionable insights for businesses, policymakers, and investors seeking to capitalize on the opportunities in India's rapidly growing wastewater treatment sector. By providing a rigorous and evidence-based analysis of the challenges, opportunities, and potential solutions, this research aims to contribute to the development of a more sustainable, efficient, and economically viable wastewater management system in India.

1.3. Objectives and the Disseration Outline

This dissertation objective focuses on the exploring challenges, technology choices, and sustainable strategies for advancing sewage treatment in India. The geographical scope encompasses urban and peri-urban areas across Indian states, chosen to represent diverse techno-economic, environmental, social and institutional challenges.

This section presents a structured overview of the thesis, outlining the organization and scope of each chapter to guide the reader through the progression of this research.

Chapter 1: Introduction, this chapter provides introduction to waste as a crucial commodity for survival, water scenario in India along with wastewater potential and scope for bridging the water demand using wastewater treatment.

Chapter 2: Review of the Literature, this chapter will delve into existing literature review on sewage treatment methods as well as the sewage treatment infrastructure avialable across Indian states and Union Teritories

Chapter 3: Framework and Methodology, in this chapter, the research methods used to explore the research questions are explained.

Chapter 4: Results and Discussion, this chapter will present results on operational challenges and technology choices, strategies for achieving sustainability, and offsetting benefits along with survey based narratives and validations.

Chapter 5: Conclusion and Future Research Proposition, the final chapter will summarize the entire study, reiterating the key findings and discussing how future research can be taken in the field.

CHAPTER 2

REVIEW OF THE LITERATURE

This chapter undertakes a comprehensive literature review on sewage treatment facilities across Indian states and union territories systematically to sightsee the research gaps. Additionally, a literature review on the advancements in sewage treatement technologies as well as the sustainable strategies that are applicable for wastewater sector is carried out.

2.1. Sewage Treatment Plants in India

Understaning about the current status of sewage treatment facilities in Indian states and union territories has garnered increasing attention in recent years due to the pressing need for efficient wastewater management and pollution control as the sewage generation is increasing (see *Figure 2.1.*). Various studies have shed light on the challenges and disparities existing across different regions of India in terms of sewage treatment infrastructure, capacity, and compliance with environmental regulations (Minde et al., 2024; Singh et al., 2023). These studies, highlighted the inadequate sewage treatment capacity in urban areas of northern Indian states, emphasizing the urgent need for infrastructure development to address the escalating pollution levels in rivers and water bodies. Similarly, underscored the disparities in sewage treatment coverage between states, with southern regions exhibiting higher treatment rates compared to states in the north and east. Furthermore, some studies provided insights into the policy frameworks and institutional mechanisms governing sewage treatment practices in Indian states, revealing a lack of uniformity in regulatory standards and enforcement mechanisms.

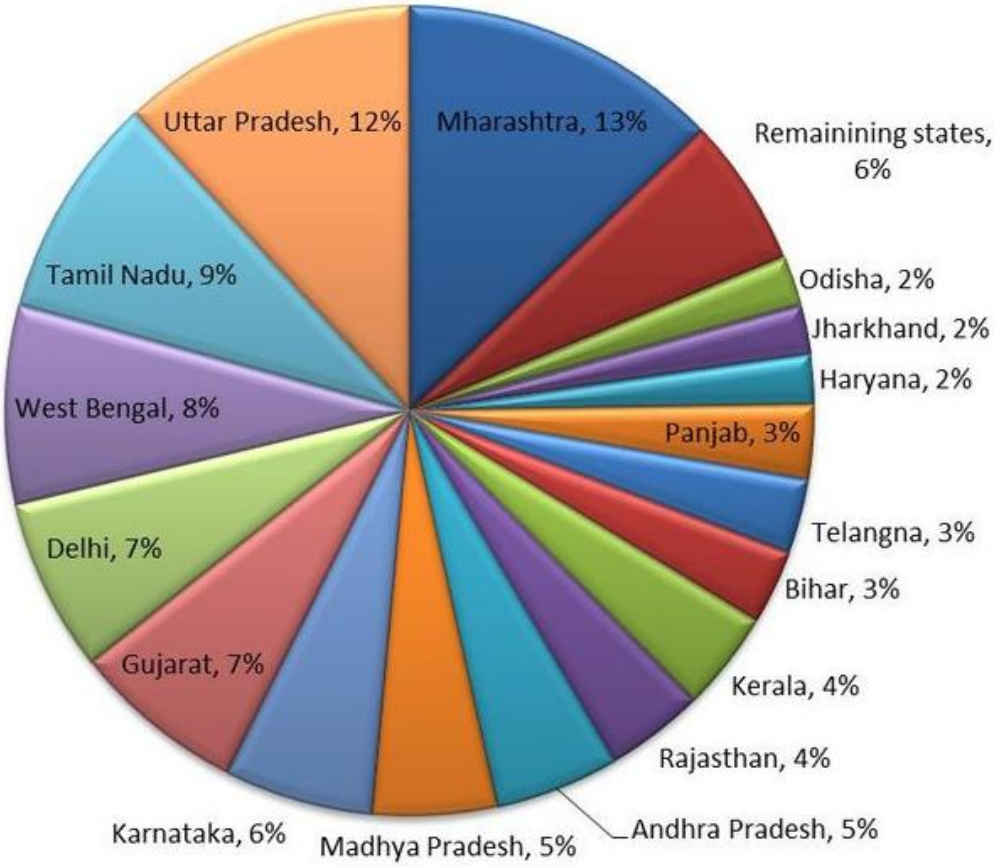


Figure 2.1. *State wise percentage generation of sewage in India. (Source: Adapted from CPCB Report 2016)*

This inconsistency has resulted in varying levels of compliance with sewage treatment norms across different states and union territories, contributing to the overall challenges in achieving comprehensive wastewater management goals. Moreover, some recent studies examined the impact of rapid urbanization on sewage treatment infrastructure in select Indian states, highlighting the strain on existing facilities and the need for sustainable solutions to accommodate growing urban populations. These studies collectively underscore the critical need for comprehensive assessments of sewage treatment infrastructure across Indian states and union territories to identify gaps, formulate targeted interventions, and enhance overall wastewater management practices to safeguard environmental and public health interests. To further understand sewage treatment infrastructure across Indian states and union territories, a detailed literature review was done on the existing facilties and action plans on new implementions by each state and union territory. The summary briefing the current status of sewage treatment infrastructure across Indian states and union territories is presented in *Table 2.1*.

Table 2.1. *Status of Sewage Treatment Plants across Indian states and union territories*

State/Union Territory	**Briefing the Current State of Sewage Treatment**	**Sources**
Andhra Pradesh	Andhra Pradesh generates an estimated 2882 million liters per day (MLD) of sewage, while the total existing and planned sewage treatment plant (STP) capacity is 853.05 MLD, distributed across 67 facilities. An analysis of the state's sewage treatment infrastructure reveals several key findings. Current installed STP capacity stands at 833	(CPCB, 2021; SPCB, 2021; PCC, 2021)

	MLD, representing only 39.61% of the estimated sewage generation. This indicates a substantial treatment deficit of 2049 MLD, equivalent to 71.09% of the generated sewage. Furthermore, of the 833 MLD installed capacity, only 443 MLD (53.18%) is currently operational. Actual utilization is even lower, at 309 MLD, with only 154 MLD of capacity demonstrably complied with regulatory standards. While activated sludge process (ASP) and moving bed biofilm reactor (MBBR) technologies are the most prevalent treatment methods, natural treatment systems exhibit a notably higher compliance rate, exceeding 50% adherence to prescribed norms.	
Andaman & Nicobar Islands	While Andaman & Nicobar Islands generates 23 MLD of sewage, the region lacks centralized sewage treatment plants (STPs), relying instead on septic tanks for wastewater management.	(CPCB, 2021; SPCB, 2021; PCC, 2021)
Arunachal Pradesh	Arunachal Pradesh, with a sewage generation of 62 MLD, lack STPs and depend solely on septic tank systems for sewage treatment. This reliance on decentralized, on-site systems highlights a potential gap in wastewater treatment infrastructure within these states.	(CPCB, 2021; SPCB, 2021; PCC, 2021)

Assam	Assam, with 809 MLD, lack STPs and depend solely on septic tank systems for sewage treatment. This reliance on decentralized, on-site systems highlights a potential gap in wastewater treatment infrastructure within these states.	(CPCB, 2021; SPCB, 2021; PCC, 2021)
Bihar	Bihar generates an estimated 2276 MLD of sewage. However, the current installed sewage treatment plant (STP) capacity is extremely limited, at only 10 MLD (0.43% of sewage generated), representing a significant treatment deficit of 2266 MLD (99.56%). While the planned and proposed STP capacity, totalling 631 MLD across 25 facilities, aims to address this gap, none of the currently installed 10 MLD capacity is operational. The stark disparity between sewage generation and operational treatment capacity underscores the urgent need for accelerated infrastructure development in the state.	(CPCB, 2021; SPCB, 2021; PCC, 2021)
Chandigarh	The Union Territory of Chandigarh generates an estimated 188 MLD of sewage. Interestingly, the total installed STP capacity is 293 MLD, distributed across seven facilities, indicating a surplus treatment capacity of 105 MLD. Of this installed capacity, 271 MLD (92.49%) is operational, with an actual	(CPCB, 2021; SPCB, 2021; PCC, 2021)

	utilization of 235 MLD (86.72% of operational capacity). The fact that actual utilized capacity surpasses the estimated sewage generation suggests the possibility of influent from neighbouring areas, the inclusion of industrial wastewater in the sewage stream, or potentially, unaccounted-for water sources contributing to the higher volume. Further investigation is warranted to determine the precise cause of this discrepancy.	
Chhattisgarh	Chhattisgarh generates an estimated 1203 MLD of sewage. Current installed sewage treatment plant (STP) capacity is only 73 MLD, representing a mere 6.07% of the generated sewage. This translates to a substantial treatment deficit of 1130 MLD (93.93%). While the entirety of the installed 73 MLD capacity is operational, the actual utilization is remarkably low, at only 6 MLD. Activated sludge process (ASP) technology appears to be the dominant treatment method in the state, although the extremely low utilization rate raises concerns about the overall effectiveness of the existing infrastructure. Further research is needed to understand the factors contributing to this low	(CPCB, 2021; SPCB, 2021; PCC, 2021)

	utilization and the potential role of alternative treatment systems.	
Daman Diu & Dadra Nagar Haveli	The Union Territory of Daman Diu & Dadra Nagar Haveli generates an estimated 67 MLD of sewage. Existing sewage treatment plant (STP) capacity totals 24 MLD (35.82% of sewage generated), spread across three facilities. This leaves a treatment gap of 43 MLD (64.17%). While all three STPs are operational, the actual utilized capacity is significantly lower, at just 7 MLD. The disparity between operational capacity and actual utilization warrants further investigation to understand the underlying factors limiting the effective use of the existing treatment infrastructure.	(CPCB, 2021; SPCB, 2021; PCC, 2021)
Goa	Goa generates an estimated 176 MLD of sewage. The current installed sewage treatment plant (STP) capacity stands at 66 MLD, representing 37.5% of the generated sewage. This reveals a treatment capacity gap of 110 MLD (62.5%). Of the 66 MLD installed capacity, 44 MLD (66.67%) is operational, with an actual utilization of 25 MLD. Notably, all operational STPs in Goa are currently complied with regulatory norms. While the existing	(CPCB, 2021; SPCB, 2021; PCC, 2021)

	capacity falls short of the sewage generation, the full compliance of operational STPs is a positive indicator. The planned capacity expansion to 104 MLD across 14 STPs, once realized, will significantly improve Goa's sewage treatment coverage.	
Gujarat	Gujarat generates an estimated 5013 MLD of sewage. The state has a substantial installed sewage treatment plant (STP) capacity of 3378 MLD (67.38% of sewage generated), distributed across 70 facilities. This leaves a treatment gap of 1635 MLD (32.61%). Of the total installed capacity, 3358 MLD (99.40%) is operational, with an actual utilization of 2687 MLD. Sequencing batch reactor (SBR) and activated sludge process (ASP) technologies are the predominant treatment methods employed in the state, surpassing the prevalence of natural treatment systems. While a treatment gap still exists, the high operational rate and significant utilization of existing capacity indicate a relatively well-developed sewage treatment infrastructure in Gujarat compared to some other states.	(CPCB, 2021; SPCB, 2021; PCC, 2021)
Haryana	Haryana generates an estimated 1816	(CPCB, 2021;

	MLD of sewage. The state possesses a total installed sewage treatment plant (STP) capacity of 1880 MLD across 153 facilities, exceeding the estimated sewage generation by 64 MLD. While the entire installed capacity is potentially operational, the actual utilization is 1284 MLD, with only 1746 MLD of that capacity demonstrably complied with regulatory standards. Sequencing batch reactor (SBR) and moving bed biofilm reactor (MBBR) technologies are the prevalent treatment methods employed in Haryana's STPs. Despite having sufficient installed capacity, the discrepancy between potential and actual utilization, along with the compliance shortfall, suggests opportunities for optimization and improved operational efficiency within Haryana's sewage treatment infrastructure.	SPCB, 2021; PCC, 2021)
Himachal Pradesh	Himachal Pradesh generates an estimated 116 MLD of sewage. The state's installed sewage treatment plant (STP) capacity is 136 MLD, exceeding the sewage generation by 20 MLD and distributed across 86 facilities. Of this installed capacity, 99 MLD (72.79%) is operational, with an actual utilization of only 51 MLD. While the installed	(CPCB, 2021; SPCB, 2021; PCC, 2021)

	capacity surpasses the current sewage generation, the relatively low operational and utilization rates indicate potential for improvement in the operational efficiency of existing and planned STPs. The planned expansion to 155 MLD total capacity should further enhance the state's sewage treatment capabilities, provided operational challenges are addressed.	
Jammu & Kashmir	Jammu & Kashmir generates an estimated 665 MLD of sewage. The current installed sewage treatment plant (STP) capacity is 218 MLD, representing only 32.78% of the generated sewage. This signifies a substantial treatment deficit of 447 MLD (67.21%). Furthermore, of the 218 MLD installed capacity, only 93 MLD (42.66%) is operational, with an actual utilization of just 49 MLD. The capacity of STPs currently complied with regulatory standards is 88 MLD. The significant gap between sewage generation and both installed and operational treatment capacity, coupled with the limited compliance of existing facilities, underscores the critical need for substantial investment and development in the region's sewage	(CPCB, 2021; SPCB, 2021; PCC, 2021)

	treatment infrastructure. The planned expansion to a total capacity of 222 MLD across 26 STPs, while a step in the right direction, will still leave a considerable treatment deficit.	
Jharkhand	Jharkhand generates an estimated 1510 MLD of sewage. The current installed sewage treatment plant (STP) capacity is extremely limited, at only 22 MLD, representing a mere 1.45% of the generated sewage. This results in a substantial treatment deficit of 1488 MLD (98.55%). While the installed STPs are capable of operating at full capacity, the actual utilization is only 15 MLD, which, importantly, meets the consented discharge norms. The planned expansion to a total capacity of 639 MLD across 12 STPs is crucial for addressing the significant treatment gap. However, ensuring the effective utilization of this expanded capacity will be essential for achieving meaningful improvements in wastewater management within the state. The fact that the currently utilized capacity is complied with norms offers a positive starting point for future development.	(CPCB, 2021; SPCB, 2021; PCC, 2021)
Karnataka	Karnataka generates an estimated 4458 MLD of sewage. The state has an	(CPCB, 2021; SPCB, 2021;

	installed sewage treatment plant (STP) capacity of 2712 MLD, representing 60.83% of the generated sewage. This leaves a treatment gap of 1746 MLD (39.17%). Of the installed capacity, 1922 MLD (70.87%) is operational, with a high actual utilization rate of 1786 MLD (92.92% of operational capacity). However, only 1168 MLD of the operational capacity is currently complied with regulatory standards. Sequencing batch reactor (SBR), oxidation pond (OP), and activated sludge process (ASP) technologies are the predominant treatment methods employed in Karnataka. While Karnataka has a relatively well-developed sewage treatment infrastructure compared to some other states, the compliance deficit highlights the need for improved operational practices and stricter adherence to regulatory norms.	PCC, 2021)
Kerala	Kerala generates an estimated 4256 MLD of sewage. The current installed sewage treatment plant (STP) capacity is significantly low, at only 120 MLD, representing a mere 2.82% of the generated sewage. This translates to a substantial treatment deficit of 4136	(CPCB, 2021; SPCB, 2021; PCC, 2021)

	MLD (97.18%). Of the 120 MLD installed capacity, 114 MLD (95%) is operational; however, the actual utilization is only 47 MLD. The substantial gap between sewage generation and both installed and utilized treatment capacity underscores the urgent need for significant investments in expanding and optimizing sewage treatment infrastructure within the state.	
Lakshadweep	Lakshadweep currently lacks any centralized sewage treatment plant (STP) infrastructure. Wastewater management in the region relies entirely on decentralized septic tank systems for sewage disposal. This reliance on on-site systems warrants further investigation into their effectiveness and potential environmental impacts, particularly given the unique ecological vulnerability of island ecosystems.	(CPCB, 2021; SPCB, 2021; PCC, 2021)
Madhya Pradesh	Madhya Pradesh generates an estimated 3646 MLD of sewage. The state's installed sewage treatment plant (STP) capacity is 1839 MLD, representing 50.44% of the generated sewage. This leaves a treatment gap of 1807 MLD (49.56%). Of the installed capacity, only 684 MLD (37.19%) is operational, with an actual utilization of 536 MLD.	(CPCB, 2021; SPCB, 2021; PCC, 2021)

	Information regarding the treatment technologies employed in 123 STPs is unavailable from the Madhya Pradesh Pollution Control Board (MPPCB). The remaining STPs primarily utilize sequencing batch reactor (SBR) and waste stabilization pond (WSP) technologies. The considerable treatment gap and the low operationalization rate of existing capacity highlight the need for substantial improvements in wastewater management infrastructure and practices within the state. Further investigation is required to determine the treatment technologies employed in the unreported STPs to provide a comprehensive assessment of the state's treatment capacity.	
Maharashtra	Maharashtra generates an estimated 9107 MLD of sewage. The state has a substantial installed sewage treatment plant (STP) capacity of 6890 MLD, covering 75.65% of the generated sewage. This leaves a treatment gap of 2217 MLD (24.35%). Of the installed capacity, 6366 MLD (92.39%) is operational, with an actual utilization of 4242 MLD. However, the capacity of STPs complied with regulatory standards is significantly lower, at only 3598	(CPCB, 2021; SPCB, 2021; PCC, 2021)

	MLD. While Maharashtra demonstrates significant progress in sewage treatment infrastructure development, the discrepancy between operational capacity and complied capacity highlights the need for improved operational practices and adherence to regulatory norms. The planned expansion to a total capacity of 9819 MLD across 195 STPs further strengthens the state's commitment to addressing the remaining treatment gap.	
Manipur	Manipur currently lacks any centralized sewage treatment plant (STP) infrastructure. Similar to Lakshadweep, wastewater management in Manipur relies entirely on decentralized septic tank systems for sewage disposal. This complete reliance on on-site systems necessitates a thorough assessment of their effectiveness and potential environmental impact, especially considering the potential for water contamination and public health concerns.	(CPCB, 2021; SPCB, 2021; PCC, 2021)
Meghalaya	Meghalaya currently has no centralized sewage treatment plant (STP) infrastructure. Sewage disposal in the state relies entirely on decentralized septic tank systems. This sole	(CPCB, 2021; SPCB, 2021; PCC, 2021)

	dependence on on-site systems raises concerns about the adequacy of wastewater treatment and the potential environmental and public health implications. A comprehensive assessment of the effectiveness and sustainability of these septic systems is warranted.	
Mizoram	Mizoram generates an estimated 103 MLD of sewage. However, the state has only one STP with a treatment capacity of 10 MLD, representing a mere 9.7% of the generated sewage. Critically, this single STP is currently non-operational, resulting in the entirety of the state's sewage being discharged untreated.	(CPCB, 2021; SPCB, 2021; PCC, 2021)
Nagaland	Nagaland currently lacks any centralized sewage treatment plant (STP) infrastructure. Sewage disposal relies solely on decentralized septic tank systems. This dependence on on-site systems necessitates a thorough evaluation of their effectiveness and potential environmental and public health consequences. The development of centralized sewage treatment infrastructure is likely crucial for ensuring sustainable and effective wastewater management in the state.	(CPCB, 2021; SPCB, 2021; PCC, 2021)
	The National Capital Territory (NCT) of	(CPCB, 2021;

