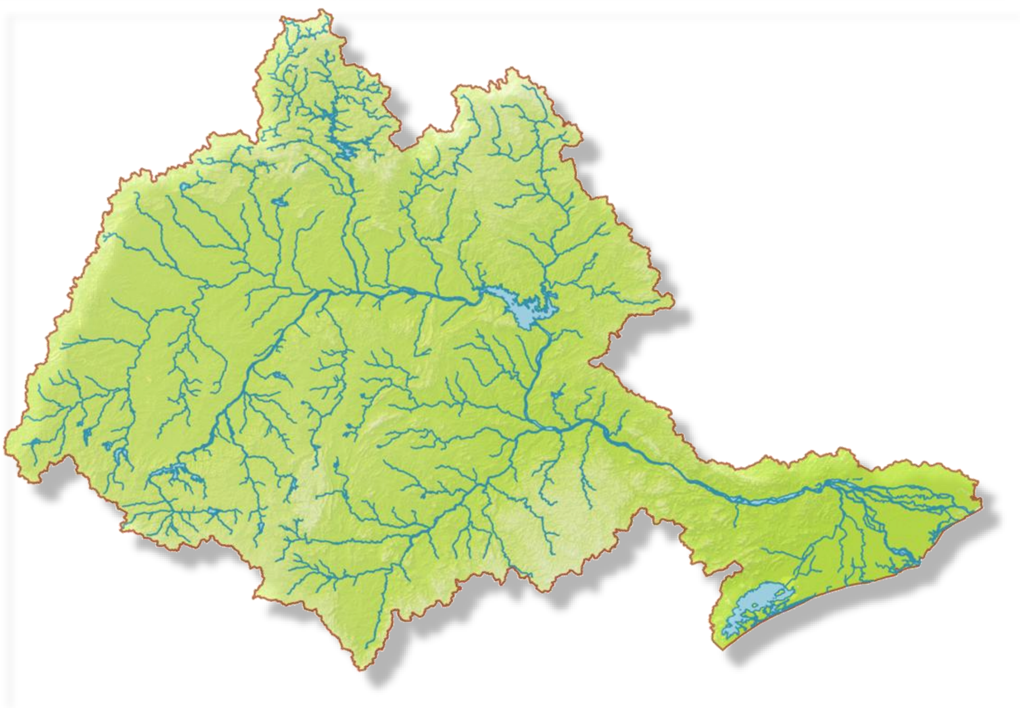
National River Conservation Directorate
Ministry of Jal Shakti,
Department of Water Resources,
River Development & Ganga Rejuvenation
Government of India

MAPPING OF BEST PRACTICES IN SOLID-LIQUID WASTE MANAGEMENT



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MAPPING OF BEST PRACTICES IN SOLID-LIQUID WASTE MANAGEMENT

Mahanadi River Basin

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National River Conservation Directorate (NRCD)

The National River Conservation Directorate, functioning under the Department of Water Resources, River Development & Ganga Rejuvenation, and Ministry of Jal Shakti providing financial assistance to the State Government for conservation of rivers under the Centrally Sponsored Schemes of 'National River Conservation Plan (NRCP)'. National River Conservation Plan to the State Governments/ local bodies to set up infrastructure for pollution abatement of rivers in identified polluted river stretches based on proposals received from the State Governments/ local bodies.

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Centres for Mahanadi River Basin Management Studies (cMahanadi)

The Centres for Mahanadi River Basin Management Studies (cMahanadi) is a Brain Trust dedicated to River Science and River Basin Management. Established in 2024 by NIT Raipur and NIT Rourkela, under the supervision of cGanga at IIT Kanpur, the center serves as a knowledge wing of the National River Conservation Directorate (NRCD). cMahanadi is committed to restoring and conserving the Mahanadi River and its resources through the collation of information and knowledge, research and development, planning, monitoring, education, advocacy, and stakeholder engagement.

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cGanga is a think tank formed under the aegis of NMCG, and one of its stated objectives is to make India a world leader in river and water science. The Centre is headquartered at IIT Kanpur and has representation from most leading science and technological institutes of the country. cGanga's mandate is to serve as think-tank in implementation and dynamic evolution of Ganga River Basin Management Plan (GRBMP) prepared by the Consortium of 7 IITs. In addition to this, it is also responsible for introducing new technologies, innovations, and solutions into India.

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Preface

In an era of unprecedented environmental change, understanding our rivers and their ecosystems has never been more critical. This report aims to provide a comprehensive overview of our rivers, highlighting their importance, current health, and the challenges they face. As we explore the various facets of river systems, we aim to equip readers with the knowledge necessary to appreciate and protect these vital waterways.

Throughout the following pages, you will find an in-depth analysis of the principles and practices that support healthy river ecosystems. Our team of experts has meticulously compiled data, case studies, and testimonials to illustrate the significant impact of rivers on both natural environments and human communities. By sharing these insights, we hope to inspire and empower our readers to engage in river conservation efforts.

This report is not merely a collection of statistics and theories; it is a call to action. We urge all stakeholders to recognize the value of our rivers and to take proactive steps to ensure their preservation. Whether you are an environmental professional, a policy maker, or simply someone who cares about our planet, this guide is designed to support you in your efforts to protect our rivers.