National Capital Territory (NCT) of Delhi	Delhi generates an estimated 3330 MLD of sewage. The region has a substantial installed sewage treatment plant (STP) capacity of 2896 MLD across 38 facilities, representing 86.96% of the generated sewage. This leaves a treatment gap of 434 MLD (13.04%). Of the installed capacity, 2715 MLD (93.75%) across 35 STPs is operational, with an actual utilization of 2412 MLD. However, the capacity of STPs complied with regulatory standards is surprisingly low, at only 90 MLD. Activated sludge process (ASP) technology is the dominant treatment method, surpassing the use of natural treatment systems. While Delhi has a relatively well-developed sewage treatment infrastructure in terms of capacity, the significant shortfall in complied capacity raises serious concerns about the effectiveness of treatment and its environmental impact. Addressing the compliance issues is crucial for ensuring the long-term sustainability of wastewater management in the region.	SPCB, 2021; PCC, 2021)
Odisha	Odisha generates an estimated 1282 MLD of sewage. The state's installed sewage treatment plant (STP) capacity is 378 MLD, representing 29.48% of the	(CPCB, 2021; SPCB, 2021; PCC, 2021)

	generated sewage. This results in a significant treatment gap of 904 MLD (70.51%). Of the 378 MLD installed capacity, only 55 MLD (14.55%) is operational, with an actual utilization of 50 MLD. The substantial gap between sewage generation and both installed and operational treatment capacity highlights the critical need for investment in expanding and optimizing sewage treatment facilities in Odisha. Improving the operational efficiency of existing infrastructure is also essential for maximizing treatment coverage.	
Puducherry	Puducherry generates an estimated 161 MLD of sewage. The installed sewage treatment plant (STP) capacity is 56 MLD across four STPs, representing 34.79% of the sewage generated. This indicates a treatment gap of 105 MLD (65.21%). While all installed STPs are capable of operating at full capacity, the actual utilization is only 30 MLD. Upflow anaerobic sludge blanket (UASB) technology is the predominant treatment method, surpassing the use of other conventional treatment systems. The significant treatment gap and the underutilization of existing capacity highlight the need for both expanding	(CPCB, 2021; SPCB, 2021; PCC, 2021)

	treatment infrastructure and improving the operational efficiency of existing STPs. The planned expansion to a total capacity of 59 MLD, while a positive step, will still leave a substantial treatment deficit.	
Punjab	Punjab generates an estimated 1889 MLD of sewage. The state has an installed sewage treatment plant (STP) capacity of 1781 MLD across 119 STPs, covering 94.28% of the generated sewage. This leaves a relatively small treatment gap of 108 MLD (5.72%). Of the installed capacity, 1601 MLD (89.89%) is operational, with a high actual utilization rate of 1360 MLD (84.94% of operational capacity). However, the capacity of STPs complied with regulatory standards is significantly lower, at only 441 MLD. Sequencing batch reactor (SBR), moving bed biofilm reactor (MBBR), and waste stabilization pond (WSP) technologies are the predominant treatment methods. While Punjab has made significant progress in developing sewage treatment capacity, the substantial gap between operational capacity and complied capacity underscores the critical need for improving operational practices and	(CPCB, 2021; SPCB, 2021; PCC, 2021)

	ensuring adherence to regulatory norms.	
Rajasthan	Rajasthan generates an estimated 3185 MLD of sewage. The state's installed sewage treatment plant (STP) capacity is 1086 MLD across 140 STPs, representing 34.10% of the generated sewage. This results in a substantial treatment gap of 2099 MLD (65.90%). Of the 1086 MLD installed capacity, 783 MLD (72.09%) is operational, with an actual utilization of 478 MLD. The capacity of STPs complied with regulatory standards is even lower, at only 224 MLD. The significant treatment deficit, coupled with the limited compliance of existing facilities, underscores the urgent need for substantial investment in expanding and upgrading sewage treatment infrastructure in Rajasthan. The planned expansion to a total capacity of 1195 MLD, while a step forward, will still leave a considerable treatment gap.	(CPCB, 2021; SPCB, 2021; PCC, 2021)
Sikkim	Sikkim generates an estimated 52 MLD of sewage. The state has an installed sewage treatment plant (STP) capacity of 20 MLD across 11 STPs, representing 38.46% of the generated sewage. This results in a treatment gap of 32 MLD (61.54%). Of the 20 MLD installed	(CPCB, 2021; SPCB, 2021; PCC, 2021)

	capacity, 18 MLD (90%) is operational, with an actual utilization of 14 MLD (77.77% of operational capacity). Fixed activated biofilter (FAB) and moving bed biofilm reactor (MBBR) technologies are the predominant treatment methods, surpassing the use of natural treatment systems. While Sikkim's operational efficiency is relatively high, the limited installed capacity necessitates significant investment in expanding treatment infrastructure to address the existing treatment gap. The planned expansion to a total capacity of 30 MLD is a positive step towards closing this gap.	
Tamil Nadu	Tamil Nadu generates an estimated 6421 MLD of sewage. The state has an installed sewage treatment plant (STP) capacity of 1492 MLD across 63 STPs, representing only 23.23% of the generated sewage. This results in a substantial treatment gap of 4929 MLD (76.77%). Remarkably, the entire installed capacity of 1492 MLD is operational; however, the actual utilization is 995 MLD. Interestingly, the capacity of complied STPs is reported as 1368 MLD, which exceeds the installed capacity. This discrepancy likely	(CPCB, 2021; SPCB, 2021; PCC, 2021)

	indicates an error in the data or a different interpretation of "complied capacity." Activated sludge process (ASP) technology is the predominant treatment method, surpassing the use of natural treatment systems. Despite having all installed STPs operational, the significant treatment gap and the discrepancy in reported complied capacity highlight the urgent need for both substantial expansion of treatment infrastructure and clarification of compliance data.	
Telangana	Telangana generates an estimated 2660 MLD of sewage. The state's installed sewage treatment plant (STP) capacity is 901 MLD across 37 STPs, representing 33.87% of the generated sewage. This leads to a significant treatment gap of 1759 MLD (66.13%). Of the installed capacity, 842 MLD (93.45%) is operational, with an actual utilization of 706 MLD. The capacity of STPs complied with regulatory standards is 637 MLD. Activated sludge process (ASP) and moving bed biofilm reactor (MBBR) technologies are the predominant treatment methods, surpassing the use of natural treatment systems. The substantial treatment gap	(CPCB, 2021; SPCB, 2021; PCC, 2021)

	and the relatively lower complied capacity highlight the need for significant investment in expanding treatment infrastructure and improving the operational performance and compliance of existing facilities.	
Tripura	Tripura generates an estimated 237 MLD of sewage. The state has only one operational STP with a capacity of 8 MLD, representing a mere 3.37% of the generated sewage. However, this single STP receives only 1.5 MLD of sewage, which is treated to meet the consented norms. Most of the sewage generated in Tripura remains untreated, posing significant environmental and public health risks. Immediate action is required to expand treatment capacity and improve sewage collection and conveyance systems to direct more wastewater to the existing and future treatment facilities.	(CPCB, 2021; SPCB, 2021; PCC, 2021)
Uttar Pradesh	Uttar Pradesh generates an estimated 8263 MLD of sewage. The state's installed sewage treatment plant (STP) capacity is 3374 MLD across 107 STPs, representing 40.83% of the generated sewage. This leads to a substantial treatment gap of 4889 MLD (59.17%). Of the installed capacity, 3224 MLD	(CPCB, 2021; SPCB, 2021; PCC, 2021)

	(95.55%) is operational, with an actual utilization of 2510 MLD (77.85% of the operational capacity). The capacity of STPs complied with regulatory standards is lower, at 2114 MLD. Sequencing batch reactor (SBR), upflow anaerobic sludge blanket (UASB), and activated sludge process (ASP) technologies are the predominant treatment methods. While Uttar Pradesh has a reasonably high operational rate for its installed STPs, the substantial treatment gap and the lower complied capacity highlight the urgent need for significant investment in expanding treatment infrastructure and improving the compliance of existing and new facilities.	
Uttarakhand	Uttarakhand generates an estimated 627 MLD of sewage. The state's installed sewage treatment plant (STP) capacity is 448 MLD across 81 STPs, covering 71.45% of the generated sewage. This leaves a treatment gap of 179 MLD (28.55%). Of the 448 MLD installed capacity, 345 MLD (77%) is operational, but the actual utilization is significantly lower at 187 MLD. Interestingly, the complied STP capacity is also reported as 345 MLD, matching the operational	(CPCB, 2021; SPCB, 2021; PCC, 2021)

	capacity. While Uttarakhand has a relatively good level of installed capacity, the significant difference between operational capacity and actual utilization suggests inefficiencies in the operation and sewage conveyance to the treatment plants. Maximizing the utilization of existing infrastructure and addressing the remaining treatment gap through the planned expansion to 515 MLD should be prioritized.	
West Bengal	West Bengal generates an estimated 5457 MLD of sewage. The state's installed sewage treatment plant (STP) capacity is 897 MLD across 65 STPs, representing a mere 16.43% of the generated sewage. This results in a massive treatment gap of 4560 MLD (83.57%). Of the 897 MLD installed capacity, only 337 MLD (37.56%) is operational, with an actual utilization of 213 MLD (63.20% of the operational capacity). The capacity of STPs complied with regulatory standards is significantly lower, at only 126 MLD. The planned expansion to a total capacity of 1202 MLD, while a positive development, will still leave a very large treatment deficit.	(CPCB, 2021; SPCB, 2021; PCC, 2021)

A comprehensive review assessment of wastewater treatment across several Indian states reveals significant disparities in infrastructure and operational efficiency. States like Meghalaya and Nagaland rely heavily on septic tanks, raising concerns about their long-term effectiveness and environmental impact, prompting a need for research into centralized treatment alternatives. Mizoram's non-functional sewage treatment plant (STP) demands immediate attention, requiring investigation into its failure and strategies for sustainable operation. Delhi, despite possessing substantial treatment capacity, suffers from low compliance, highlighting the need for improved enforcement and exploration of alternative technologies. Other states, including Odisha, Rajasthan, Tripura, Uttar Pradesh, and Telangana, face large treatment gaps necessitating significant investment in new infrastructure and research into suitable technologies. Conversely, states like Puducherry and Uttarakhand have operational STPs but face challenges with underutilization, demanding research into optimizing operations and improving sewage conveyance. Finally, Punjab and Tamil Nadu grapple with discrepancies between installed and actual treatment capacity, requiring investigation into process optimization and data clarification. Sikkim, while boasting high operational efficiency, needs capacity expansion.

2.2. Sewage Treatment Stages and Methods

Sewage treatment is done in three stages, namely primary, secondary and teritory stages, as illustrated in *Figure 2.2.*, and the percentage removal (cumulative, from initial state) of constituents or characteristics of sewage after successive stages of treatment (not including sludge) are given in *Table 2.2.*

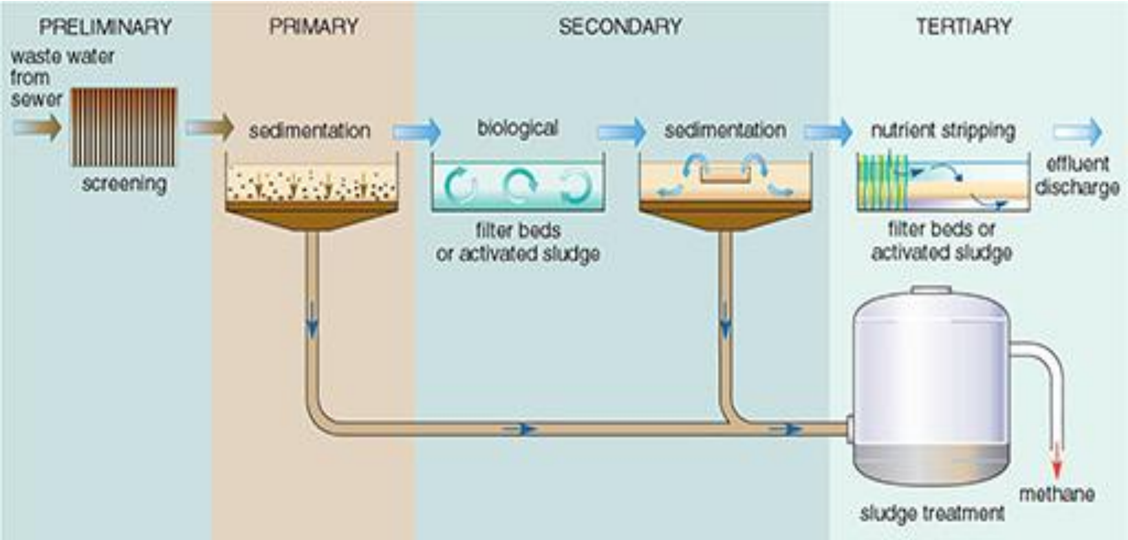


Figure 2.2. *Flow diagram showing the stages of treatment in a sewage treatment plant. (Source: Sewage treatment processes, The Open University, 2025)*

2.2.1. Primary Stage

The primary stage of wastewater treatment focuses on eliminating large, suspended, and buoyant materials from untreated sewage. This process incorporates two main methods: screening, which captures solid debris, and gravitational sedimentation, which removes particles in suspension. While this stage primarily relies on mechanical separation of solids from liquids, chemical additives may occasionally be employed to enhance the settling process. The effectiveness of this initial treatment is notable, as it typically results in a 20-40% decrease in the wastewater's Biochemical Oxygen Demand (BOD) and a substantial 50-60% reduction in total suspended solids. This crucial first step lays the foundation for subsequent, more advanced treatment processes.

__Table 2.2.__ The percentage removal (cumulative, from initial state) of constituents or characteristics of sewage after successive stages of treatment (not including sludge). (Source: Sewage treatment processes, The Open University, 2025)

Constituent	**Primary**	**Secondary**	**Tertiary**
Suspended Solids	60-70	80-95	90-95
BOD	20-40	70-90	>95
Phosphorus	10-30	20-40	85-97
Nitrogen	10-20	20-40	20-40
E. Coli Bacteria	60-90	90-99	>99
Viruses	30-70	90-99	>99
Cadmium and Zinc	5-20	20-40	40-60
Copper, Lead and Chromium	40-60	70-90	80-89

2.2.2. Secondary Stage

Secondary wastewater treatment uses biological methods to purify water further following the physical primary treatment process. In wastewater treatment, the secondary stage emerges as a critical phase in the overall treatment process. The effectiveness of this stage in removing dissolved organic matter that escapes initial treatment. The biological processes involved in secondary treatment have been extensively researched. Microorganisms play a pivotal role, metabolizing organic substances and converting them into carbon dioxide, water, and biomass. This microbial action, coupled with additional settling, has been shown to significantly reduce both suspended solids and biological oxygen demand (BOD), with significant removal rates. Feasibility of using sludge as a co-substrate in biogas production, aligning with circular economy principles in wastewater management could also be possible based on my industry experience. If this is opted, the subsequent treatment stages should be nitrification, denitrification, and disinfection, which are the subjects of ongoing research in the industry. It is noteworthy that while the activated sludge process remains prevalent, a growing body of research explores alternative treatment methods. These include various pond systems, trickling filters, up-flow anaerobic sludge blanket (UASB) reactors, artificial wetlands, microbial fuel cells, and methanogenic reactors. Each of these methods will have specific advantages and potential applications in different contexts. In conclusion secondary wastewater treatment, with ongoing efforts to improve efficiency, resource recovery, and environmental sustainability sounds progressing and has great future in sustainable transition journey of water sector. Future research directions may focus on optimizing these processes, particularly in the context of emerging contaminants and the increasing need for water reuse strategies.

2.2.3. Tertiary Stage

The tertiary treatment in wastewater processing is essential for removing specific contaminants that persist after secondary treatment. This advanced stage aims to eliminate up to 99% of all impurities, rendering the water suitable for various uses, including potable purposes. Research has focused on several advanced methods, often used in combination, to achieve this high level of purification. These include ultrasonication (US), ultraviolet light treatment (UV), and ozonation (O_3). Each of these methods targets different aspects of water contamination, particularly addressing residual bacterial and heavy metal contamination. Studies have explored the mechanisms by which ultrasonication renders microorganisms inviable. Key findings suggest that this process involves both free-radical attack and physical disruption of cell membranes. The literature indicates that ultrasonication, either alone or in combination with other treatments, facilitates the deagglomeration of microorganisms, thereby enhancing the efficacy of chemical disinfectants. The synergistic effects of combined treatments have been a focus of numerous studies. For instance, research has demonstrated that the combination of US, UV, and O_3 produces free radicals that attack cell membranes of biological contaminants, allowing chemical oxidants to penetrate and disrupt internal cellular structures. In the context of specific industrial applications, such as textile wastewater treatment, combined methods have shown particular promise. Studies have reported on the effectiveness of ultrasound as a pre-treatment step when used in conjunction with UV radiation Further research has explored various combinations of ultrasound and UV radiation with TiO_2 photocatalysis and ozone to optimize the wastewater disinfection process. An important trend in the literature is the emphasis on continuous monitoring and quality assessment throughout the treatment process. This approach ensures that the treated water meets appropriate purification standards before being made available for irrigation, drinking, or other domestic uses. In conclusion, the literature underscores the complexity and effectiveness of tertiary wastewater treatment, highlighting the importance of combined technologies and rigorous quality control in achieving high standards of water purification. Ongoing research in this field continues to refine these processes, aiming to improve efficiency and expand the applications of treated wastewater in various sectors.

2.3. Recent Advancements in Wastewater Treatment Technologies

The increasing demand for clean water, coupled with growing concerns about water scarcity and pollution, has driven significant advancements in wastewater treatment technologies. While conventional secondary treatment processes effectively remove suspended solids and biodegradable organic matter, they often fall short of removing emerging contaminants, such as pharmaceuticals, endocrine disruptors, and microplastics (Petrie et al., 2015). As a result, advanced tertiary treatment technologies have emerged as critical tools for achieving stringent water quality standards and enabling water reuse (Crini & Lichtfouse, 2019).

2.3.1. Membrane Filtration Technologies

Membrane filtration technologies, including reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF), have become increasingly prevalent in tertiary treatment applications (Shannon et al., 2008). RO, in particular, has demonstrated exceptional capability in removing dissolved salts, organic compounds, and microorganisms, making it suitable for producing potable water from wastewater (Schäfer et al., 2011). However, RO systems can be energy-intensive and prone to fouling, necessitating pretreatment steps and careful operational management (Lee et al., 2011). UF and MF are often employed as pretreatment steps to remove suspended solids and protect downstream membrane processes (Judd, 2011).

2.3.2. Advanced Oxidation Processes (AOPs)

Advanced oxidation processes (AOPs) offer a promising approach for degrading recalcitrant organic contaminants that are not effectively removed by conventional treatment methods (Andreozzi et al., 1999). AOPs, such as ozonation, UV/H2O2, and Fenton's reagent, generate highly reactive hydroxyl radicals that can oxidize a wide range of organic compounds (Glaze et al., 1987). Ozonation has been shown to be effective in removing pharmaceuticals and endocrine disruptors (Huber et al., 2005), while UV/H2O2 is particularly useful for treating low-level organic contamination (Parsons, 2004). However, AOPs can be energy-intensive and may require careful control of operating parameters to optimize performance and minimize the formation of harmful byproducts (von Sonntag & von Gunten, 2012).

2.3.3. Adsorption Technologies

Adsorption technologies, such as activated carbon adsorption and ion exchange, provide another avenue for removing specific contaminants from water. Activated carbon is widely used to remove taste, odor, and color from water, as well as to adsorb a variety of organic compounds (Babić et al., 2007). Ion exchange resins can be tailored to remove specific ions, such as nitrate, perchlorate, and heavy metals (Clifford, 1999). However, adsorption technologies can be limited by the capacity of the adsorbent material and the need for regeneration or replacement (Crittenden et al., 2012).

2.3.4. Biological Treatment Technologies

Biological treatment technologies, such as moving bed biofilm reactors (MBBRs) and membrane bioreactors (MBRs), offer a cost-effective and environmentally friendly approach for removing organic matter and nutrients from wastewater (Metcalf & Eddy, 2014). MBBRs provide a large surface area for biofilm growth, allowing for high treatment efficiency (Rusten et al., 2006). MBRs combine biological treatment with membrane filtration, providing a compact and efficient treatment process that can produce high-quality effluent (Judd, 2011).

2.4. Review of Sustainable Strategies in Wastewater Treatment

The growing global challenges of water scarcity, pollution, and climate change have spurred a paradigm shift in wastewater management, moving away from traditional "end-of-pipe" treatment approaches towards more sustainable and resource-oriented strategies (Corominas et al., 2013). Sustainable wastewater treatment aims to minimize environmental impacts, reduce energy consumption, recover valuable resources, promote social equity, and embrace the principles of the circular economy (Lens et al., 2001).

2.4.1. The Circular Economy and Wastewater Treatment

The circular economy seeks to minimize waste and maximize the value of resources by keeping them in use for as long as possible (Ellen MacArthur Foundation, 2015). In the context of wastewater treatment, this means viewing wastewater not as a waste product, but as a valuable source of resources that can be recovered and reused, closing the loop and minimizing the need for virgin materials (Ghisellini et al., 2016).

Table 2.3. *Resource recovery options from wastewater*

Resource Recovery Route	Description
Water Reuse	Treated wastewater can be reused for a variety of purposes, including irrigation, industrial cooling, toilet flushing, and even potable water supply (Asano et al., 2007). Water reuse can alleviate water scarcity, reduce the demand on freshwater resources, provide a reliable water source for various applications, and reduce the energy and resources needed to extract and treat freshwater (Jiménez & Asano, 2008).
Energy Recovery	Wastewater contains significant amounts of organic matter that can be converted into biogas through anaerobic digestion (Appels et al., 2008). Biogas can be used to generate electricity and heat, reducing the reliance on fossil fuels, mitigating greenhouse gas emissions, and creating a closed-loop energy system within the wastewater treatment plant (McCarty et al., 2011).

Nutrient Recovery	Wastewater is rich in nutrients, such as nitrogen and phosphorus, which are essential for plant growth (Cordell et al., 2009). Recovering these nutrients can reduce the demand for synthetic fertilizers, which are energy-intensive to produce and can contribute to water pollution, and create a circular nutrient cycle, reducing reliance on mined resources (Driver et al., 1999). Nutrient recovery technologies include struvite precipitation, ammonia stripping, and membrane-based nutrient recovery (Rittmann et al., 2011).
Other Resources	Wastewater can also be a source of other valuable resources, such as cellulose, bioplastics, and precious metals (Werner et al., 2014). Recovering these materials can create new revenue streams and reduce the demand for virgin resources, contributing to a more circular economy.

2.4.2. Resource Recovery from Wastewater

One of the key pillars of sustainable wastewater treatment, and a cornerstone of the circular economy, is resource recovery. Wastewater contains a wealth of valuable resources (as shown in *Table 2.3.*), including water, energy, nutrients, and organic matter (Schröder et al., 2015). Recovering these resources can not only reduce the environmental burden of wastewater treatment but also generate economic benefits and contribute to a more circular economy (Guest et al., 2009).

2.4.3. Decentralized Wastewater Treatment Systems

Decentralized wastewater treatment systems (DEWATS) offer a sustainable alternative to centralized treatment plants, particularly in rural areas and developing countries (Langergraber & Muellegger, 2005). DEWATS are typically smaller, simpler, and less energy-intensive than centralized systems, making them more affordable and easier to operate (Foxon et al., 2006). DEWATS can also be designed to recover resources, such as water and nutrients, for local use, promoting a localized circular economy (Tilley et al., 2008).

2.4.4. Nature-Based Solutions

Nature-based solutions (NBS), such as constructed wetlands and treatment ponds, offer a sustainable and cost-effective approach for wastewater treatment (Vymazal, 2010). NBS utilize natural processes, such as plant uptake, microbial activity, and sedimentation, to remove pollutants from wastewater (Kadlec & Wallace, 2008). NBS can also provide a range of co-benefits, such as habitat creation, flood control, and carbon sequestration, contributing to a more resilient and circular ecosystem (Bastian et al., 2011).

2.4.5. Life Cycle Assessment

Life cycle assessment (LCA) is a valuable tool for evaluating the environmental impacts of different wastewater treatment strategies (Finnveden et al., 2009). LCA can be used to compare the environmental performance of different technologies, identify hotspots in the treatment process, and optimize the design of sustainable wastewater treatment systems, ensuring that they align with the principles of the circular economy (Corominas et al., 2013).

2.4.6. Social and Economic Considerations

Sustainable wastewater treatment must also consider social and economic factors. It is important to ensure that wastewater treatment technologies are affordable, accessible, and culturally appropriate (Winblad & Kilama, 1985). Community participation and stakeholder engagement are essential for the successful implementation of sustainable wastewater treatment projects, fostering a sense of ownership and promoting the adoption of circular economy principles at the local level (Parkinson & Tayler, 2003).

CHAPTER 3

FRAMEWORK AND METHODOLOGY

Building upon a comprehensive review of existing literature, this chapter delineates a critical research gap concerning the advancement of sewage treatment in India. To address this gap, a set of focused research questions along with a case study desin incorporating specific methods for analysis are presented. Furthermore, this chapter outlines a analytical framework designed to guide the exploration of potential solutions accompanied by a robust data collection strategy. This comprehensive approach provides stakeholders with the necessary tools and context to contribute meaningfully to the investigation of challenges, technology choices, and sustainable strategies for advancing sewage treatment in India.

3.1. Research Gap and Questions

India's pursuit of improved sanitation and water quality has led to significant investments in sewage treatment infrastructure. However, the overarching goal of advancing sewage treatment in India faces multifaceted challenges that demand comprehensive investigation. While progress has been made in expanding treatment capacity, a persistent gap exists between installed, operational, and effectively utilized infrastructure. This inefficiency underscores the need to understand the underlying technical, economic, and managerial obstacles hindering optimal performance. Furthermore, the selection and implementation of appropriate technology choices for sewage treatment in India require careful consideration. While various treatment technologies are available, their suitability and effectiveness can vary significantly depending on local conditions, resource availability, and environmental considerations. Research is needed to evaluate the performance and cost-effectiveness of different technologies in the Indian context, considering both centralized and decentralized approaches.

Moreover, achieving sustainable strategies for sewage treatment in India necessitates a shift towards resource recovery, circular economy principles, and environmentally sound practices. While interest in sustainable approaches like Decentralized Wastewater Treatment Systems (DEWATS) and Nature-Based Solutions (NBS) is growing, knowledge gaps remain regarding their optimal design, operation, and long-term performance in diverse Indian settings. Further research is needed to identify and address the social, economic, and policy barriers to the widespread adoption of sustainable sewage treatment practices. Therefore, this deseration aims to address these critical research gaps by investigating the challenges, evaluating technology choices, and identifying sustainable strategies for advancing sewage treatment in India. By providing a comprehensive analysis of these issues, this research will contribute to the development of more effective and context-specific solutions for improving water quality, protecting public health, and promoting environmental sustainability in India.

Based on the identified research gaps from the literature review chapter, I have formualted six potential research questions that broadly addresses the aim of the desearation, see *Table 3.1*.

__Table 3.1.__ Research questions and rationale along with dissertation themes mapping

Research Question	Rationale	Dissertation objective's theme
What are the primary technical, economic, environmental and managerial challenges hindering the optimal performance of existing sewage treatment plants (STPs) in India?	This question directly addresses the operational efficiency gap and seeks to identify the root causes of underperformance.	Challenges Theme
What are the social, economic, and policy barriers to the widespread adoption of sustainable sewage treatment practices (including resource recovery and reuse) in India, and how can these barriers be overcome?	This question addresses the systemic challenges to sustainability, focusing on the factors that hinder the transition to more environmentally sound practices.	Challenges Theme
How do different sewage treatment technologies compare in terms of their effectiveness,	This question tackles the technology choices aspect of your thesis, aiming to provide	Challenges and Technological

cost-effectiveness, and suitability for various contexts in India (e.g., urban vs. rural, industrial vs. domestic wastewater)?	a comparative analysis of different options.	Choices Themes
What are the key factors influencing the successful implementation and long-term sustainability of Decentralized Wastewater Treatment Systems (DEWATS) and Nature-Based Solutions (NBS) for sewage treatment in India?	This question delves into the sustainable strategies theme, exploring the practical considerations for adopting these approaches	Challenges, Technological Choices, and Sustainable Strategies Themes
How can circular economy principles be effectively integrated into sewage treatment strategies in India to promote resource recovery, reduce waste, and create economic opportunities?	This question explores the potential for transforming wastewater management into a circular system that generates value from waste.	Technological Choices and Sustainable Strategies Themes
What policy and governance frameworks are most effective	This question seeks to understand the role of	Challenges Theme

in promoting the adoption of advanced sewage treatment technologies and sustainable practices in India?	government and regulations in driving innovation and sustainability in the sector.	

3.2. Case Study Design

Padmini VNA (PVNA) Mechatronics Ltd. Sector 35 Plant is choosen as a a case study in advancing sustainable sewage treatment through technology adoption. PVNA, a plant located in Sector 35, is committed to sustainable operations and responsible water resource management. This case study examines PVNA's strategic initiative to upgrade its water treatment infrastructure. The primary objective of this upgrade is to significantly reduce water consumption, enhance the quality of treated water for various applications, and promote environmentally sustainable practices within the plant. This case study is particularly relevant in the context of India's growing need for advanced and sustainable sewage treatment solutions, as the country faces increasing water scarcity and environmental challenges.

3.2.1. Existing System

Existing Water Management System: Currently, PVNA relies on a combination of borewell water and a main water supply line to meet its daily water requirements, which average approximately 65KL. This water is treated to varying degrees for different applications, including drinking water, air handling units (AHU), cooling towers, kitchen usage, handwashing, and flushing. Wastewater, estimated at 50KL per day, is treated using a sewage treatment plant (STP) with a capacity of 50KL. The treated water is then discharged into a rainwater harvesting pit for regeneration. However, a significant portion of the treated water is disposed of in the drain due to high levels of total dissolved solids (TDS) and other mineral content, rendering it unsuitable for reuse in various applications. *Figure 3.1.* illustrates the existing water handling system at PVNA.

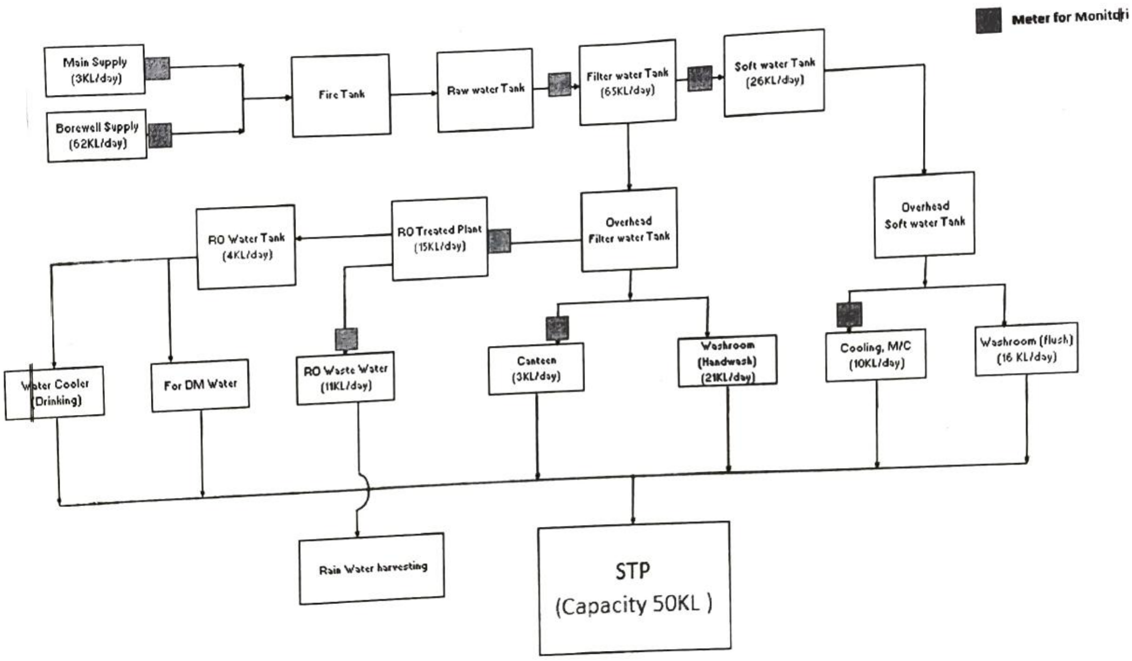


Figure 3.1. *Layout of water handling system at PVNA. (Used With Permission)*

3.2.2. Challenges with Exisitng System

Challenges with the Existing System: The existing water management system at PVNA faces several key challenges:

High TDS in STP Treated Water: The high TDS levels in the STP treated water limit its reuse potential, particularly for applications such as cooling towers, AHU, and gardening. As shown in *Table 3.2*, the TDS level in the STP outlet water is 1692 mg/L, which exceeds the acceptable limits for many reuse applications.

Low Recovery Rate of Existing RO System: The existing reverse osmosis (RO) system, used for producing drinking water, has a low recovery rate of approximately 27%. This means that for every 15KL of water processed, only 4KL of drinking water is generated, resulting in a significant amount of reject water.

Disposal of RO Reject Water: The RO reject water, with its high TDS concentration, is currently drained into the rainwater harvesting tank. This practice poses a potential threat to the quality of the harvested rainwater and limits its usability.

Acidic pH of Existing RO Water: The pH value of the existing RO water is less than or equal to 6, making it acidic and not recommended for drinking without further treatment.

Table 3.2. *STP outlet water test report*

Parameters	**Unit**	**Values (STP Treated Water)**
Source of Water		STP Treated water
Temperature	Deg C	Min-25 & Max. 28

Color		20
Odour		Not specified
pH @ 25 deg		7.33-8.51
TSS	PPM	15
COD	Mg/L	28
BOD at 27 Degree celsius	Mg/L	6.1
Oil & Grease	Mg/L	3
Turbidity	NTU	<1
Total Hardness as CaCo3	Mg/L	291
Iron as Fe	Mg/L	0.37
Chloride as Cl	Mg/L	521
Residual free Chlorine	Mg/L	<0.1
Calcium as Ca	Mg/L	58.2
Magnesium as Mg	Mg/L	34.9
TDS	Mg/L	1692
Sulphate as S04	Mg/L	81.8
Fluoride as F	Mg/L	0.64
Total Alkalinity as CaCO3	Mg/L	234
Chromium total (Cr)	Mg/L	<0.01
Hexa Chromium as CR+6	Mg/L	<0.01
Nitrate as NO03	Mg/L	28.3
Zinc as Zn	Mg/L	<0.01

Phenolic Compunds C6H5OH	Mg/L	0.001
Copper as Cu	Mg/L	<0.01
Mangnese as Mn	Mg/L	<0.01
Arsenic as As	Mg/L	<0.01
Aluminium as Al	Mg/L	<0.01
Cyanide as CN	Mg/L	<0.02
Lead as Pb	Mg/L	<0.01
Cadmium as Cd	Mg/L	<0.001
Nickel as Ni	Mg/L	<0.01
Mercury as Hg	Mg/L	0.001
Boron as B	Mg/L	<0.01
Sulphideas S	Mg/L	<0.1
Total Ammonia	Mg/L	<0.1
Anionic Detergents	Mg/L	<0.01
Sodium as Na	Mg/L	410
Total Caliform	MPN/100	500
E.Coli per 100 ml		Present

3.2.3. Problem Statement and Proposed Upgrades

The existing water management system at PVNA is unsustainable due to its high reliance on freshwater sources, the limited reuse of treated wastewater, and the generation of significant waste streams. There is a clear need for PVNA to adopt a more integrated and sustainable approach to water management that reduces its environmental footprint, conserves water resources, and promotes circular economy principles. To address the challenges outlined above, PVNA has proposed a comprehensive upgrade to its water treatment infrastructure.

The proposed solution involves the following key components:

Ultrafiltration (UF) System for STP Outlet Water: The installation of a UF system to treat the STP outlet water. This will reduce the TDS and other contaminants, making the treated water suitable for reuse in various applications. The proposed UF system is designed to treat 50 KLD of STP outlet water. The system will utilize a membrane-based filtration process to remove suspended solids, bacteria, and other contaminants, producing high-quality treated water suitable for reuse. PVNA considered several vendors for the UF system, including Wipro Water Solutions, Indian Ion Exchange Services, and Max Dew Chemicals. *Tables 3.3* and *3.4* provides the technical specifications of the UF systems along with the instruments to be used.

Table 3.3. *technical specification of standard UF model no. "WW UF 2500 LPH"*

Description	**Capacity**	**Moc**	**Qty**
Raw Water Storage Tank	-	-	By Client
UF Feed Pump	2.8 m3/h @ 3.0 mwc	CI	1 No.

UF Backwash pump	7.5 m3/hr @ 25 mwc	CI-CI	1 no.
UF Membranes – Dead End/Cross flow operation mode	50-55 LMH	PVDF	1 No
UF skid	Suitable	MSEP	1 no.
CEB Dosing Pump (HCl & NaOH)	0 – 5 LPH	PP	2 No.
CEB Dosing Tank (HCl & NaOH)	50 Ltrs	LDPE	2 No.
Softener with Manual MPV “WWSF_FRP2162”	533 mm Dia x 1575 mm Ht	FRP	1 No.
Resin	329 Ltr		
Brine Tank with ejector	HDPE 300 Ltr		
Treated Water tank	Suitable volume	Civil/FRP/LDPE	By Client
Pipes, Fittings & Valves	As per process requirement	UPVC	1 lot

Table 3.4. *Instruements used for UF model no.“WW UF 2500 LPH”*

Instruments	**Qty.**	**Location**
Rotameter	2	Inlet of UF, Outlet of Softener

Flow Transmitter	1	UF outlet line
Pressure Gauge (Local Gauges)	1 Lot.	Inlet & Outlet of Vessel, At the common discharge of pumps, Across UF system
Level Switch	1 Lot.	Dosing Tank

High-Recovery RO System for Drinking Water Production: The procurement of a new RO system with a high recovery rate (75%) to improve the efficiency of drinking water production and reduce the volume of reject water. The proposed RO system will have a capacity of 1000 LPH and a recovery rate of 75%. This will significantly improve the efficiency of drinking water production compared to the existing RO system. The RO system will also include a pH correction system to ensure that the drinking water meets the required quality standards. PVNA considered several vendors for the RO system, including Wipro Water Solutions, Indian Ion Exchange Services, and Max Dew Chemicals. *Tables 3.5* and *3.6* provides the technical specifications of the UF systems along with the instruments to be used.

Quadsun Evaporator for Handling RO Reject Water: The installation of a Quadsun Evaporator to evaporate the RO reject water, eliminating the need for disposal and further reducing the environmental impact. The Quadsun Evaporator is designed to evaporate the RO reject water, reducing its volume and eliminating the need for disposal. The evaporator will utilize a multi-stage evaporation process to maximize efficiency and minimize energy consumption.

Table 3.5. *Technical specification of standard RO model no.“1000 LPH RO-Q-STD”*

Description	**Capacity**	**Moc**	**Qty**
PRE-TREATMENT			
Raw Water Storage Tank	-	-	By Client
Filter Feed Pump	1.5 m3/h @ 30 mwc	CI	1w+1s
Media Filter with Manual MPV, First fill of Media & Frontals “WWPSF_FRP1354”	335 Dia x 1375 Ht(mm)	FRP	1 No.
RO PLANT			
Antiscalent Dosing Pump	0 – 5 LPH	PP	1 No.
Antiscalent Dosing Tank	50 Ltrs	HDPE/LDPE	1 No.
Cartridge Filter	1.4 m3/h @ 5 microns	Spun – PP	1 No.
High Pressure Pump	Suitable m3/hr @ 12 bar	CI casing, SS304 impeller	1 No.
RO Membranes	4" membranes	PA	1 lot
Pressure tubes	4" Pressure tubes	FRP	1 set
RO skid	-	MSEP	1 No.
RO Permeate Water Storage Tank	Suitable	SS/LDPE	By Client

pH Correction Dosing Pump	0 – 3 LPH	PP	1 No.
pH Correction Dosing Tank	50 Ltrs	HDPE/LDPE	1 No.
INTER CONNECTING PIPING			
Pipes, Fittings & Valves	As per process requirement	UPVC	1 lot

Table 3.6. *Instruements used for RO model no.“1000 LPH RO-Q-STD”*

Instruments	**Qty.**	**Location**
Rotameter	2	Inlet of filter, RO Reject Recycle
Flow Transmitter	1	RO Permeate Line
Pressure Gauge (Local Gauges)	1 Lot.	Inlet & Outlet of Vessel, Across RO, RO Reject
pH/ Conductivity Meter	1	RO Outlet
ORP meter	1	RO inlet header.

3.2.4. Investment Cost of Proposed Upgrades

The total investment for upgrading PVNA's water treatment infrastructure, based on the Wipro proposals, amounts to INR 17,21,880. This includes INR 7,07,540 for the 1000 LPH RO system and INR 10,14,340 for the 2500 LPH UF system. The costs encompass the base price of the equipment, an 18% Goods and Services Tax (GST), transportation charges, and transit insurance. It's crucial to note that these figures represent the direct costs of system procurement and do not account for additional expenses outlined in the “List of Exclusions”, such as civil foundation work, raw water storage tanks, and operational costs. *Table 3.7* summariese the cost and *Table 3.8* gives the detailed cost including the GST.

Table 3.7. *Investment cost of proposed RO and UF systems at PVNA's STP without GST.*

System	**Base Cost (INR)**	**Transportation (INR)**	**Transit Insurance (INR)**	**GST (18%)**
RO System	5,53,000	52,000	3,000	Extra on base cost
UF System	8,13,000	52,000	3,000	Extra on base cost

Table 3.8. *Investment cost of proposed RO and UF systems at PVNA's STP with 18% GST.*

System	**Base Cost (INR)**	**GST (INR)**	**Transportation (INR)**	**Transit Insurance (INR)**	**Total Cost (INR)**
RO System	5,53,000	99,540	52,000	3,000	7,07,540
UF System	8,13,000	1,46,340	52,000	3,000	10,14,340

3.3. Method-methods Approach

Here, to understand and explore solutions for the research questions, I applied a mixed method approach where used the methods like life cycle assessment (LCA) to understand the carbon mitigation potential, technol-economic assessment (TEA) to understand the cost of wastewater treatment, groundwater and energy savings numerical assessment to understand the reduced groundwater dependeny due to wastewater treatment promotion and the energy savings from the water extraction from the ground watertable. In below subsections, the individual methods how I applied were briefly explained.

3.3.1. Life-cycle assessment (LCA)

LCA is a decision support tool capable of providing the decision maker with an evaluation of the environmental performance of a product or service as e.g. water supply systems. Internationally LCA is being used to assess the environmental impacts of water systems e.g. to aid a decision on choosing between several technologies for water supply. The application of LCA to water systems is still developing as these systems are rather complex and the LCA must cover all relevant environmental impact categories. This desertation employs LCA as per the *Figure 3.2*, a rigorous and standardized methodology (ISO 14040 series), to evaluate the environmental impacts associated with the implementation of RO and UF systems at Padmini VNA Mechatronics.

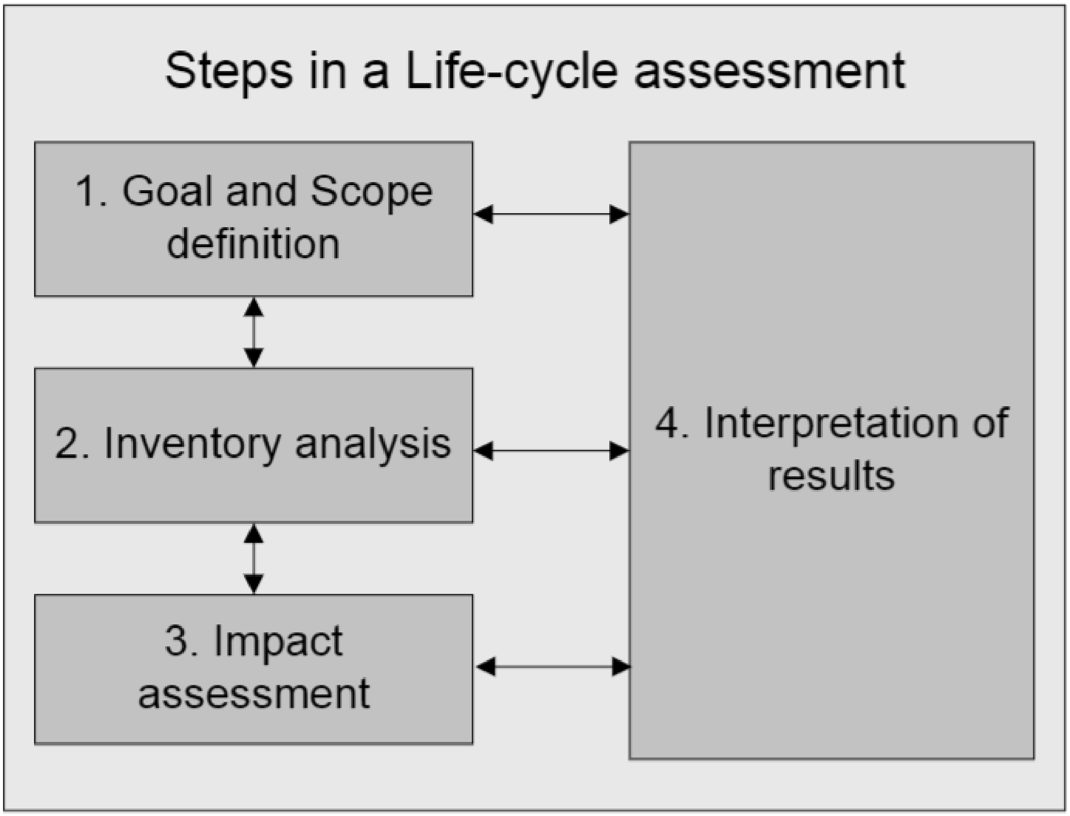


Figure 3.2. *Steps in Life-cycle assessment (modified according to ISO, 2006).*

By encompassing all stages from system component manufacturing to operation and potential end-of-life, the LCA framework provides a holistic understanding of the environmental burdens. The study aims to quantify key impact categories, including global warming potential, eutrophication potential, and resource depletion, to identify environmental hotspots and inform sustainable decision-making regarding wastewater management strategies at PVNA. The findings will contribute to a more comprehensive understanding of the environmental trade-offs associated with different treatment technologies and provide valuable insights for optimizing the sustainability of industrial water management practices.

3.3.2. Techno-economic Assessment (TEA)

TEA based on an equivalent uniform annual cash flow (EUAC) is more advisable (). This is because the goal is to estimate the service cost, and EUAC is a method of calculating the total cost of a project over its lifetime, considering both initial and ongoing costs.

The lifecycle costing approach will involve the following steps:

- Identify all the costs associated with water treatment systems
- Calculate the present value of all the costs. This can be done by discounting the future costs to their present value, using a discount rate that reflects the time value of money.
- Calculate the EUAC by dividing the present value of the costs by the number of years over which the costs will be incurred.
- The results of the life cycle costing analysis will provide information on the cost-effectiveness of water treatment systems. This information can be used to make decisions about whether to implement the system, and about the best way to implement it.

Eq. (3.1) represents the generic model for life cycle costing.

$$Life\ Cycle\ Costing\ = Capital\ Cost + Recurring\ Costs - Residual\ Value \quad (3.1)$$

From Eq. (3.1), the recurring costs are the operations and maintenance costs associated with the water treatment plant. However, in the context of the advanced water treatment plants, there is a need for an additional cost component, and in some cases water disposal costs to be estimated especially to know the cost benefits of using wastewater plant; considering this cost, the recurring cost can be estimated as shown in Eq. (3.2).

$$Recurring\ Costs = \ Lifetime\ Operations\ Cost + Lifetime\ Maintenance\ Costs + \ Disposal\ Costs \tag{3.2}$$

Up on substituting Eq. (3.2) in Eq. (3.1), and by taking the principles of economics on present value, the overall life cycle costing can be represented as Eq. (3.3)

$$Life\ Cycle\ Costing\ = Capital\ Cost + Present\ Value\ of\ Lifetime\ Operations\ Cost + Present\ Value\ of\ Lifetime\ Maintenance\ Costs + Present\ Value\ of\ Disposal\ Costs - Present\ Value\ of\ Residual\ Value \tag{3.3}$$

The LCC calculation involves the following steps:

- Determination of costs and cash flows over the system life or considered time frame.
- Determination of an appropriate real interest or discount rate(s).
- Calculate a discounting factor for each year over the system life; the discount factor is given in Eq. (3.4):

  $$DF_t = \left\{\frac{1}{(1+i)^n}\right\} \tag{3.4}$$

  where i is the discount rate, and n is the number of years.

- For each year's cash flows, sum all incomes and expenses to determine the net cash flow for that year in nominal terms.
- Multiply each year's net cash flow by the appropriate discount factor.
- Sum the discounted net cash flows to derive the net present value.
- Estimate the life cycle cost.

The LCC analysis allows us to evaluate between investments by summing the present value of all future incomes and expenses, but that does not give us an insight into the expected cash flows that will occur. A common engineering cost approach for this evaluation is the equivalent uniform annual cash flow (EUAC) approach. The EUAC thus provides consistency in the cost analysis, see Eq. (3.5).

$$EUAC = LCC \times \frac{i(1+i)^{n}}{(1+i)^{n-1}} \quad (3.5)$$

The LCC method described above is leveraged to wastewater treatment systems that are discussed earlier; see Eq. (3.6).

$$LCC = CapEx_{C} + \left\{\frac{i\times(i+1)^{n}}{(i+1)^{n}-1} \times OpEx_{C}\right\} - \left\{\frac{i}{(i+1)^{n}-1} \times RV_{C}\right\} \quad (3.6)$$

where $CapEx_{C}$ is the sum of the capital cost of the infrastructure in a region c; $OpEx_{C}$ is the operational and maintenance costs in a region c; and RV_{C} is the residual value in a region c.

Based on system descriptions provided earlier, the data required for the LCC model as per the model described above were collected. We built the LCC model in excel based on the modelling Eqs. (3.1) to (3.6) for understanding the economic feasibility. The individual cost components we considered for the LCC approach are as follows.

- Capital Cost: It is either the purchase price of an item or the initial cost of the set-up in the case of a project. In most cases, it also includes the cost of installation.
- Recurring Cost: It represents all those costs after the purchase which primarily include operating and maintenance expenses.
- Operations Cost: These costs are associated with the usage of the assets, for example, energy, chemicals, membrane and other related consumables.
- Maintenance Cost: These costs are associated with repair and replacement expenses.
- Disposal Cost: These costs are incurred at the time of asset disposal, for example, landfilling.
- Residual Costs: These represent the asset's value at the end of its useful life.

3.3.3. Ground Water Savings

Allowing groundwater extraction only when the used water is not treated. Using Eq. (3.7), the required groundwater extraction can be estimated after accounting for reducing water consumption (Kumar and Chopra, 2021).

$$GW = W - RW \qquad (3.7)$$

Where GW is the groundwater to be extracted after discounting the rainwater and water consumption reduction due to shading effect [Liters]; W is the water required [Liters];

3.3.4. Energy Savings

The energy consumption for extracting and pumping water can be estimated using Eq. (3.8).

$$EC_{GW} = \frac{m_{GW} \times g \times h}{3.6 \times 10^6 \times \eta_p \times (1 - E_{t\&d\ loss})} \tag{3.8}$$

where EC_{GW} is the energy consumption for extracted groundwater [kWh]; m_{GW} is the mass of the groundwater to be extracted, g is the acceleration due to gravity [m/s^2]; h is the total dynamic head considering the water table height (assumed as 100 m), pumping height [m], drawdown (can be assumed as 3 m), and the friction losses as 15%. (Kumar and Chopra, 2021)

3.4. TESEI Analytical Framework

To provide a structured and comprehensive approach to analyzing the complexities of sewage treatment in India, this research introduces the TESEI analytical framework. This framework, encompassing five key dimensions – Technological, Economic, Social, Environmental, and Institutional – and their associated sub-factors, offers a holistic lens through which to examine the challenges, technology choices, and sustainable strategies for advancing sewage treatment. The dimensions and factors incorporated within TESEI were carefully selected based on an extensive review of existing literature, the identified research gaps, preliminary insights gleaned from the designed case study, and opinions from experts in the field. As shown in Figure 3.3, by integrating these diverse perspectives, the TESEI framework aims to facilitate a nuanced understanding of the multifaceted issues at play and inform the development of effective and sustainable solutions.

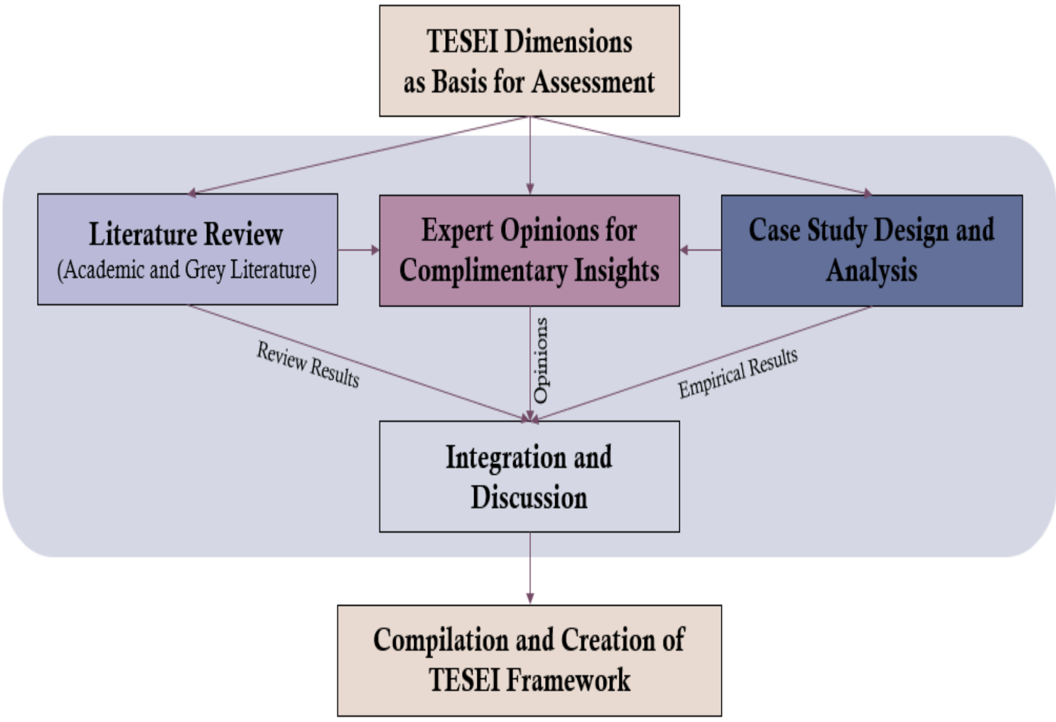


Figure 3.3. *Applying TESEI Analytical Framework*

Figure 3.3, illustrates a research approach centered around the development of a TESEI Framework for advancing sewage treatment in India. The process begins with "TESEI Dimensions as Basis for Assessment", which informs three parallel research streams: a "Literature Review" encompassing academic and grey literature as a data, gathering “Expert Opinions for Complimentary Insights”, and “Case Study Design and Analysis”. The literature review yields “Review Results”, expert consultations provide “Opinions”, and the case study generates “Empirical Results”. These three streams converge in an “Integration and Discussion” phase, where the findings are synthesized. Finally, this integrated understanding leads to the “Compilation and Creation of TESEI Framework”, representing the culmination of the research effort.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents the results obtained from three streams along with a discussion focusing on the challenges, technolgy choices available and sustainable strategis as per the TESEI analytical framework shown in *Figure 3.3.*

4.1. Analysis of Sewage Treatment Plants in India

The first set of results are based on the literature review, which would allow us to understand the sewage treatment in India in her states and UTs. The analysis of data obtained from literature review (as per section 2.1 of the chapter 2) are carried out with respect to installed capacity, operational capacity, actual utilization and technological adopted along with compliance status. Overall India wise sewage treatment plant summary can be seen in *Figure 4.1*. Also, the state-wise sewage generation and treatment capacity of urban centers-India is tabulated in *Table 4.1*.

Sewage generation estimated to 72,368 MLD whereas installed treatment capacity is 31841 MLD (43.9 %). Out of 31,841 MLD installed capacity developed, operationalized capacity is 26,869 MLD (84 %). Similarly, actual utilized capacity is 20,235 MLD (75 %) out of 26,869 MLD operational capacity. This is due to lack of infrastructure for conveyance system (Household connectivity, sewer lines, Sewage pumping stations). STPs based on various treatment technologies are installed by the States which ranges from conventional to advanced technologies. STPs based on

Sequential Batch Reactor (SBR) treatment technology are installed and predominate in most of the States / UTs.

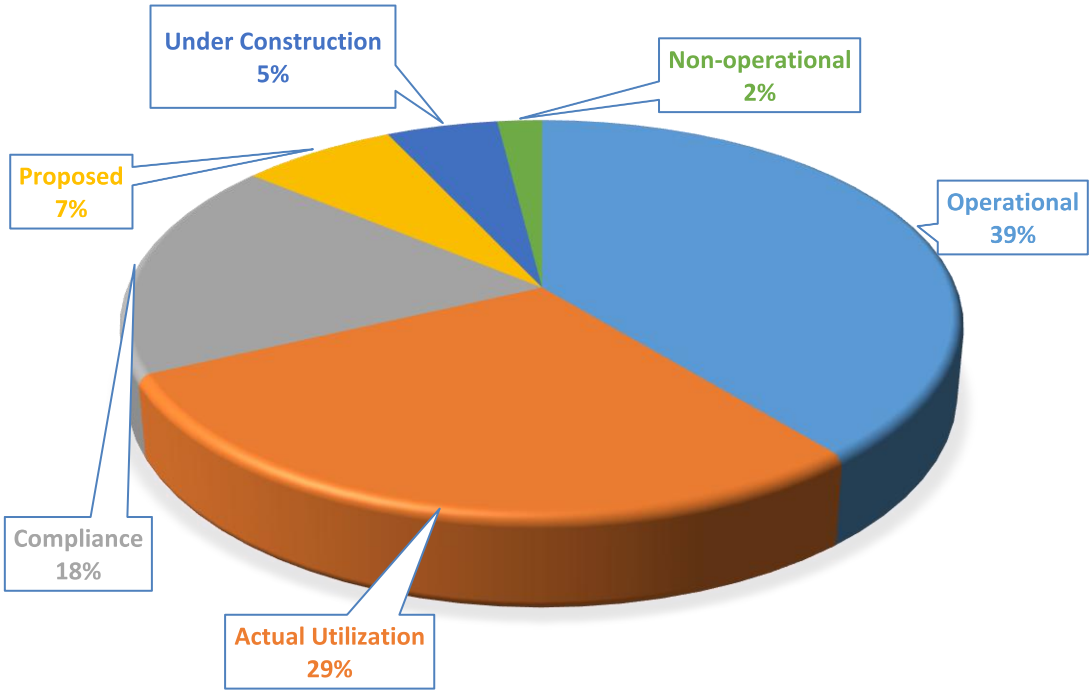


Figure 4.1. *Status-wise capacity of STPs in India. (Data Source:CPCB, 2021)*

This is followed by ASP technology based STPs. In total, 490 STPs are designed on SBR technology followed by 321 STPs designed on Activated Sludge Process (ASP). 76 STPs are based on Upflow- Anaerobic Sludge Blanket (UASB) technology. Apart from conventional treatment technologies, STPs based on natural treatment systems are also established all over the country. 67 STPs are based on Waste Stabilization Pond system and 61 STPs belong to the category of Oxidation Ponds. States of Maharashtra, Gujarat, Uttar Pradesh, NCT of Delhi and Karnataka are the top 5 States which have installed significant sewage treatment facilities. These 5 States jointly contribute to 19, 250 MLD i.e. 60.5 % of the total installed treatment capacity of the country. In addition to the above ones, States of Haryana, Madhya Pradesh, Punjab,Tamil Naduand Rajasthan i.e. these 10 States contribute to the tune of 86 % (approx..) towards total installed treatment capacity. Arunachal Pradesh, Andaman & Nicobar Islands, Lakshadweep, Manipur, Meghalaya and Nagaland have not installed sewage treatment plants. 08 States / UTs (Gujarat, Himachal Pradesh, Kerala, Pondicherry, Sikkim, Chandigarh, Chhattisgarh, Madhya Pradesh) has not provided the status of compliance. Considering, treatment capacity developed per capita, Chandigarh (240 lpcd), Haryana (184 lpcd), NCT of Delhi (151 lpcd), Punjab (141 lpcd) and Maharashtra (115 lpcd) have higher treatment capacity. 29 States / UTs have treatment capacity of less than 100 lpcd. State of Maharahtra has highest installed treatment capacity as well as highest complied treatment capacity. However, per capita installed capacity is maximum observed in UT of Chandigarh (240 lpcd) whereas Maharashtra is having per capita treatment capacity of 115 lpcd. State of Haryana has the maximum complied per capita treatment capacity (142 lpcd) whereas Maharashtra is having complied per capita treatment capacity of 58 lpcd. NCT of Delhi has the fourth highest treatment capacity of 2896 MLD and per capita treatment capacity is 151 lpcd (3rd highest) wheres complied treatment capacity is only 4 lpcd.

Table 4.1. *State-wise sewage generation and treatment capacity of urban centers-India. (Source: CPCB, 2021)*

States/UTs	**Sewage Generation (in MLD)**	**Installed Capacity (in MLD)**	**Proposed Capacity (in MLD)**	**Total Treatment Capacity (in MLD) including planned/proposed**	**Operational Treatment Capacity (in MLD)**
Andaman & Nicobar Islands	23	0	0	0	0
Andhra Pradesh	2882	833	20	853	443
Arunachal Pradesh	62	0	0	0	0
Assam	809	0	0	0	0
Bihar	2276	10	621	631	0
Chandigarh	188	293	0	293	271
Chhattisgarh	1203	73	0	73	73

Dadra & Nagar Haveli	67	24	0	24	24
Goa	176	66	38	104	44
Gujarat	5013	3378	0	3378	3358
Haryana	1816	1880	0	1880	1880
Himachal Pradesh	116	136	19	155	99
Jammu & Kashmir	665	218	4	222	93
Jharkhand	1510	22	617	639	22
Karnataka	4458	2712	0	2712	1922
Kerala	4256	120	0	120	114
Lakshadweep	13	0	0	0	0
Madhya Pradesh	3646	1839	85	1924	684
Maharashtra	9107	6890	2929	9819	6366
Manipur	168	0	0	0	0
Meghalaya	112	0	0	0	0
Mizoram	103	10	0	10	0
Nagaland	135	0	0	0	0
NCT of Delhi	3330	2896	0	2896	2715

Orissa	1282	378	0	378	55
Pondicherry	161	56	3	59	56
Punjab	1889	1781	0	1781	1601
Rajasthan	3185	1086	109	1195	783
Sikkim	52	20	10	30	18
Tamil Nadu	6421	1492	0	1492	1492
Telangana	2660	901	0	901	842
Tripura	237	8	0	8	8
Uttar Pradesh	8263	3374	0	3374	3224
Uttarakhand	627	448	67	515	345
West Bengal	5457	897	305	1202	337
Total	*72368*	*31841*	*4827*	*36668*	*26869*

4.2. Challenges the Sewage Treatment Plants Facing in India

Several states face a significant treatment gap, requiring substantial investment in new infrastructure (Odisha, Rajasthan, Tamil Nadu, Telangana, Tripura, Uttar Pradesh, West Bengal). Many states also struggle with low complied capacity despite having operational STPs, raising concerns about treatment effectiveness and compliance (Delhi, Punjab, Rajasthan, Uttar Pradesh, West Bengal). Underutilization of existing capacity is another key challenge (Puducherry, Uttarakhand), indicating inefficiencies in operation or conveyance. Additionally, some states require capacity expansion to meet growing needs (Mizoram, Sikkim). Finally, there are unique challenges such as reliance on septic tanks (Meghalaya, Nagaland) and non-operational STPs (Mizoram), necessitating specific research and interventions. In *Table 4.2*, selected states current situation and the observed challenges along with future research focus is shown.

Table 4.2. *Current situation and the observed challenges along with future research focus*

<table>
<tr><th>State & UTs</th><th>Situation</th><th>Observed Challenge and Future Focus</th></tr>
<tr><td>Meghalaya</td><td rowspan="2">Reliance solely on septic tanks necessitates research on their effectiveness, longevity, and environmental impact.</td><td rowspan="2">Investigate the feasibility and cost-effectiveness of centralized treatment options.</td></tr>
<tr><td>Nagaland</td></tr>
<tr><td>Mizoram</td><td>The non-operational STP requires immediate investigation and action.</td><td>Research should focus on the reasons for its failure and strategies for long-term operational sustainability. Significant capacity expansion is also needed.</td></tr>
<tr><td>Delhi</td><td>Despite high installed capacity, the low complied capacity raises concerns</td><td>Research should focus on improving compliance and exploring alternative treatment technologies.</td></tr>
</table>

	about treatment effectiveness.	
Odisha	The large treatment gap requires significant investment in new infrastructure.	Research should investigate optimal treatment technologies and locations for new STPs.
Puducherry	While all installed STPs are operational, actual utilization is low.	Research should explore the reasons for underutilization and strategies for maximizing treatment capacity.
Punjab	The gap between operational and complied capacity needs to be addressed.	Research should focus on optimizing existing treatment processes and improving compliance.
Rajasthan	The significant treatment gap and low complied capacity	Necessitate substantial investment and research into appropriate technologies and strategies for expanding treatment coverage.
Sikkim	While operational efficiency is high, the limited installed capacity needs to be expanded.	Research should focus on optimizing capacity expansion plans and ensuring long-term sustainability.

Tamil Nadu	The large treatment gap requires substantial investment.	-Research should investigate the effectiveness of existing treatment technologies and explore alternative solutions. -The discrepancy in complied capacity data needs clarification.
Telangana	The significant treatment gap and relatively low complied capacity	Require investment in both expanding and upgrading treatment infrastructure.
Tripura	The extremely limited treatment capacity necessitates urgent investment in new infrastructure.	Research should focus on appropriate technologies and strategies for rapidly expanding treatment coverage.
Uttar Pradesh	The substantial treatment gap and lower complied capacity	Require significant investment and research into optimizing treatment processes and improving compliance.
Uttarakhand	The underutilization of operational capacity needs to be addressed.	Research should focus on optimizing operational practices and improving sewage conveyance systems.

West Bengal	The massive treatment gap, low operational rates, and limited complied capacity	Require substantial investment and research into appropriate technologies and strategies for expanding treatment coverage.

Figure 4.2 shows which challenge is the major one and how many states or UTs are facing. Also, a detailed list of challenges explored compiled under TESEI framework is shown in *Table 4.3.*

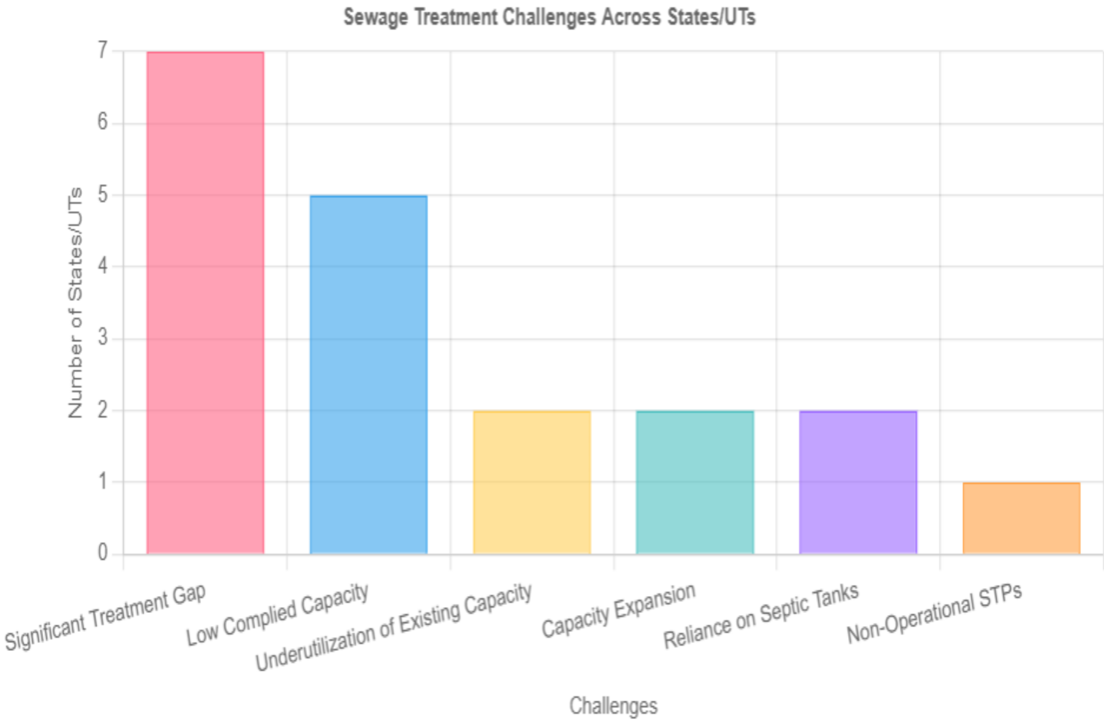


Figure 4.2. *Key challenges for STPs identified in Indian states and UTs.*

Table 4.3. *Key challenges Indian STPs facing categoriesed as per TESEI analytical framework*

Category	**Challenge**
	Population growth
	Urbanization
	Increasing water demand
	Limited freshwater resources
	High reliance on traditional water sources
	Water scarcity
	Conflicting demands for shared water resources
	Public health
	Complexity in governance
Social	Industrialization
	Water supply access and security
	Migrating population
	Political and management stagnation
	Social status and water use variability
	Public acceptance variability
	Changes in land use
	External drinking water & privatization
	Interstate water conflicts
	Low willingness to pay

	Poor sanitation hygiene
Technical	Aging infrastructure
	Increasing system complexity
	Inadequate water distribution system
	Leakages and failures of water systems
	Water data
	Capacity constraints
	Maintenance and performance issues
	Intermittent water supply
	Pumping water over long distance
Environmental	Climate shifts
	Drought
	Flooding
	Water quality degradation
	Environmental degradation
	Over exploitation of water resources
	Ecological condition of receiving water
	Urban low flow condition
	Insufficient wastewater treatment
	System emissions
Economic	Economic growth and high living standards
	Resources expenditure constraints

	Difficulties in financing the aging infrastructures
	Non-revenue water
Institutional	Lack of clear mandates and coordination
	Inadequate regulatory framework
	Limited institutional capacity
	Poor monitoring and evaluation
	Lack of community participation
	Corruption and lack of transparency
	Political interference

4.3. Technology-wise Capacity Distribution of STPs

The sewage treatment sector exhibits a diverse range of technologies, with a total installed capacity of 36,180 MLD. Sequencing Batch Reactors (SBR) lead in both capacity (10,638 MLD, 29.4%) and number of plants (490), closely followed by Activated Sludge Processes (ASP) with 9486 MLD (26.2%) and 321 plants. A significant portion, 8497 MLD (23.5%) across 364 plants, falls under the "Any Other" category, suggesting a need for further investigation into the specific technologies employed. Upflow Anaerobic Sludge Blanket (UASB) contributes a notable 3562 MLD, but with only 76 plants, indicating larger individual plant capacities. Technologies like EA, FAB, WSP, and OP represent smaller fractions of the overall capacity. The dominance of SBR and ASP warrants further exploration into their cost-effectiveness and performance, while a deeper understanding of the "Any Other" category is crucial for a comprehensive assessment of the sector. *Table 4.4.* Technolgical distribution with respect to number and capacity of STPs.

Table 4.4. *Technolgical distribution with respect to number and capacity of STPs. (Source: CPCB, 2021)*

Technology	**Capacity in MLD**	**Number of STPs**
ASP	9486	321
EA	474	30
SBR	10638	490
MBBR	2032	201
FAB	242	21
UASB	3562	76
WSP	789	67
OP	460	61
Any Other	8497	364

When it comes to % distrutuon of technology (see *Figure 4.3.*), SBR (Sequencing Batch Reactor) is the most prevalent treatment technology, accounting for 29% of the pie chart. ASP (Activated Sludge Process) is the second most common, representing 26%. A significant portion (24%) falls under the category of “Any Other” which suggests a diversity of treatment approaches or a lack of specific data for those technologies. UASB (Upflow Anaerobic Sludge Blanket) accounts for a notable 10%. The remaining technologies (MBBR, WSP, EA, OP, and FAB) each represent a relatively small percentage of the total. Based on the literature data, *Table 4.5*. describes the scale merit of ASP.

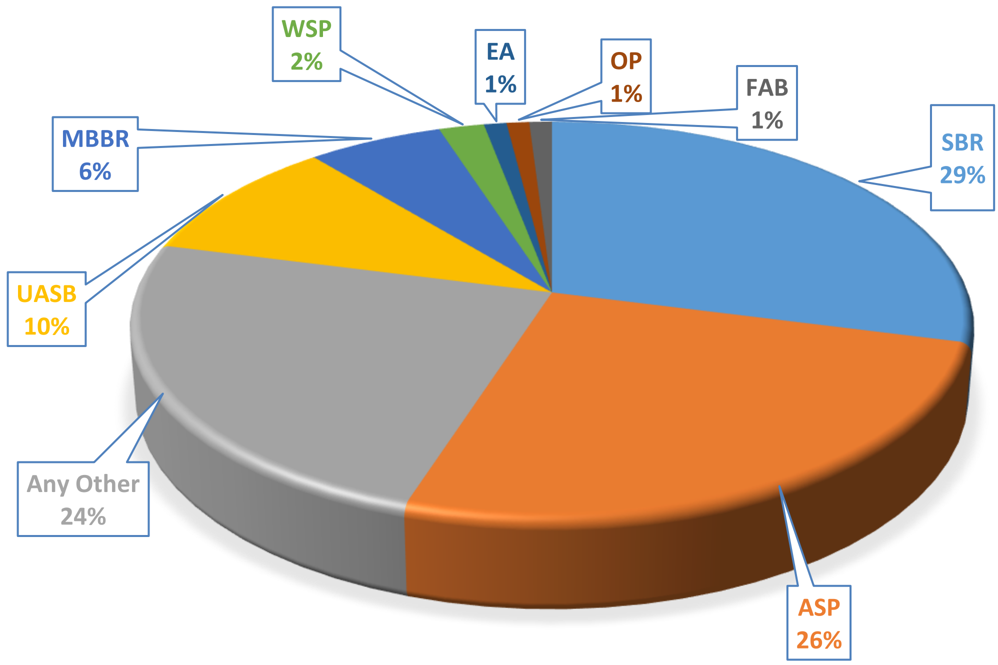


Figure 4.3. *Technology-wise capacity distribution of STPs. (Data Source:CPCB, 2021)*

Table 4.5. *Summary of capital and annual O&M cost, and land requirement for UASB, WSP, and ASP. (Source: Sato et., 2007)*

Process	**Treatment volume (m^3/d)**	**Capital cost (US$/$m^3/d$)**	**Land requirement ($m^2/m^3/d$)**	**Annual O&M cost (US$/$m^3/d$)**
UASB	36,000	441	14	20
UASB+pond	20,000–400,000	34.7–45.6	1.70–1.98	NA
UASB+pond	NA	68.5–85.6	1.1–1.7	NA
WSP	20,000–400,000	12.4–18.0	12.5–14.0	NA
WSP	NA	25.7–34.3	5.6–15.6	NA
ASP	2150	186	9.5	47
ASP	20,000–400,000	50.0–60.8	0.73–1.01	NA
ASP	NA	102.8–119.9	1.1–1.4	NA

Note: NA means not applicable

4.4. Insights from Adoption of Advanced Teritiary Treatment in STPs.

With cities expanding rapidly and sewage production on the rise, closing the current gap in sewage treatment is critical, as is anticipating future treatment demands. Since existing facilities are only operating at 75% of their potential, improving the network for transporting sewage—including installing more sewer lines and connecting homes—is vital to handle current and projected needs. Moreover, given that only 23% of treated sewage meets the quality standards set by state pollution regulators, better operation and upkeep of treatment plants are essential to achieve the required purification levels. Local governments should prioritize using treated sewage for non-drinking purposes like watering plants, irrigating land, fighting fires, cooling industrial equipment, flushing toilets, and cleaning surfaces. Supplying treated sewage to industrial areas for their further processing and reuse should also be a priority. The case study that is designed also falls under this. It is observed that, most of the STPs in India use primary and secondary stage of treatment, only a minor share is falling under teritiary. However, inorder to understand how this transition woud help, I analysed the designed case study results following the mixed methods approach I disussed earlier.

4.4.1. Expected Benefits to the PVNA

The proposed upgrades resulted in significant benefits as shown in *Tables 4.6* and *4.7* for PVNA. These benefits includes:

Reduction in Daily Borewell Water Consumption: The installation of the UF and RO systems is projected to reduce the daily borewell water consumption from 81kL to 44kL, a reduction of approximately 46%.

Increased Reusability of Treated Water: The UF system will enable the reuse of STP treated water for various applications, including cooling towers (12 KLD), flushing (16 KLD), gardening (6 KLD), and AHU (15 KLD).

Elimination of RO Reject Water Disposal: The Quadsun Evaporator will eliminate the need to dispose of RO reject water, preventing potential contamination of the rainwater harvesting system and reducing the overall environmental impact.

Table 4.6. *Reduction in fresh water consumption using UF Plant to treat STP water*

Application	Present fresh water consumption (in KL)	Water from UF plant (in KL)	Total fresh water saved (in KL)
Cooling Tower	8-12	12	0
Handwash, Hand faucet	23	-	0
Flush	16	16	16
Canteen	3	-	-
Gardening	0	6	6
AHU	0	15	15
Total	65	49	37

Table 4.7. *Reduction in waste water generation in RO plant*

Description	Exisitng scenario				New RO scenario		
	Inlet (in KL)	**Present water consumption (in KL)**	**Wastewater generated (in KL)**	**Handling method**	**Inlet (in KL)**	**Waste water generated (in KL)**	**Total water saved (in KL)**
RO	15-22.5	4-6	11-16.5	Drain in rain water harvesting pit	5.3-8	1.3-2	9.7-14.5

4.4.2. Life Cycle Assessment Results

Life cycle assessmens considering the 16 impact categories as per ReCiPe Midpoint (H) method following the ISO guidelines were carried out, the methodological approach followed here was already explained in Chapter 3. The functional unit is 1 m^3 of water treated for wastewater treated in STP, 1m^3 non-drinakbale water treated in UF and RO plants, 1m^3 tapwater extracted from the groundwater table, and 1 kWh for the electricity drawn from northern grid. Observed results are shown in *Figures 4.4. to 4.7.*

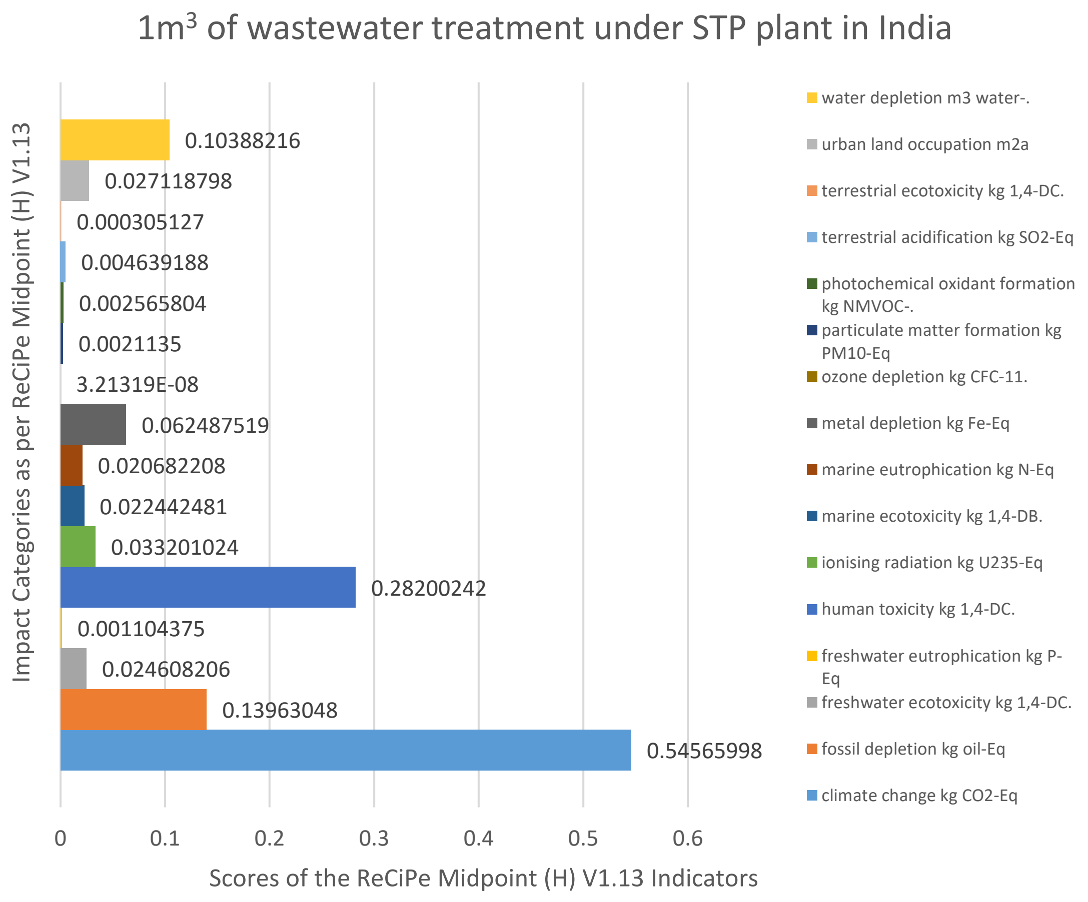


Figure 4.4. *Life cycle assessment results showing the 16 impact categories as per ReCiPe Midpoint (H) method for 1 m^3 of wastewater treated.*

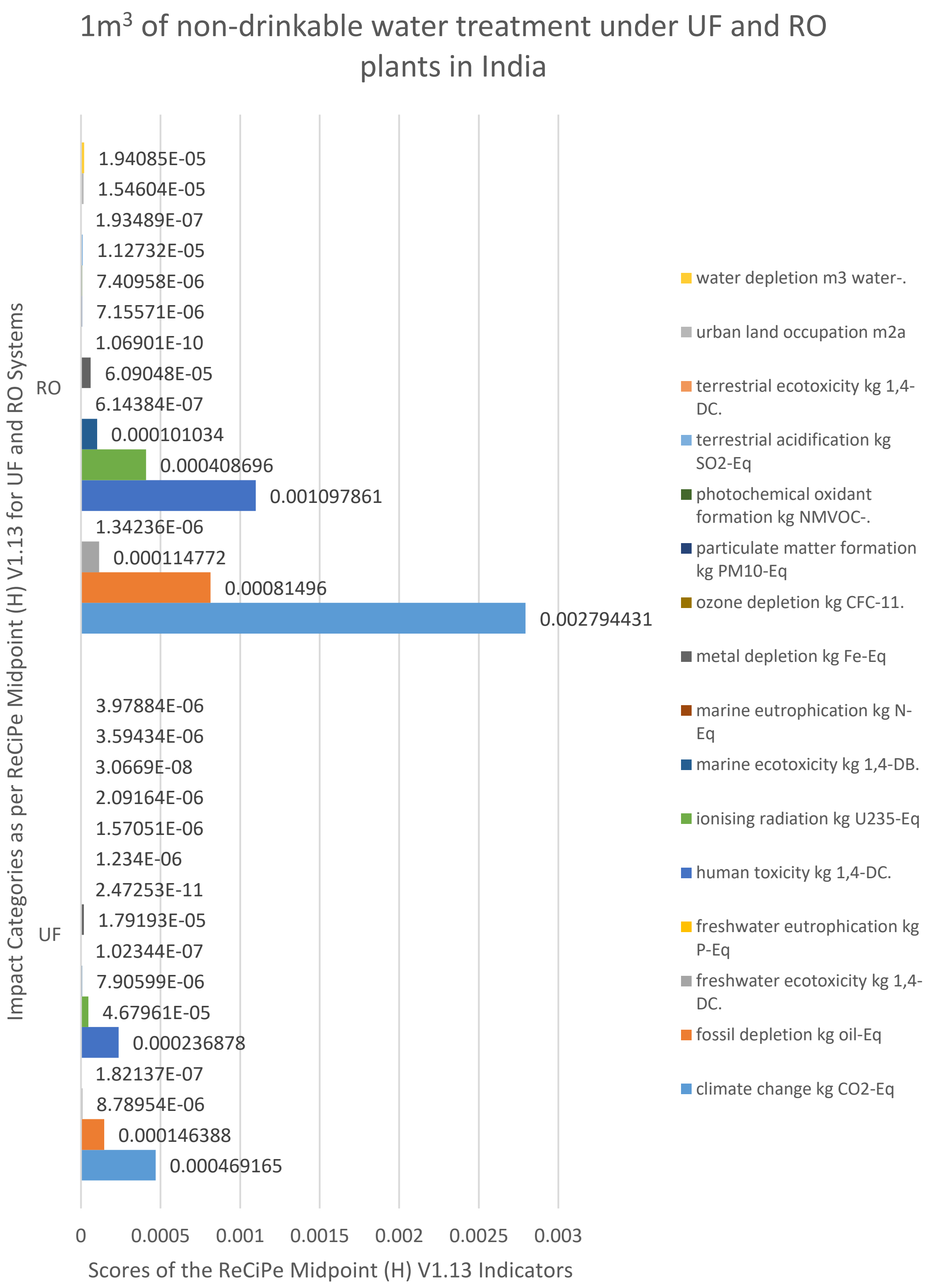


Figure 4.5. *Life cycle assessment results showing the 16 impact categories as per ReCiPe Midpoint (H) method for 1 m3 of non-drinkable wastewater treated.*

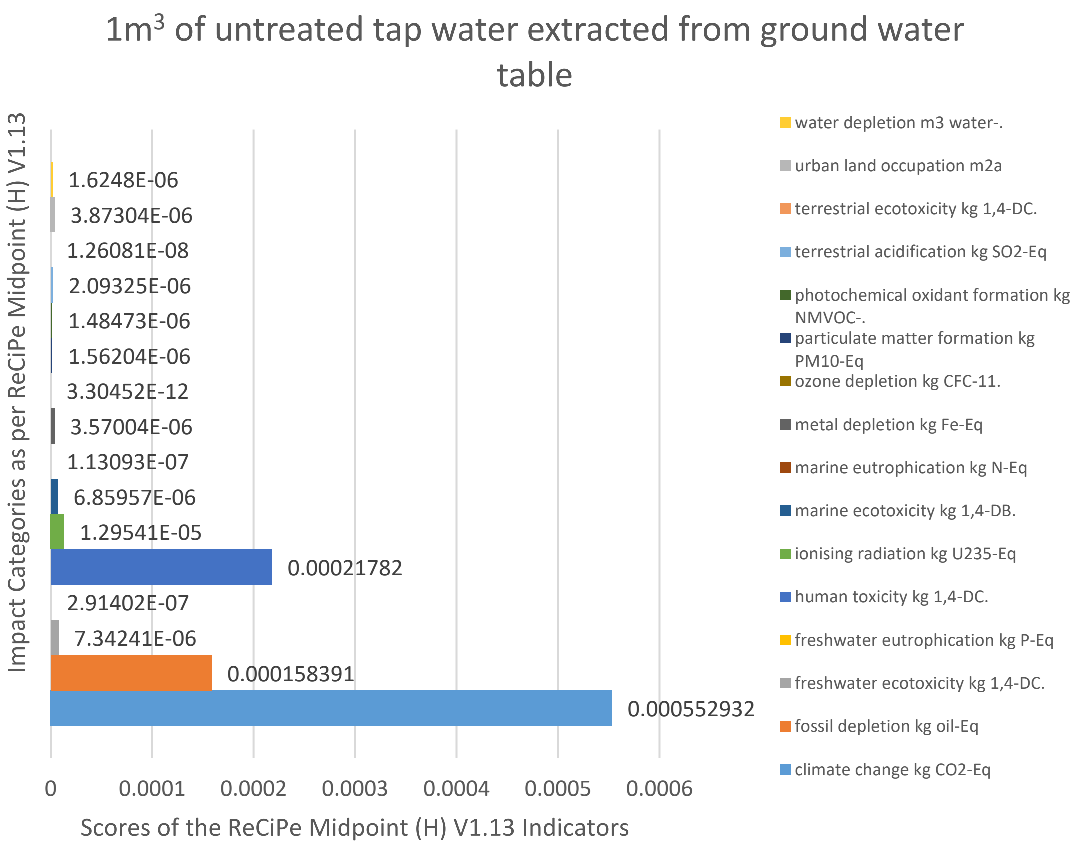


Figure 4.6. *Life cycle assessment results showing the 16 impact categories as per ReCiPe Midpoint (H) method for 1 m3 of untreated tap water extracted from the ground water table.*

The observed results from Figures 4.4. to 4.5 suggests that climate change impacts i.e., the carbon dioxide equvilent greenhouse gas release from treating 1 m^3 of wastewater in STP is 0.5456 kgCO2-Eq., 1 m3 of water treated in UF is 0.0004691 kgCO2-Eq., and 1 m3 of water treated in RO is 0.002794 kgCO2-Eq. Also, the tapwater (untreated) would release around 0.0005529 kgCO2-Eq emission if extracted from groudwater table in India.

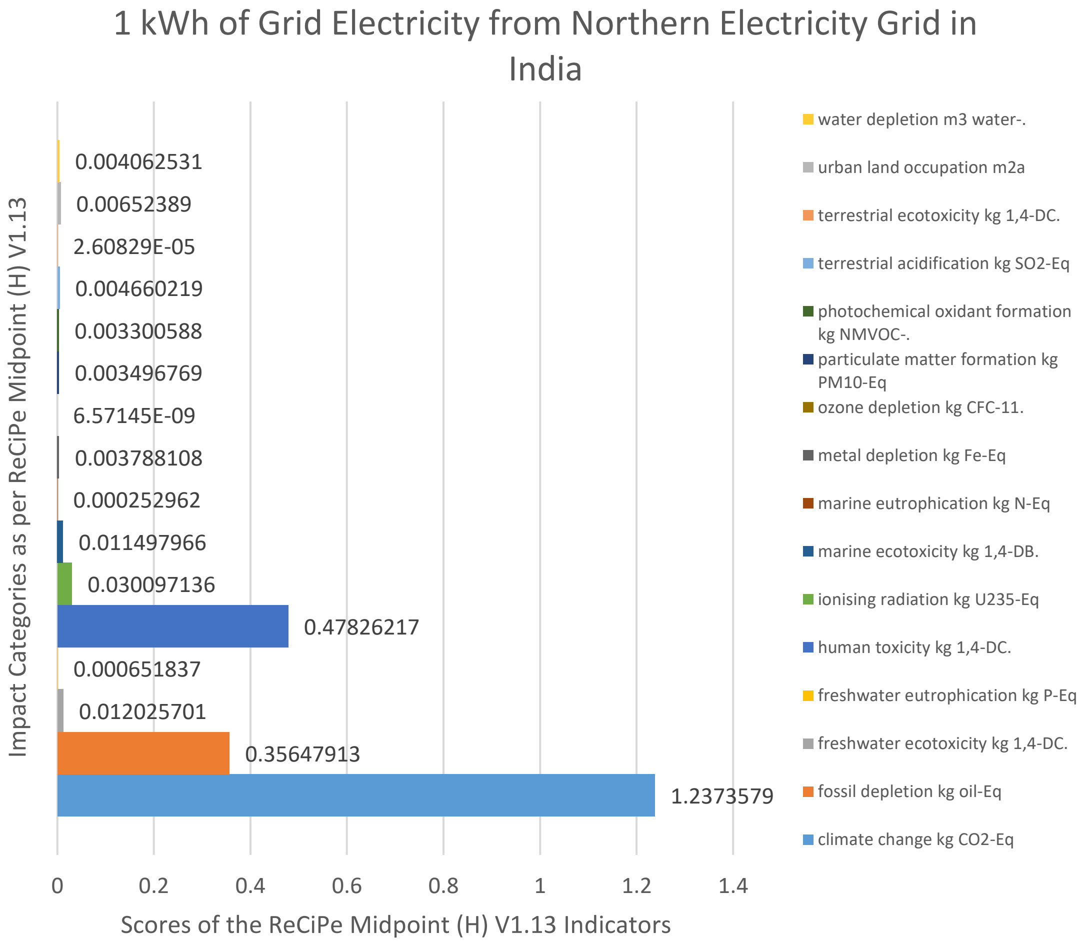


Figure 4.7. *Life cycle assessment results showing the 16 impact categories as per ReCiPe Midpoint (H) method for 1 kWh of electricity from Northern Grid of India*

4.4.3. Carbon Mitigation due to Water Savings

The benefits showed a significant amount of freshwater reduction, which eventually should be drawn from the borewell. As a result, energy savings and carbon mitigation was possible. With the adoption of tertiary treatment, the mitigated cabron potental were estimated and presented based on the RO and UF performance and LCA results shown earlier sections, see *Figure 4.8.*

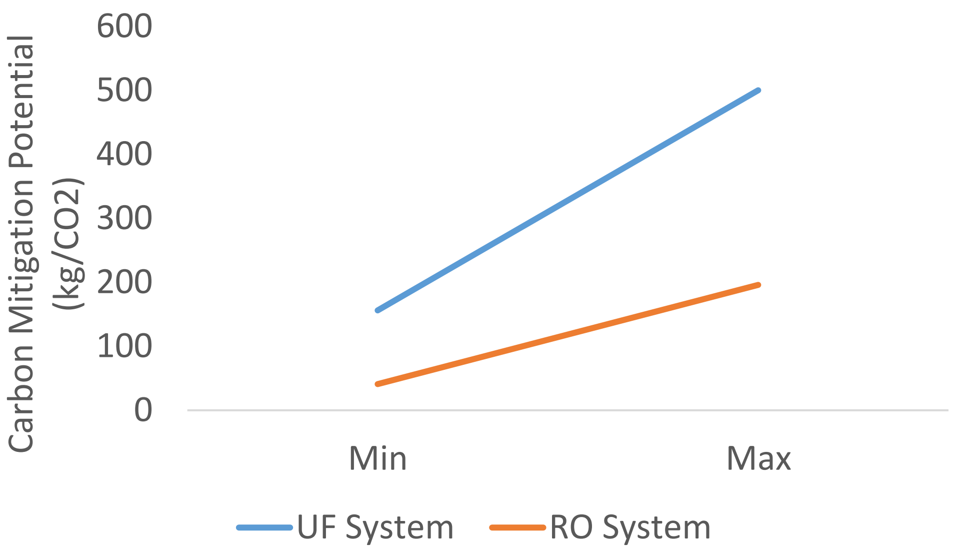


Figure 4.8. *Carbon mitigation potential due to water saving in Ro and UF systems for the PVNA company.*

4.4.4. Cost Analysis

Based on the input costs and TEA method shown in chapter 3 and the water treatment system choosen, the capex breakdown for 1 LPH of water treated in UF and RO system is estimated, see in *Figure 4.9.*

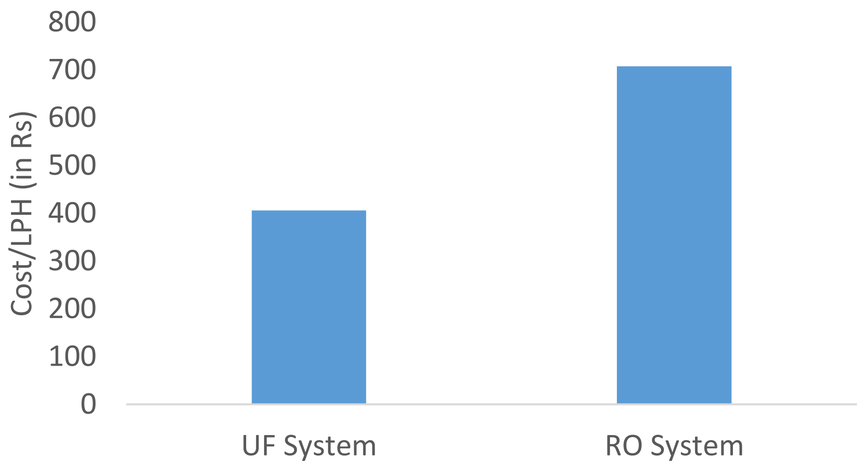
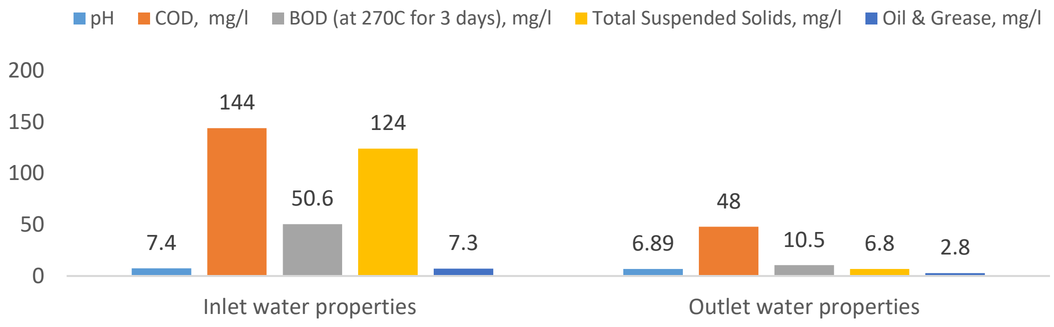


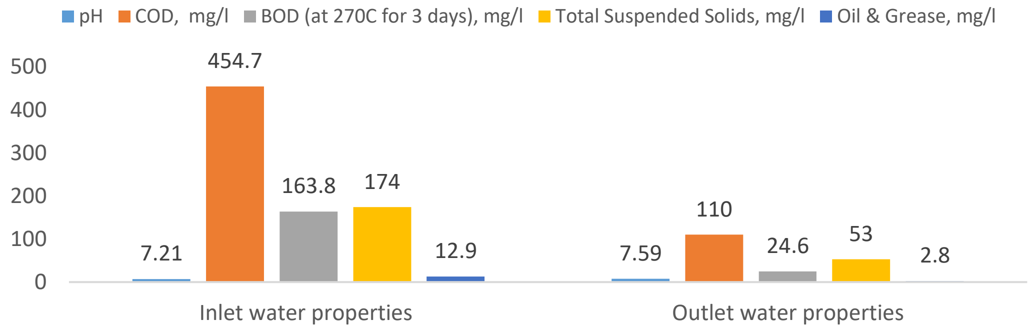
Figure 4.9. *Cost-breakdown per LPH for UF and RO system***.**

4.4.5. Treated Water Quality from STPs, ETPs, UF and RO

Treated water quality results of the water samples from STPs, and ETPs were shown in *Figures 4.10 to 4.14.* It is observed that the outlet water properties from STPs and ETPs were much in the limits of the treatment guidelines. In Figure 4.10, varying results of water quality can be seen though the wastewater produced fall under the industrial sector of automtive manaufacturing. This is due to the nature of operations being carried out and the kind of chemicals and contamination elements going into the water.



(a)



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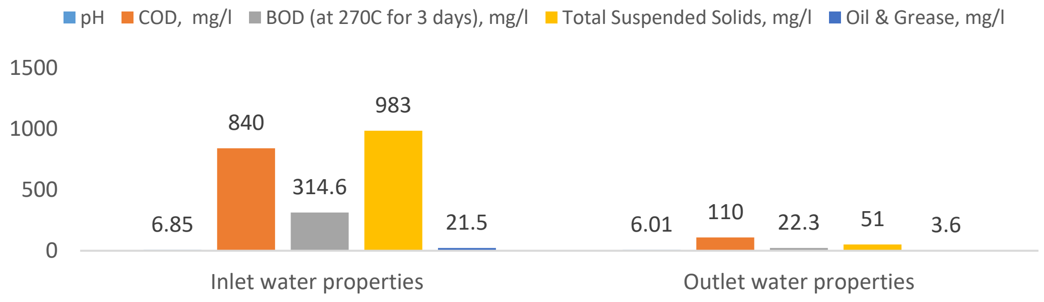

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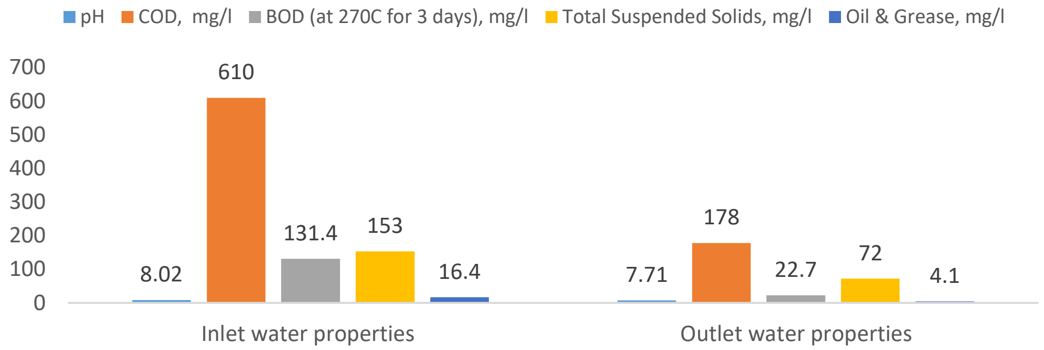

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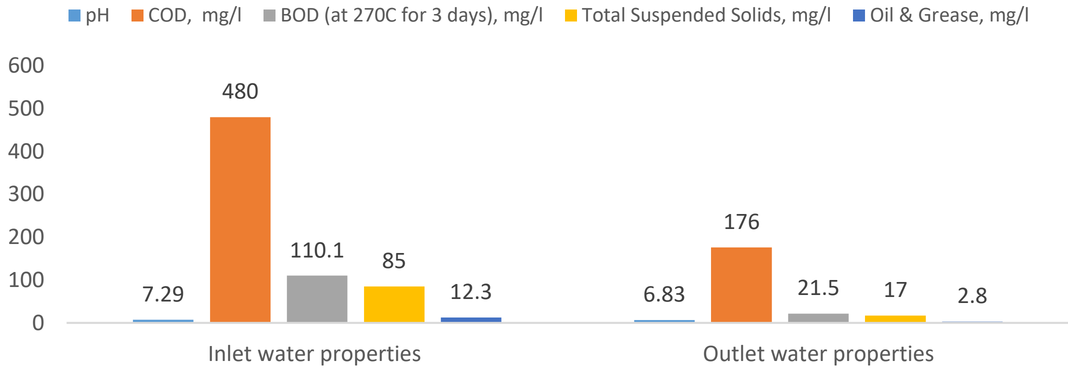

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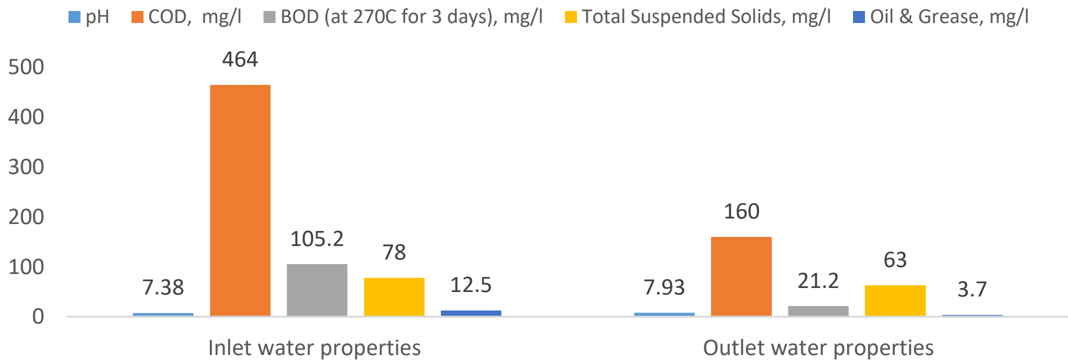


(f)

Figure 4.10. *Water quality parameters (both inlet and outlet) measured from STPs/ETPs for automotive parts manufacturing company (a). STP located in Gurugram, India; (b). ETP located in Gurugram, India ; (c). STP located in Noida, India ; (d). ETP located in Faridabad, India; (e). ETP located in Faridabad, India; (f). ETP located in Bhiwadi, India..*

Similarly, in Figure 4.11, the water sample results from textile manufacturing company is shown, followed by results from construction company in Figure 4.12, hotels in Figure 4.13, and a residential estate in Figure 4.14.

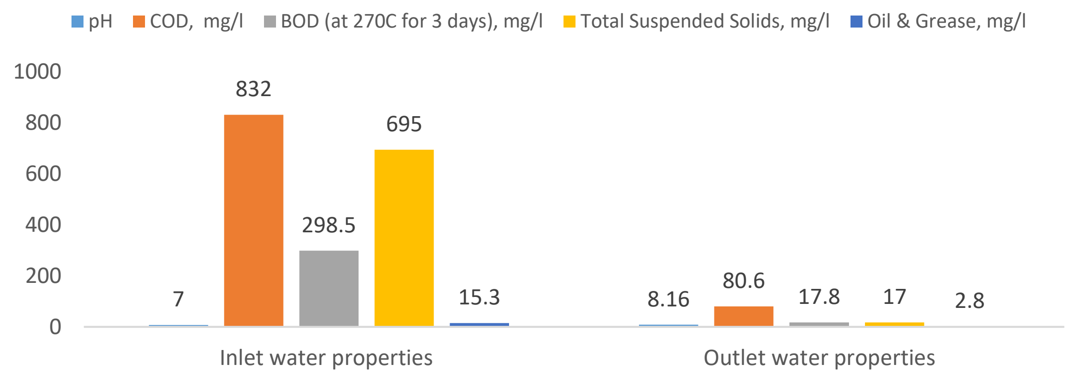


Figure 4.11. *Water quality parameters (both inlet and outlet) measured from an ETP installed at textiles manufacturing company located in Ludhiana, India*

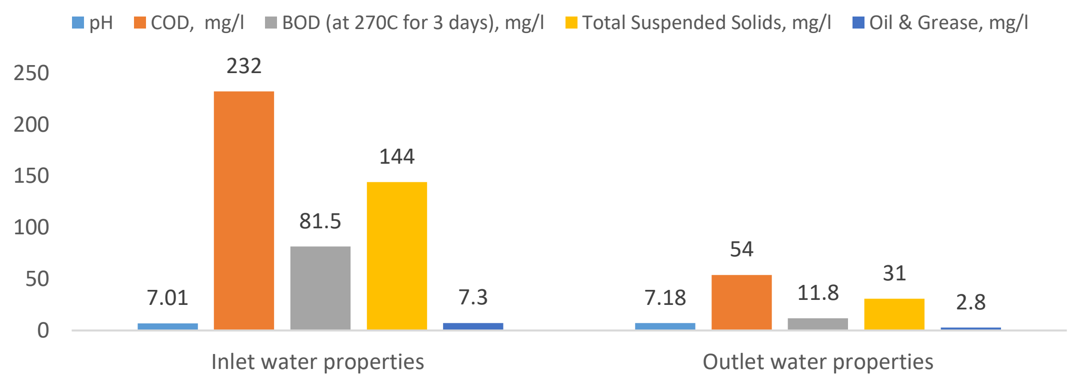
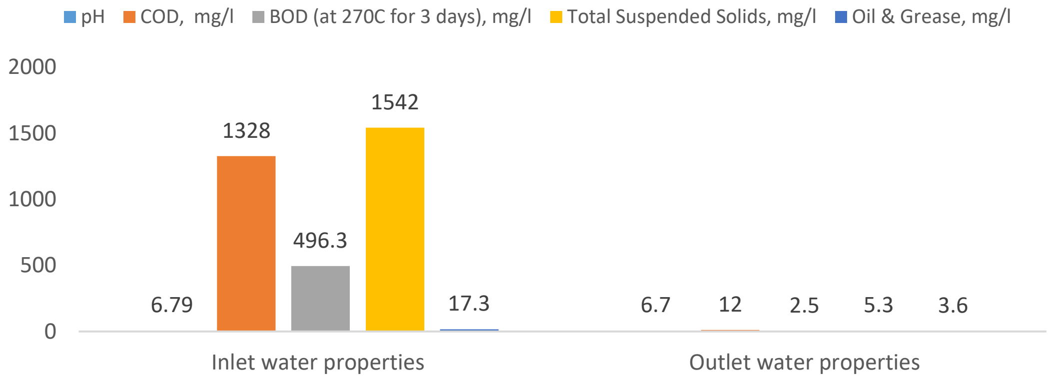
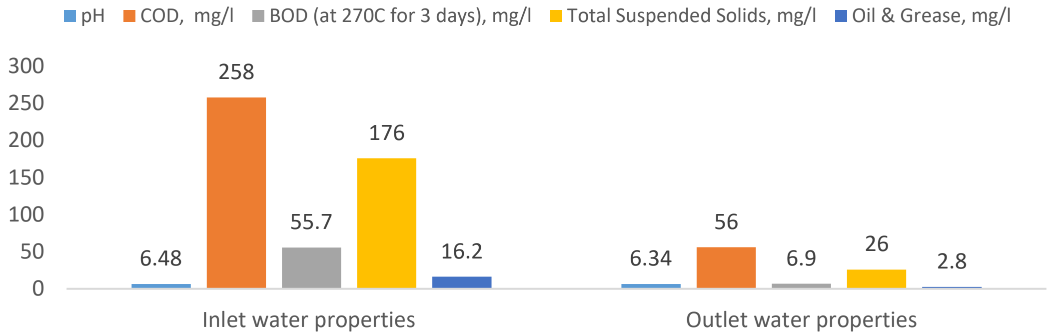


Figure 4.12. *Water quality parameters (both inlet and outlet) measured from an STP installed at construction company located in Noida, India*

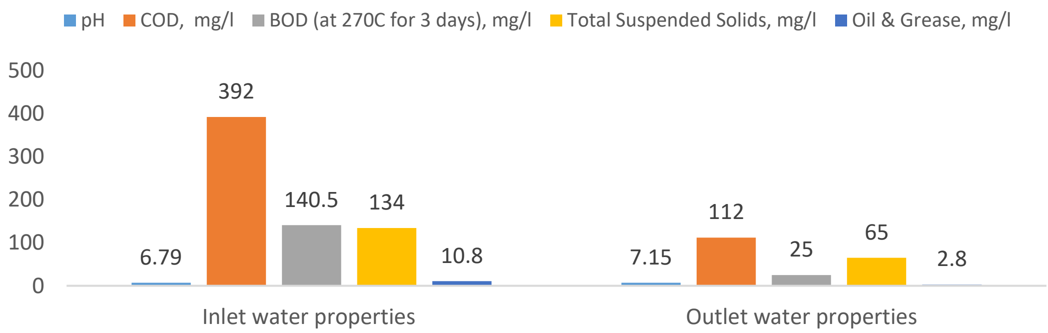


(a)



(b)

Figure 4.13. *Water quality parameters (both inlet and outlet) measured from an wastewater treatment plant installed at a hotel located in (a). STP in Delhi, India; (b). ETP in Noida, India*



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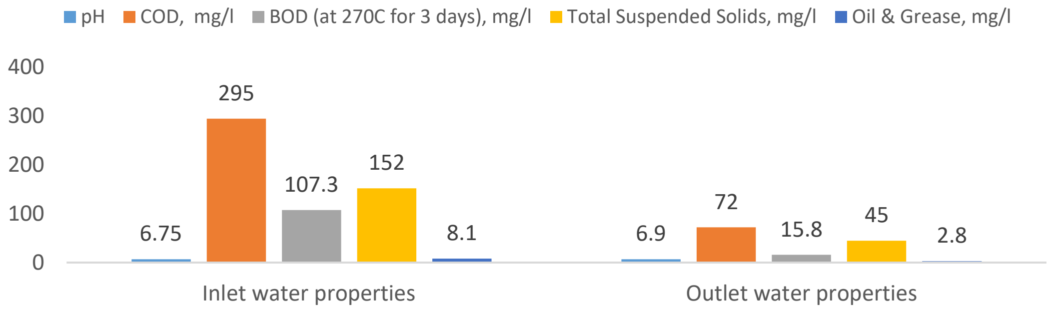

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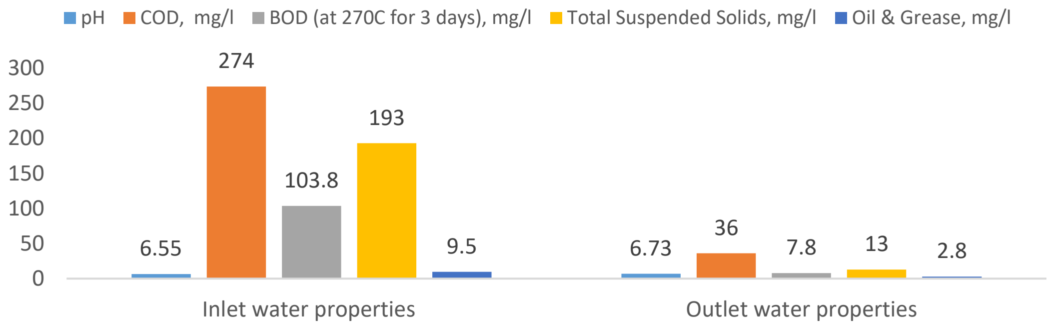


(c)

Figure 4.14. *Water quality parameters (both inlet and outlet) measured from an STP installed at residential estate located in (a). Gurugram, India; (b). Noida, India; and (c). Gurugram, India.*

The output water quality data is given in *Tables 4.8* and *4.9.* from the Reverse Osmosis (RO) plant stands out for its ability to drastically reduce Total Dissolved Solids (TDS), aiming for a TDS level between 100 and 150 ppm. This makes it suitable where low TDS is a critical requirement. It also incorporates a pH correction step to achieve a slightly acidic to neutral pH (6.5-7.5). In contrast, the Ultrafiltration (UF) and Softener plant focuses on reducing hardness to below 5 mg/L. However, it doesn't significantly alter the TDS of the water; it remains approximately the same as the feed water. The

UF system also reduces Total Suspended Solids (TSS). The treated water pH is slightly acidic, ranging from 6.0 to 6.8. Therefore, the choice between the two hinges on your specific water quality goals. If your priority is to substantially lower TDS, the RO plant is the way to go. If your main concern is reducing hardness while maintaining a similar TDS level to the source water, the UF and Softener plant would be more appropriate.

Table 4.8. *Outlet water quality data from Padmini 1000 LPH RO plant*

Parameters	**Unit**	**Values**
TDS (Before pH Correction)	ppm	100 -150 @ 25 Deg C
pH (After Correction)	---	6.5 – 7.5

Table 4.9. *Outlet water quality data from* Padmini UF soft (UF and Softener Plant).

Parameters	**Unit**	**Values**
Hardness	Mg/l	< 5
TDS	Mg/l	Approx same as feed quality
pH	---	6.0 – 6.8
TSS	Mg/l	<5

4.5. Sustainable Strategies and the Expert Validation

Achieving sustainability in sewage treatment plants is crucial for protecting the environment, conserving resources, and ensuring the long-term viability of wastewater treatment processes. Based on the observation, we have found some strategies that can help sewage treatment plants operate in a more sustainable manner, see *Table 4.10.*

Table 4.10. *Strategies for achieving sustainability*

Area to be focused	**Actions to be followed and strategies to be Implemented**
Energy Efficiency	- Consider renewable energy sources and implement energy-efficient technologies such as energy recovery systems, LED lighting, and optimized pumping systems to reduce energy consumption.
Water Conservation	-Implement water reuse and recycling programs within the plant to minimize freshwater consumption. -Optimize water treatment processes to reduce water wastage and improve overall efficiency.
Nutrient Recovery	Implement nutrient recovery technologies to extract valuable resources like phosphorus and nitrogen from wastewater for reuse in agriculture or industry.
Green Infrastructure	-Incorporate green infrastructure elements such as vegetated swales, constructed wetlands, and permeable surfaces to manage stormwater runoff and improve water quality. -Green roofs and rain gardens can help reduce the load on treatment plants by capturing and treating rainwater on-site.
Optimized Chemical Usage	-Minimize the use of chemicals in treatment processes by optimizing dosing rates and exploring alternative treatment methods.

	-Implement advanced oxidation processes or biological treatment methods to reduce reliance on chemical additives.
Advanced Treatment Technologies	-Invest in advanced treatment technologies such as membrane bioreactors, UV disinfection, and ozonation to improve treatment efficiency and water quality. -Explore innovative solutions like anaerobic digestion for energy recovery from biosolids.
Monitoring and Control Systems	-Implement real-time monitoring and control systems to optimize plant operations, identify inefficiencies, and reduce energy and resource consumption. -Use data analytics and predictive maintenance tools to anticipate issues and improve overall plant performance.
Community Engagement	-Educate the community about the importance of wastewater treatment and the impacts of improper disposal. -Encourage public participation in water conservation efforts and pollution prevention initiatives.
Regulatory Compliance	-Ensure compliance with environmental regulations and standards to protect water quality and public health. -Stay informed about emerging regulations and proactively implement measures to meet future requirements.

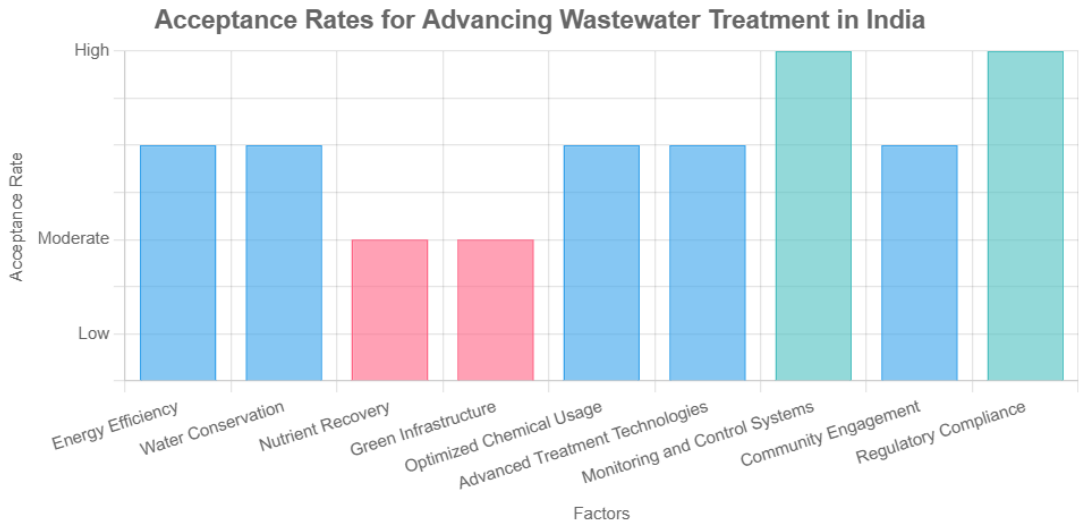


Figure 4.15. *Acceptance rate as a validation metric of the factors to be considered as sustainable strategies for advancing wastewater treatment in India*

Upon exploring the sustainable strategies, I wanted to understand how these strategies will be viwed among the wastewater treatment community in India. Surprisingly, the advancing wastewater treatment in India faces a landscape of varying acceptance levels across suggested key factors, see *Figure 4.15*. While Regulatory Compliance and Monitoring and Control Systems receive high ratings due to their recognized importance, challenges remain in enforcement and implementation costs, respectively. Energy Efficiency, Water Conservation, Optimized Chemical Usage, Advanced Treatment Technologies, and Community Engagement all garner moderate acceptance. These areas are acknowledged as important, but concerns about cost, public perception, technical expertise, and effective communication hinder widespread adoption. Nutrient Recovery and Green Infrastructure currently have low acceptance, primarily due to a lack of familiarity, concerns about market viability, and questions about effectiveness in the Indian context. Overcoming these hurdles will require targeted research, demonstration projects, supportive policies, and community engagement initiatives to showcase the benefits and address the specific challenges in each area.

The detailed narratives encompassing perspectives from plant operators, environmental engineers, regulatory officials, research scientists, and community representatives, provides a comprehensive validation of the multifaceted challenges and opportunities in advancing wastewater treatment practices, see *Apendix A*. The consensus among plant operators and environmental engineers underscores the practical importance of strategies such as optimizing chemical usage and implementing real-time monitoring and control systems. Regulatory officials' emphasis on regulatory compliance validates the critical role of adherence to environmental standards in safeguarding public health and water quality. The insights from research scientists highlight the potential of innovative technologies like nutrient recovery and advanced treatment methods, while the perspectives of community representatives emphasize the importance of community engagement and addressing public concerns. The convergence of these diverse viewpoints strengthens the validity of the survey findings, reinforcing the need for a holistic approach that integrates technological advancements, regulatory frameworks, and community participation to achieve sustainable and effective wastewater treatment solutions.

The other way is, treating sewage treatment plant sludge is a critical aspect of wastewater management to ensure proper disposal, reduce environmental impact, and potentially recover valuable resources (see *Figure 4.16* for solids presnece in sludge).

Here are some common methods used for treating sewage treatment plant sludge, see *Table 4.11*. Calorific value of sludge, alomg with electricity potential available in the sludge produced in STPs using differnet STP technology were given in *Figures 4.17* to *4.18*. *Figure 4.19* shows the sludge to product levelised cost epseiclaly when the sludge was converted into electricity.

Table 4.11. *Sludge treatment approaches for achieving sustainability*

Treatment Approach	**Actions to be followed and strategies to be Implemented**
Dewatering	-Dewatering is the process of removing water from sludge to reduce its volume and make it easier to handle and transport. -Common dewatering techniques include mechanical methods like belt presses, centrifuges, filter presses, and drying beds.
Digestion	-Digestion is a biological process that stabilizes organic matter in sludge, reduces pathogens, and produces biogas. -Anaerobic digestion is a common method where microorganisms break down organic matter in the absence of oxygen, producing methane-rich biogas.

Composting	-Composting involves mixing sewage sludge with bulking agents like wood chips or yard waste to create a nutrient-rich soil conditioner. -The composting process helps stabilize the organic matter in sludge, reduce odors, and produce a beneficial product for use in landscaping and agriculture.
Thermal Treatment	-Thermal treatment methods like incineration and pyrolysis can be used to thermally degrade organic matter in sludge and reduce its volume. -Incineration involves burning sludge at high temperatures to destroy pathogens and reduce the volume of solids, while pyrolysis converts organic matter into biochar or syngas.
Land Application	-Treated sewage sludge, also known as biosolids, can be applied to land as a soil conditioner and fertilizer. -Properly treated biosolids can improve soil fertility, enhance crop growth, and promote sustainable agriculture practices.
Alkaline Stabilization	-Alkaline stabilization involves mixing sludge with alkaline materials to reduce pathogens and stabilize organic matter. -This process raises the pH of the sludge, making it less odorous and improving its handling characteristics

Chemical Stabilization	-Chemical stabilization methods involve the addition of chemicals like polymers or coagulants to sludge to improve dewaterability and reduce odors. -Chemical conditioning can enhance the dewatering process and produce a more stable sludge product.
Biological Nutrient Removal	-Biological nutrient removal processes can be used to recover nutrients like phosphorus and nitrogen from sludge for reuse in agriculture or industry. -Enhanced biological phosphorus removal and nitrogen removal processes can help reduce nutrient discharge and promote resource recovery.

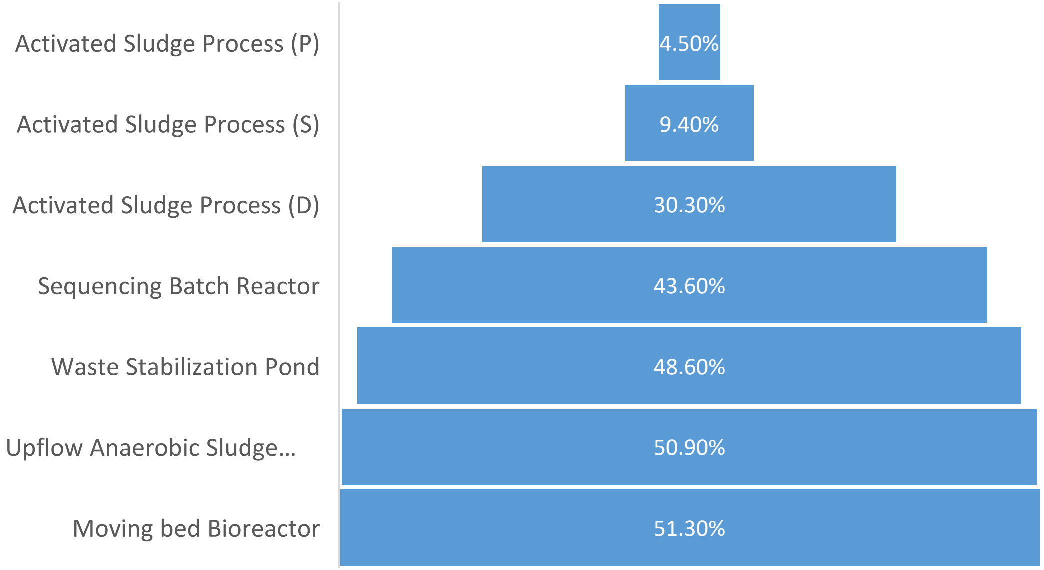


Figure 4.16. *% of total solids present in the sludge (it it weight is considered 100%) produced in various technologises. Data Source: Singh et al, 2020.*

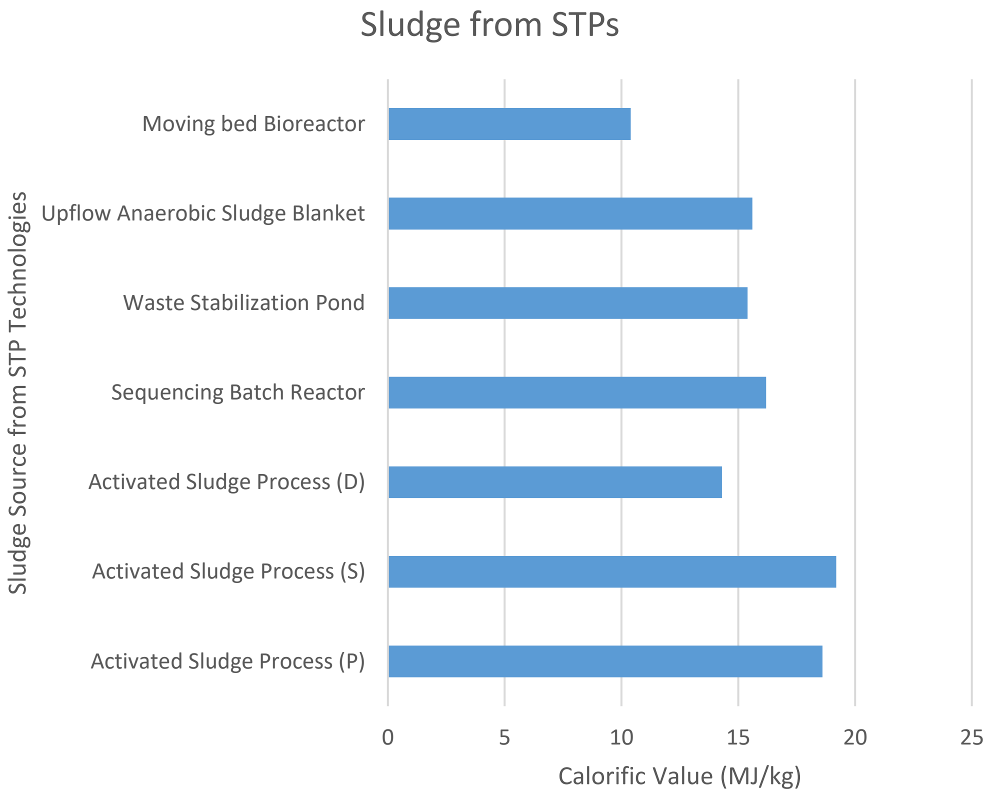
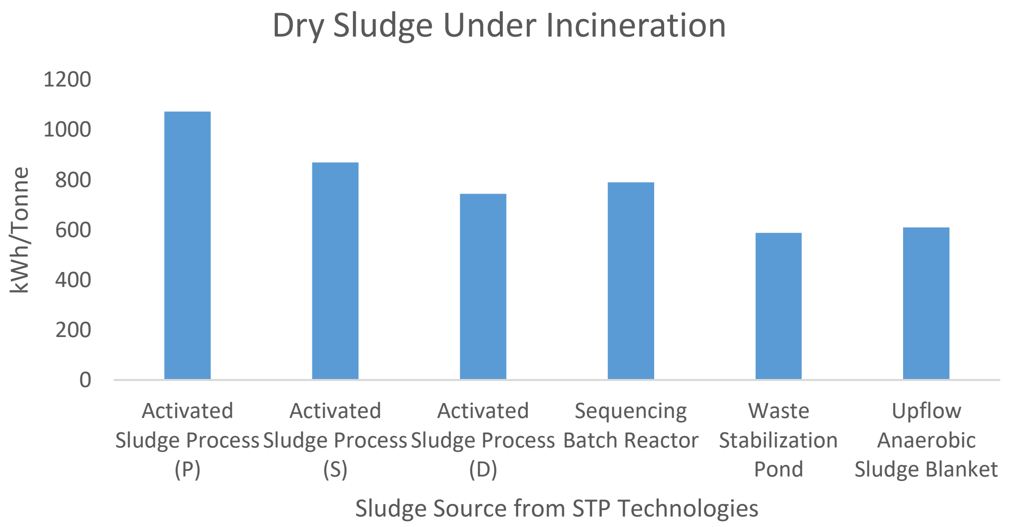


Figure 4.17. *Calorfic value present in the sludge produced from STPs. Data Source: Singh et al, 2020.*

In Figure 4.17, a comparative analysis of electricity consumption (kWh/tonne) for treating different sludge sources using Incineration and Anaerobic Digestion was given. The sludge sources include ASP(P), ASP(S), SBR, MBBR, WSP, and UASB. In general, Incineration requires significantly more electricity than Anaerobic Digestion across all sludge types. For instance, ASP(P) sludge treated via Incineration consumes 1073.9 ± 53.7 kWh/tonne, whereas Anaerobic Digestion requires only 525.5 ± 26.3 kWh/tonne. Similarly, WSP sludge shows a consumption of 588.6 ± 29.4 kWh/tonne with Incineration, compared to 227.1 ± 11.4 kWh/tonne with Anaerobic Digestion.

These results underscore the energy efficiency of Anaerobic Digestion as a sludge treatment method compared to Incineration.



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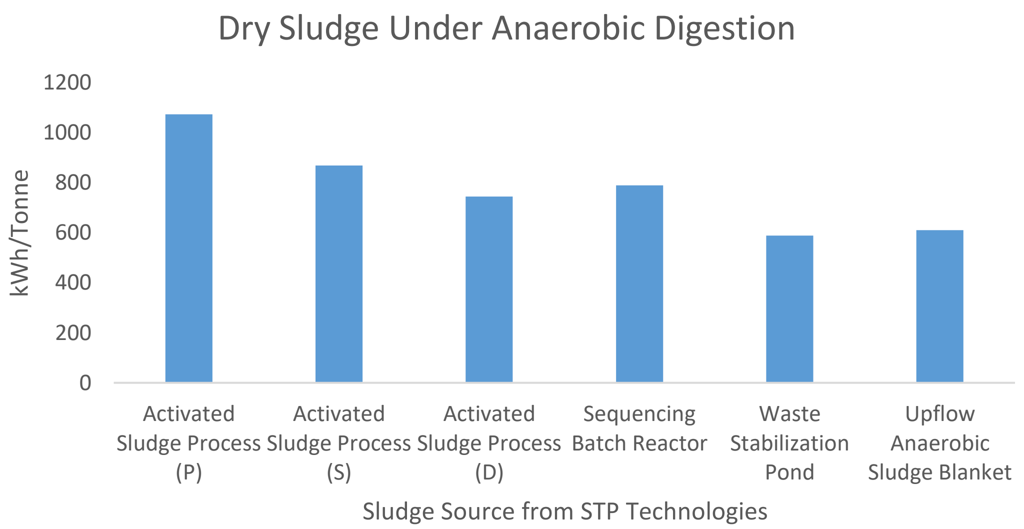

(b)

Figure 4.18. *Electricity potential available in the sludge produced in STPs under (a). Incineration; (b). Anaerobic digestion. Data Source: Singh et al, 2020.*

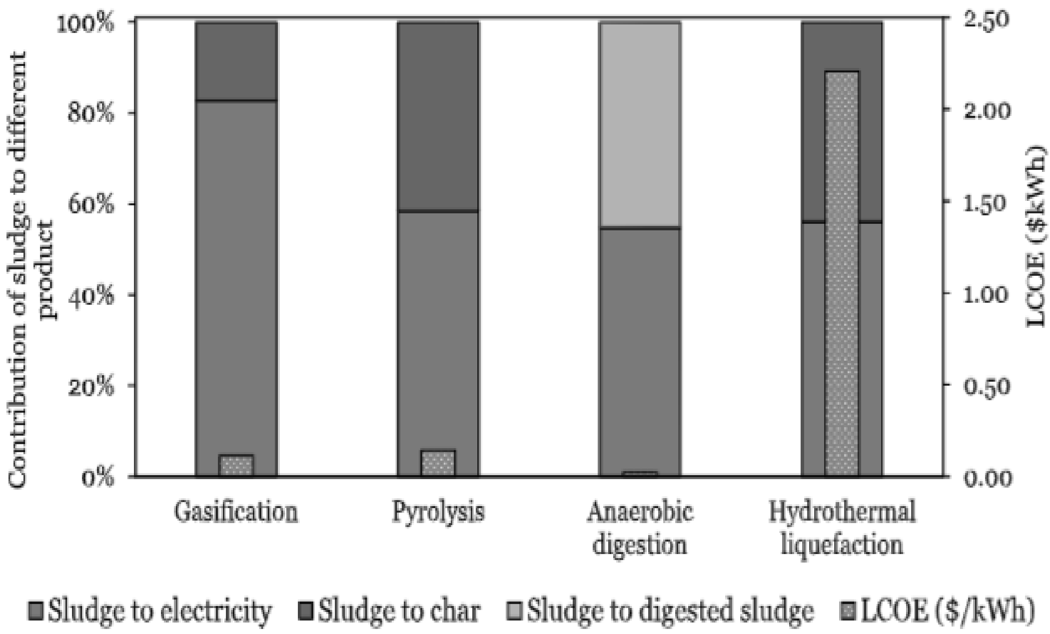

Figure 4.19. *Conversion of sludge to product and LCOE ($/kWh). Adapted from Singh et al, 2020.*

Circular economy principles, particularly in the context of water resources management, focus on maximizing resource recovery through wastewater treatment (UNESCO, 2020). This approach involves not only treating wastewater to a high standard but also exploring the economic opportunities that arise from reusing treated water. In this section, the economic and market potential of reusing treated water in the irrigation sector is analyzed, given that this sector constitutes a significant portion of water demand in India. By implementing efficient wastewater treatment processes and promoting the safe reuse of treated water, several economic benefits and opportunities can be realized. Reusing treated water in the irrigation sector offers several advantages, including, shown in *Table 4.12.*

Table 4.12. *Offsetting benefits*

Offsetting Benefits	**How to Achieve the Benefits**
Reduced freshwater consumption	Using treated wastewater for irrigation can help alleviate the strain on freshwater resources, particularly in water-stressed regions like India
Cost savings	Reusing treated water can lead to cost savings for farmers and agricultural businesses by reducing reliance on expensive freshwater sources
Nutrient-rich water	Treated wastewater often contains nutrients that can benefit crops, potentially reducing the need for additional fertilizers
Sustainable farming practices	Incorporating treated water reuse into agricultural practices promotes sustainability and aligns with circular economy principles
Income generation	The sale of treated water for irrigation purposes can create new revenue streams for wastewater treatment facilities
Environmental benefits	Properly treated wastewater used for irrigation can improve soil fertility and reduce pollution of water bodies

4.6. Discussion

Based on literature review and case study design, we obserbed that there exists many challenges, technology options, and numerous sustainable strategies. However, transitinng to sustainable sewage treatment is possible when all the challenges were overcome. To validate the challenges explored in this disseration, I conducted a survey based on the created TESEI matrix of challenges. To validate these, a survey response form was created asking the stakeholders of the sewage treatment plants to give their opinions with options as Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree.

I rolled out this form to 358 people, however I only received 50 responses were received, that are further analysed, see *Figures 4.20* to *4.25.*

The technical challenges are clearly dominated by concerns about aging infrastructure (78% strongly agree), highlighting the urgent need for investment in upgrades and maintenance. Leakages and failures of water systems (68% strongly agree) and inadequate water distribution systems (60% strongly agree) are also major concerns. The relatively lower agreement on water data suggests a potential gap in awareness or understanding of its importance.

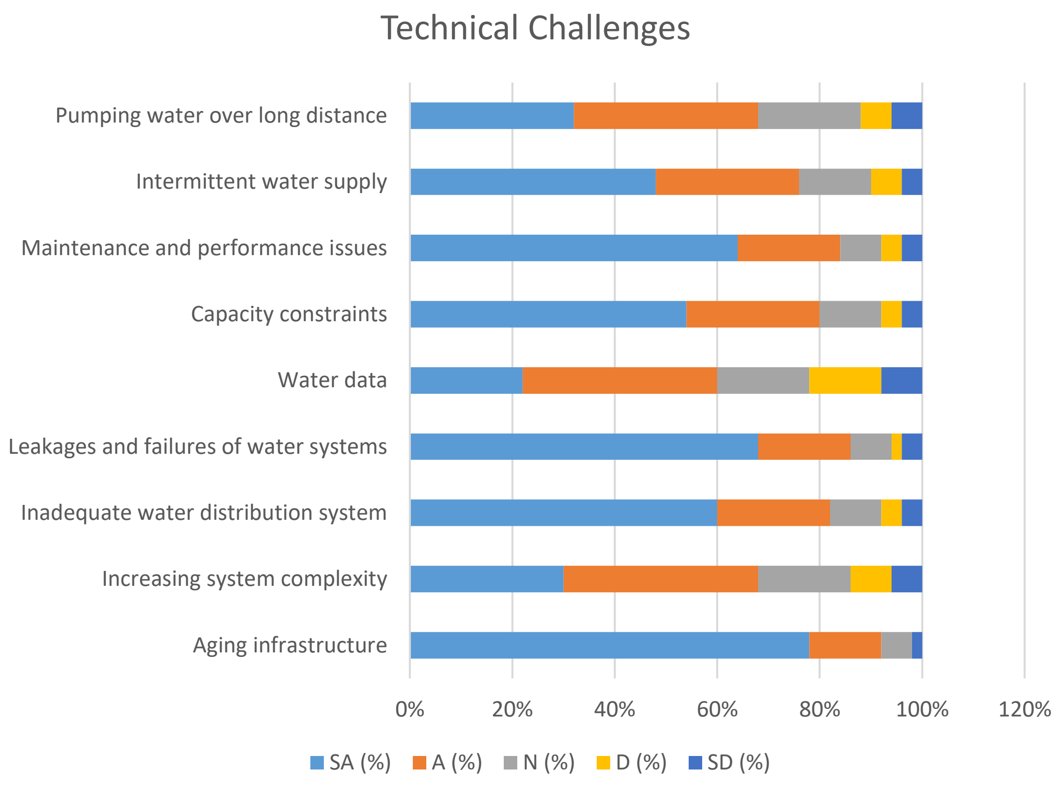

Figure 4.20. *Stakeholder responses over the explored technical challenges. Note: Strongly Agree (SA), Agree (A), Neutral (N), Disagree (D), Strongly Disagree (SD)*

The economic challenges highlight the significant impact of resources expenditure constraints (62% strongly agree) and difficulties in financing the aging infrastructures (68% strongly agree) on water management. Non-revenue water (58% strongly agree) is also a major concern, indicating the need for improved efficiency and revenue generation.

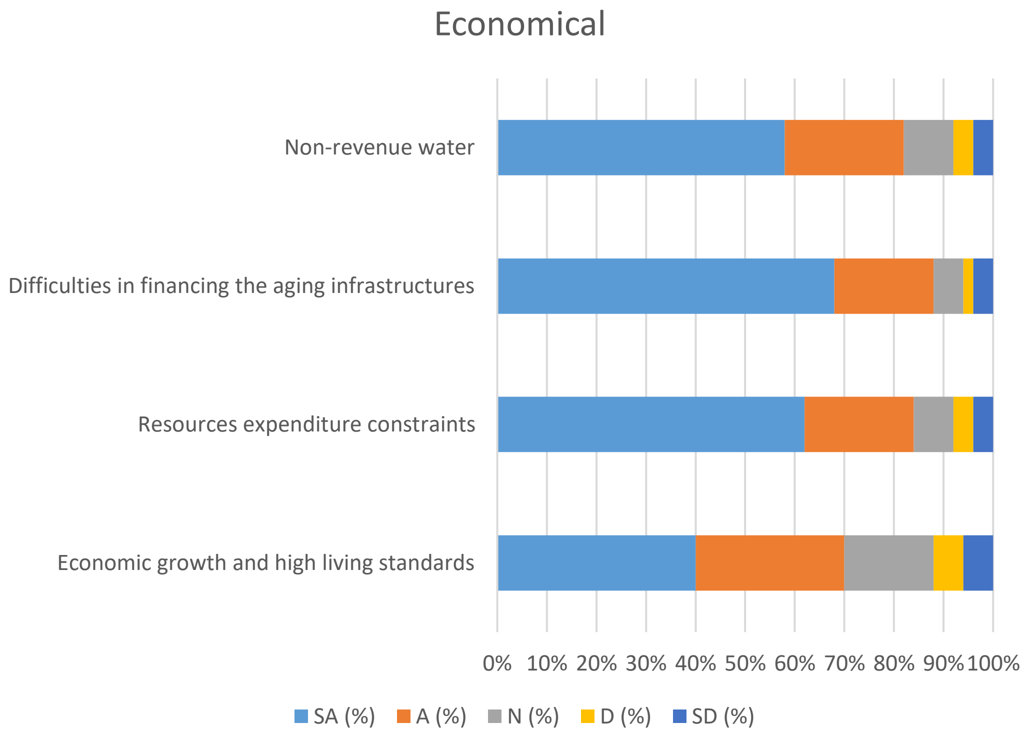

Figure 4.21. *Stakeholder responses over the explored economic challenges. Note: Strongly Agree (SA), Agree (A), Neutral (N), Disagree (D), Strongly Disagree (SD)*

The social challenges reveal a strong consensus around the urgency of issues like limited freshwater resources (72% strongly agree) and increasing water demand (62% strongly agree). Water scarcity (66% strongly agree) is also perceived as a significant threat. However, there's more variability in opinions regarding social status and water use and public acceptance variability, suggesting a need for more nuanced understanding and targeted interventions. Low willingness to pay also shows a significant level of disagreement (26%) and strong disagreement (16%), indicating potential barriers to implementing water management strategies.

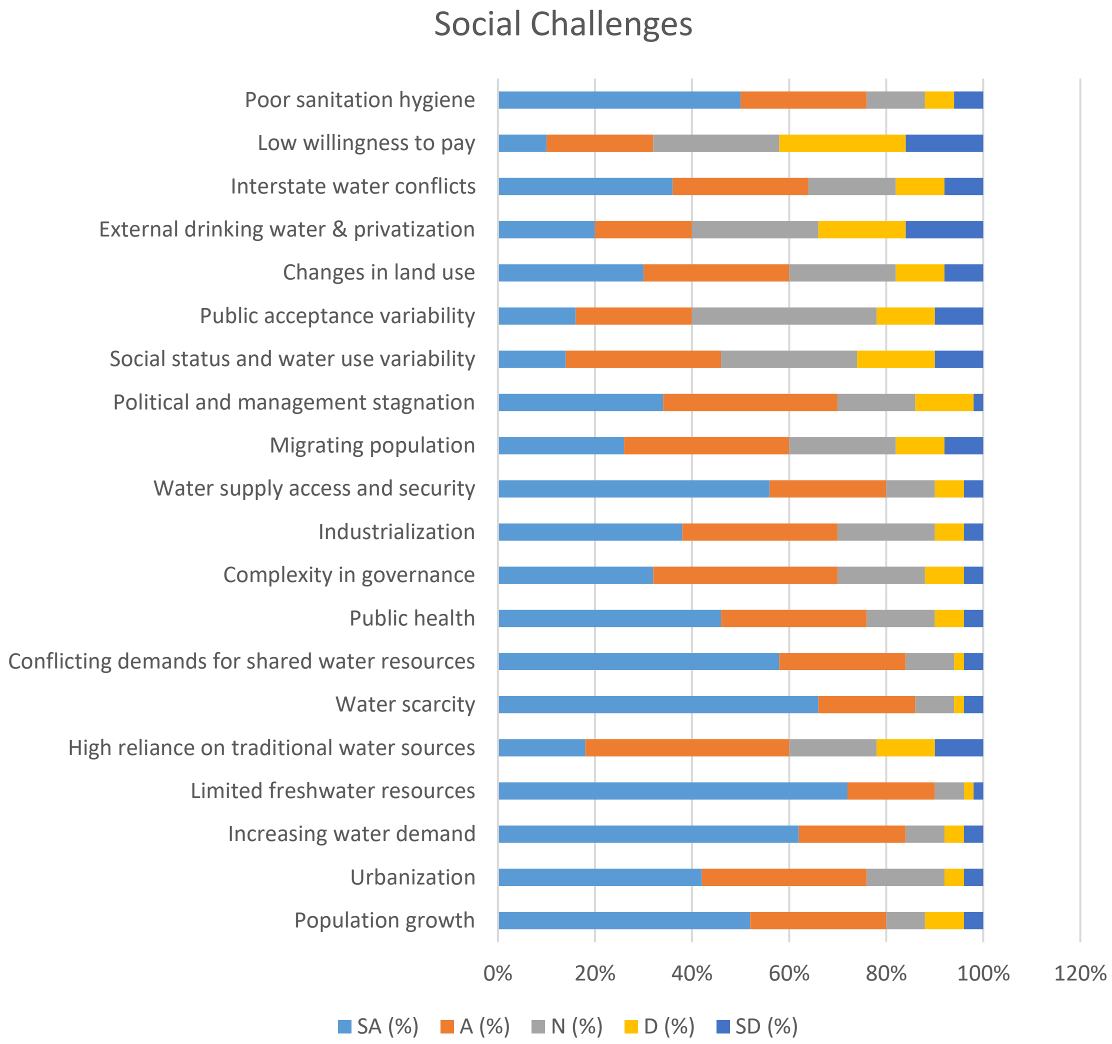

Figure 4.22. *Stakeholder responses over the explored social challenges. Note: Strongly Agree (SA), Agree (A), Neutral (N), Disagree (D), Strongly Disagree (SD)*

The environmental challenges show overwhelming agreement on the severity of issues like drought (80% strongly agree), climate shifts (74% strongly agree), water quality degradation (76% strongly agree), and over-exploitation of water resources (78% strongly agree). This underscores the urgent need for sustainable water management practices and climate change mitigation strategies. Urban low flow conditions and system emissions have relatively lower agreement, suggesting a need for more awareness and research in these areas.

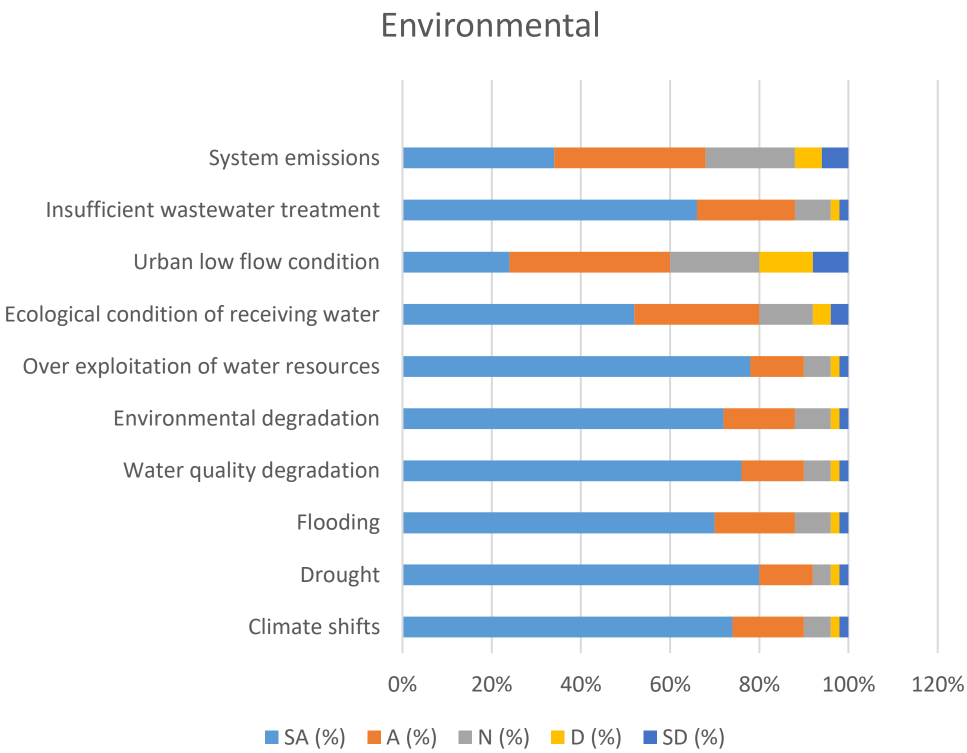

Figure 4.23. *Stakeholder responses over the explored environmental challenges. Note: Strongly Agree (SA), Agree (A), Neutral (N), Disagree (D), Strongly Disagree (SD).*

The institutional challenges reveal a strong consensus on the negative impact of corruption and lack of transparency (72% strongly agree) and political interference (68% strongly agree) on effective water management. Limited institutional capacity (64% strongly agree) and inadequate regulatory framework (60% strongly agree) also require urgent attention.

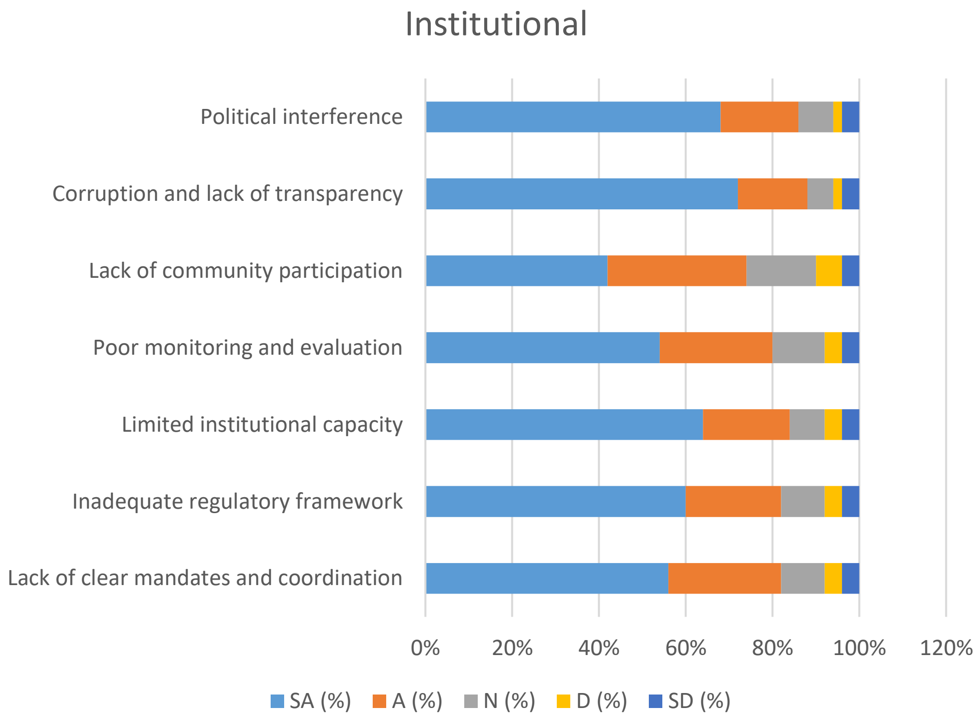

Figure 4.24. *Stakeholder responses over the explored institutional challenges. Note: Strongly Agree (SA), Agree (A), Neutral (N), Disagree (D), Strongly Disagree (SD).*

CHAPTER 5

CONCLUSIONS AND FUTURE RESEARCH PROPOSITIONS

5.1. Conclusions

Given the rapid urbanization and consequent increase in sewage generation, it is imperative to address the current gap in sewage treatment. In addition to bridging this gap, there is a critical need to align future treatment capacity requirements. Current findings reveal that only 75% of the operationalized treatment capacity is being utilized. The simulated survey results, when viewed through the lens of India's sewage treatment system, paint a concerning picture. The strong agreement on water quality degradation (76% strongly agree) and insufficient wastewater treatment (66% strongly agree) in the environmental challenges category directly reflects the reality of widespread untreated sewage discharge in India. This is further compounded by the technical challenges, where aging infrastructure (78% strongly agree) and leakages and failures of water systems (68% strongly agree) highlight the dilapidated state of many existing sewage treatment plants (STPs) and the distribution networks. The economic challenges, especially resource expenditure constraints (62% strongly agree) and difficulties in financing the aging infrastructures (68% strongly agree), underscore the financial limitations that impede the development and maintenance of adequate sewage treatment facilities. The social challenges also resonate strongly. Poor sanitation hygiene (50% strongly agree) is a direct consequence of inadequate sewage management, leading to public health risks. The low willingness to pay (only 10% strongly agree) for improved water and sanitation services poses a significant hurdle to financing upgrades and expansions of the sewage treatment infrastructure. Furthermore, the institutional challenges, particularly corruption and lack of transparency (72% strongly agree) and limited institutional capacity (64% strongly agree), hinder effective implementation and monitoring of sewage treatment projects. In summary, the simulated survey responses highlight the urgent need for a multi-pronged approach to address India's sewage treatment crisis.

This approach must encompass:

- Significant investments in upgrading and expanding sewage treatment infrastructure.
- Improved monitoring and enforcement of environmental regulations.
- Community engagement and awareness campaigns to promote sanitation hygiene and increase willingness to pay for improved services.
- Strengthening institutional capacity and promoting transparency in project implementation.
- Innovative financing mechanisms to overcome resource constraints.

5.2. Future Research Propositions

To build upon this analysis and inform effective solutions, future research should focus on the following areas:

Assess the performance and effectiveness of existing STPs in India. This research could evaluate the treatment efficiency, operational costs, and environmental impacts of different STP technologies under varying conditions. Additionally, state policies predominantly reference CPCB/SPCB discharge standards for quality benchmarks, but they often lack specific quality standards tailored to the intended use of TWW.

Identify the key barriers to the adoption of decentralized wastewater treatment systems in urban and rural areas of India. Also, most state policies lack comprehensive details on the treatment processes. Additionally, these policies often provide only a brief mention of tertiary treatment processes and associated technologies. This research could explore the technical, economic, social, and institutional factors that influence the uptake of decentralized systems.

Evaluate the potential of nature-based solutions (e.g., constructed wetlands) for sewage treatment in India. This research could assess the treatment performance, cost-effectiveness, and co-benefits of nature-based solutions compared to conventional STPs.

Investigate the role of public-private partnerships (PPPs) in financing and managing sewage treatment infrastructure in India. This research could examine the successes and challenges of PPP projects and identify best practices for ensuring equitable and sustainable outcomes.

Assess the impact of community-led sanitation initiatives on improving sanitation hygiene and reducing open defecation in India. This research could evaluate the effectiveness of community-based approaches in promoting behaviour change and fostering a sense of ownership and responsibility for sanitation services.

Develop integrated models to assess the long-term impacts of different sewage treatment scenarios on water quality, public health, and economic development in India. This research could provide valuable insights for policymakers and planners to make informed decisions about sewage management strategies.

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Appendix A. Questions and Summary of Responses

The following are the questions asked for qualitive perspectives gatherings on understanding the sustainable strategies options and the hidden challenges Indian wastewater treatment sector face. The questions were asked to the expert groups in the field in varying roles and domains. The considered ones are Plant Operators, Environmental Engineers, Regulatory Officials, Research Scientists, Community Representatives.

Plant Operators

Q1. In your daily operations, what are the biggest challenges you face in terms of energy consumption?

Operator 1: Erratic power supply is a huge problem. We have frequent outages and voltage fluctuations, which damage equipment and disrupt treatment.

Operator 2: Old, inefficient pumps are common. Replacing them is a challenge due to budget constraints.

Operator 3: Manual operations are still prevalent. We lack automated systems to optimize energy use.

Operator 4: Sludge management is energy-intensive, especially in smaller plants with limited resources.

Operator 5: Lack of skilled technicians to maintain and repair equipment leads to energy wastage.

Q2. What specific technologies or strategies do you believe would be most effective in reducing energy consumption at our plant, considering the practical constraints of daily operations?

Operator 1: Solar power is a good option, but the initial investment is high. Government subsidies would help.

Operator 2: Energy-efficient pumps and motors are essential, but they need to be robust and easy to maintain.

Operator 3: Automated controls would be great, but we need training to operate and troubleshoot them.

Operator 4: Biogas generation from sludge is promising, but it requires careful management to avoid odor problems.

Operator 5: Simple, low-cost solutions like proper insulation and leak detection can make a big difference.

Q3. What are your biggest concerns regarding the implementation of water reuse and recycling programs from an operational standpoint?

Operator 1: Ensuring water quality is paramount. We need reliable treatment processes to remove pathogens and pollutants.

Operator 2: Public acceptance is a major hurdle. People are often skeptical about using recycled water.

Operator 3: The cost of advanced treatment technologies is a concern. We need affordable solutions.

Operator 4: Maintaining the system during monsoon season is challenging due to heavy rainfall and flooding.

Operator 5: Coordination with other agencies, like irrigation departments, is essential for successful implementation.

Q4. What kind of training or support would you need to effectively operate and maintain advanced treatment technologies?

Operator 1: Hands-on training in local languages is crucial. We need to understand the technology in our own context.

Operator 2: Regular refresher courses are needed to keep up with the latest advancements.

Operator 3: Access to a network of experienced operators for troubleshooting and knowledge sharing would be invaluable.

Operator 4: Support from equipment vendors in terms of spare parts and maintenance services is essential.

Operator 5: Opportunities to visit successful water reuse projects in other parts of India would be inspiring.

Q5. How can monitoring and control systems be designed to be more user-friendly and helpful for plant operators?

Operator 1: Simple, visual displays are best. We need to see the key parameters at a glance, even in low-light conditions.

Operator 2: Alarms that are easy to understand and respond to are essential.

Operator 3: Remote monitoring capabilities would be helpful, but we need reliable internet connectivity.

Operator 4: Data logging and trending capabilities would help us identify patterns and optimize performance, but the data needs to be presented in a clear and concise manner.

Operator 5: Systems that can be operated using local languages would be a huge advantage.

Environmental Engineers

Q1. From a design perspective, what are the most promising renewable energy sources for wastewater treatment plants in our region?

Engineer 1: Solar power is a good option, especially for smaller plants in rural areas. We need to optimize panel placement and storage solutions.

Engineer 2: Biogas from anaerobic digestion is promising, but we need to address odor control and ensure efficient gas utilization.

Engineer 3: Wind power is feasible in some coastal areas, but it requires careful assessment of wind resources and grid connectivity.

Engineer 4: Hydropower is an option in hilly regions, but it can have environmental impacts on river ecosystems.

Engineer 5: Hybrid systems that combine multiple renewable energy sources are often the most reliable and cost-effective.

Q2. What innovative approaches can be used to optimize pumping systems and reduce energy consumption in wastewater treatment plants?

Engineer 1: Using variable frequency drives (VFDs) to match pump speed to flow rate.

Engineer 2: Implementing smart pump control systems that optimize pumping schedules based on real-time demand and energy prices.

Engineer 3: Using gravity-fed systems whenever possible to reduce the need for pumping.

Engineer 4: Selecting high-efficiency pumps and motors that are designed for Indian conditions.

Engineer 5: Regularly inspecting and maintaining pumps to ensure they're operating efficiently and preventing leaks.

Q3. What are the key design considerations for implementing water reuse and recycling programs while minimizing potential health risks?

Engineer 1: Implementing multiple barriers to prevent contamination, such as pre-treatment, filtration, disinfection, and monitoring.

Engineer 2: Selecting appropriate treatment technologies based on the intended use of the recycled water, considering local water quality standards.

Engineer 3: Developing a comprehensive risk management plan that addresses potential hazards and ensures public safety.

Engineer 4: Ensuring that the recycled water meets all applicable water quality standards and is safe for its intended use.

Engineer 5: Communicating effectively with the public to address concerns and build trust in the safety of recycled water.

Q4. How can green infrastructure elements be effectively integrated into wastewater treatment plant designs to manage stormwater runoff and improve water quality?

Engineer 1: Using vegetated swales and rain gardens to capture and filter stormwater runoff, especially in urban areas.

Engineer 2: Constructing wetlands to treat stormwater and provide habitat for wildlife, but land availability can be a constraint.

Engineer 3: Using permeable pavements to reduce runoff and recharge groundwater, but they require regular maintenance to prevent clogging.

Engineer 4: Installing green roofs to reduce runoff and provide insulation for buildings, but they can be expensive to install and maintain.

Engineer 5: Integrating green infrastructure into the overall site design to create a more aesthetically pleasing and environmentally friendly facility, considering local climate and soil conditions.

Q5. What are the most cost-effective and sustainable alternative treatment methods for reducing chemical usage in wastewater treatment plants?

Engineer 1: Using membrane bioreactors (MBRs) to remove pollutants without the need for chemical additives, but they can be expensive to operate.

Engineer 2: Implementing advanced oxidation processes (AOPs) to break down pollutants using UV light or ozone, but they require skilled operators.

Engineer 3: Using constructed wetlands to treat wastewater naturally, but they require large land areas.

Engineer 4: Optimizing biological treatment processes to reduce the need for chemical disinfection, but they require careful monitoring and control.

Engineer 5: Using bioaugmentation to enhance the performance of biological treatment systems, but it requires careful selection of microbial cultures.

Regulatory Officials

Q1. What are the most critical environmental regulations and standards that wastewater treatment plants in our region need to comply with?

Official 1: Effluent discharge standards for pollutants like BOD, COD, TSS, and nutrients, as specified by the Central Pollution Control Board (CPCB).

Official 2: Sludge management and disposal rules to prevent contamination of soil and groundwater, as per the Hazardous Waste Management Rules.

Official 3: Water quality standards for receiving waters to protect aquatic life and human health, as defined by state pollution control boards.

Q2. What are the biggest challenges you face in enforcing environmental regulations and standards for wastewater treatment plants?

Official 1: Limited resources for inspections and monitoring, especially in remote areas.

Official 2: Lack of technical expertise at some plants, leading to non-compliance.

Official 3: Political interference and corruption, which can hinder enforcement efforts.

Q3. What incentives or support can be provided to encourage wastewater treatment plants to proactively implement measures to meet future regulatory requirements?

Official 1: Financial assistance through government schemes like the National Mission for Clean Ganga (NMCG).

Official 2: Technical assistance and training programs for plant operators, organized by the CPCB and state pollution control boards.

Official 3: Recognition and awards for plants that demonstrate environmental excellence.

Q4. How can regulatory frameworks be adapted to promote the adoption of innovative and sustainable wastewater treatment technologies?

Official 1: Streamlining the environmental clearance process for new technologies."

Official 2: Providing incentives for plants to pilot test innovative technologies through public-private partnerships.

Official 3: Developing performance-based regulations that focus on outcomes rather than specific technologies, allowing for flexibility and innovation.

Q5. What are the most effective strategies for ensuring transparency and accountability in wastewater treatment plant operations?

Official 1: Mandating public disclosure of effluent discharge data and environmental monitoring reports.

Official 2: Conducting regular inspections and audits by independent third parties.

Official 3: Establishing a grievance redressal mechanism for citizens to report environmental violations.

Research Scientists

Q1. What are the most promising areas of research in nutrient recovery from wastewater, and what are the potential applications of recovered nutrients?

Scientist 1: Developing cost-effective and scalable technologies for recovering phosphorus from wastewater, such as struvite precipitation.

Scientist 2: Exploring the use of recovered nutrients as biofertilizers for agriculture, especially for organic farming.

Scientist 3: Investigating the potential of recovered nutrients for producing bioplastics and other value-added products.

Scientist 4: Developing technologies for removing nitrogen from wastewater and converting it into ammonia or other useful products, such as fertilizers.

Q2. What are the most innovative and cost-effective advanced treatment technologies for improving treatment efficiency and water quality?

Scientist 1: Developing new membrane materials that are more resistant to fouling and require less energy to operate, using nanotechnology.

Scientist 2: Exploring the use of constructed wetlands for tertiary treatment of wastewater, especially in rural areas.

Scientist 3: Developing biological treatment systems that can remove a wider range of pollutants, including microplastics and pharmaceuticals.

Scientist 4: Investigating the use of artificial intelligence and machine learning to optimize wastewater treatment plant operations and reduce energy consumption.

Q3. How can data analytics and predictive maintenance tools be used to optimize wastewater treatment plant performance and reduce resource consumption?

Scientist 1: Developing algorithms that can predict equipment failures and schedule maintenance proactively, based on real-time data.

Scientist 2: Using data analytics to identify patterns in wastewater flow and composition and optimize treatment processes, accordingly, reducing chemical usage.

Scientist 3: Developing models that can predict the impact of different operating scenarios on plant performance, allowing for better decision-making.

Scientist 4: Using data analytics to identify opportunities for energy savings and resource recovery, such as biogas generation.

Q4. What are the potential environmental and economic benefits of using anaerobic digestion for energy recovery from biosolids?

Scientist 1: Reducing greenhouse gas emissions by capturing and using biogas as a renewable energy source.

Scientist 2: Generating renewable energy that can be used to power the plant or sold to the grid, reducing reliance on fossil fuels.

Scientist 3: Reducing the amount of sludge that needs to be disposed of in landfills, minimizing environmental impacts.

Scientist 4: Producing a valuable fertilizer byproduct that can be used in agriculture, reducing the need for chemical fertilizers.

Q5. How can research findings be effectively translated into practical applications for wastewater treatment plants?

Scientist 1: Collaborating with plant operators and engineers to pilot test new technologies in real-world settings.

Scientist 2: Developing user-friendly software and tools that can help plants implement research findings, such as decision support systems.

Scientist 3: Publishing research findings in accessible formats, such as technical reports and case studies.

Scientist 4: Organizing workshops and training sessions for plant operators and engineers, in local languages, to disseminate research findings and promote adoption of new technologies.

Community Representatives

Q1. What are the biggest concerns of the community regarding wastewater treatment plant operations?

Representative 1: Foul odors emanating from the plant, especially during certain times of the day.

Representative 2: Potential for spills or leaks that could contaminate local water sources, such as rivers and groundwater.

Representative 3: Impact of the plant on property values and the overall quality of life in the neighbourhoods.

Q2. What information would be most helpful for the community to understand the importance of wastewater treatment and water conservation?

Representative 1: Clear and concise explanations of how the plant protects public health and the environment, in local languages.

Representative 2: Information on how the plant is meeting environmental regulations and minimizing its impact on the community.

Representative 3: Practical tips on how residents can conserve water at home and reduce their water bills.

Q3. What are the most effective ways to engage the community in water conservation efforts and pollution prevention initiatives?

Representative 1: Organizing community events and workshops on water conservation and waste management.

Representative 2: Providing educational materials in multiple languages and formats, such as brochures, posters, and videos.

Representative 3: Partnering with local schools and community organizations to promote water conservation and environmental awareness.

Q4. What measures can be taken to ensure that wastewater treatment plant operations are transparent and accountable to the community?

Representative 1: Holding regular public meetings to discuss plant operations and address community concerns.

Representative 2: Providing access to plant data and reports on a user-friendly website.

Representative 3: Establishing a community advisory board to provide input on plant operations and policies.

Q5. What are the potential benefits of wastewater treatment plant improvements for the community, such as improved water quality and reduced environmental impacts?

Representative 1: Cleaner rivers and lakes for recreation, such as swimming and fishing.

Representative 2: Reduced risk of waterborne diseases and improved public health.

Representative 3: Improved property values and a more attractive neighbourhood.

Appendix B. Summary of Responses

Strongly Agree (SA), Agree (A), Neutral (N), Disagree (D), Strongly Disagree (SD)

Table B1. Social Challenges

Challenge	**SA**	**A**	**N**	**D**	**SD**
Population growth	26	14	4	4	2
Urbanization	21	17	8	2	2
Increasing water demand	31	11	4	2	2
Limited freshwater resources	36	9	3	1	1
High reliance on traditional water sources	9	21	9	6	5
Water scarcity	33	10	4	1	2
Conflicting demands for shared water resources	29	13	5	1	2
Public health	23	15	7	3	2
Complexity in governance	16	19	9	4	2
Industrialization	19	16	10	3	2
Water supply access and security	28	12	5	3	2
Migrating population	13	17	11	5	4
Political and management stagnation	17	18	8	6	1
Social status and water use variability	7	16	14	8	5
Public acceptance variability	8	12	19	6	5
Changes in land use	15	15	11	5	4

External drinking water & privatization	10	10	13	9	8
Interstate water conflicts	18	14	9	5	4
Low willingness to pay	5	11	13	13	8
Poor sanitation hygiene	25	13	6	3	3

Table B2. Technical Challenges

Challenge	**SA**	**A**	**N**	**D**	**SD**
Aging infrastructure	39	7	3	0	1
Increasing system complexity	15	19	9	4	3
Inadequate water distribution system	30	11	5	2	2
Leakages and failures of water systems	34	9	4	1	2
Water data	11	19	9	7	4
Capacity constraints	27	13	6	2	2
Maintenance and performance issues	32	10	4	2	2
Intermittent water supply	24	14	7	3	2
Pumping water over long distance	16	18	10	3	3

Table B3. Environmental Challenges

Challenge	SA	A	N	D	SD
Climate shifts	37	8	3	1	1
Drought	40	6	2	1	1
Flooding	35	9	4	1	1
Water quality degradation	38	7	3	1	1
Environmental degradation	36	8	4	1	1
Over exploitation of water resources	39	6	3	1	1
Ecological condition of receiving water	26	14	6	2	2
Urban low flow condition	12	18	10	6	4
Insufficient wastewater treatment	33	11	4	1	1
System emissions	17	17	10	3	3

Table B4. Economic Challenges

Challenge	SA	A	N	D	SD
Economic growth and high living standards	20	15	9	3	3
Resources expenditure constraints	31	11	4	2	2
Difficulties in financing the aging infrastructures	34	10	3	1	2
Non-revenue water	29	12	5	2	2

Table B5. Institutional Challenges

Challenge	SA	A	N	D	SD
Lack of clear mandates and coordination	28	13	5	2	2
Inadequate regulatory framework	30	11	5	2	2
Limited institutional capacity	32	10	4	2	2
Poor monitoring and evaluation	27	13	6	2	2
Lack of community participation	21	16	8	3	2
Corruption and lack of transparency	36	8	3	1	2
Political interference	34	9	4	1	2