We extend our heartfelt gratitude to the numerous contributors who have generously shared their stories and expertise. Their invaluable input has enriched this report, making it a beacon of knowledge and a practical resource for all who read it. It is our hope that this report will serve as a catalyst for positive environmental action, fostering a culture of stewardship that benefits both current and future generations.

As you delve into this overview of our rivers, we invite you to embrace the opportunities and challenges that lie ahead. Together, we can ensure that our rivers continue to thrive and sustain life for generations to come.

Centre for Mahanadi River Basin
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Solid Waste Management (SWM) has become a critical environmental and public health concern, particularly in rapidly urbanizing countries like India. The surge in waste generation has significantly attributed to the rise in population, industrialization, and changing consumption patterns. A substantial quantity of municipal solid waste is left untreated and frequently dumped in landfills or open dumps, which has detrimental effects on the environment, notably soil deterioration, air pollution, and water body contamination (Meena et al., 2023; Mazzoli et al., 2024). Illegally dumped municipal solid waste has been considered as one of the elements contributing to the decline of river water quality in the Mahanadi River Basin (Das et al., 2025). Therefore, adopting effective and sustainable waste management techniques is so crucial. The primary objectives of this study are to identify best practices in solid waste management, analyze successful national and international case studies, and explore technological innovations with a focus on regions like Odisha, and the Mahanadi basin.

1.2 Liquid Waste Management

An efficient liquid waste management is very essential for protecting health, maintaining water quality, and ensuring sustainable river basin management. Due to rapid urbanization, industrial growth and increasing water consumption have increased the volume of wastewater generated from domestic, industrial sector, healthcare centers, and commercial activities. If it is not managed liquid waste can contaminate surface water, groundwater, and soil systems, leading to ecological degradation and increased risks to human health. There were diverse approaches around the globe have been adopted to manage liquid waste through a combination of policy frameworks, technological innovations, institutional mechanisms, and community-based practices. These approaches were referred to as best practices provide valuable insights into effective strategies for wastewater treatment, reuse, disposal, and pollution prevention. Mapping of such best practices helps identifying solutions that are technically feasible, environmentally sustainable, and adaptable to basin-specific conditions. However, Best practice of mapping is particularly important in river basins where wastewater management directly influences river health, ecosystem functioning, and water availability for multiple sectors. The identification and evaluation of successful case studies from national and international contexts enable evidence based decision making and support the development of scalable models suitable for specific basin conditions.

This report focuses on analyzing best practices in liquid waste management with emphasize on technological and institutional policy interventions that contribute to improved wastewater treatment, resource recovery, and pollution reduction. While the framework includes both solid and liquid waste management to establish a structured understanding of effective waste management approaches. This report follows a structural approach that begins with the identification and review of relevant national and international case studies, followed by some emerging technological innovations in liquid waste management. These insights show scalable and sustainable management models suitable for the targeted basin along with an assessment of their adaptability and feasibility across different basin zones. The study further represents recommendations and highlights of the roles and responsibilities of key stakeholders in facilitating the effective implementation of best practices, promoting sustainable wastewater management, and supporting long-term water resource protection.

1.2.1 Objectives

- To review national case studies demonstrating successful implementation of liquid waste management techniques.
- To analyze international best practices that provide key insights for improving wastewater management systems.
- To identify technological innovations that enhance efficient treatment, resource recovery, and environmental protection.
- To access scalable models that can be adapted to basin-specific, socio-economic and environmental conditions.
- To evaluate feasibility and adaptability of selected practices across different basin zones.
- To develop recommendations highlighting institutional roles, governance mechanisms, and stakeholder participation for effective implementation.

Through this structured framework this report aims to support integrated river basin management by identifying practical evidence-based strategies that improve wastewater management outcomes and contribute to long-term environmental sustainability.

2 National Case Studies

2.1 Solid Waste Management

India offers a variety of solid waste management practices, with a few cities emerging as leaders in innovation, governance, and community participation. In India, the practices of solid waste management vary considerably from one city to another, but there are several urban centers that have emerged as successful models owing to their innovative and sustainable approaches **(Kumar et al., 2020**).

2.1.1 Madhya Pradesh (Indore-digital twin model)

Indore is the best example of solid waste management in India. The city has achieved 100 per cent door-to-door collection and complete segregation of waste at source into wet, dry and hazardous categories. The Indore model's major strength is strong citizen participation backed by strict enforcement, GPS-based monitoring of collection vehicles and real time tracking systems. The city produces more than 1000 tonnes of waste each day, but most of it is processed in composting, recycling and waste-to-energy plants. Recent innovations include biomining of legacy waste, conversion of green waste to fuel (wood pellets) and mobile-based on-demand waste collection systems such as "QuickSaaf". These initiatives reflect a shift toward circular economy and smart governance (Source : Indore Smart City-Solid Waste management).

2.1.2 Ma**harashtra (Pune & Kolhapur Model)**

Pune created a people-centric model bringing informal waste workers into the mainstream using the SWaCH cooperative. Waste pickers are formally recognised and are involved in door-to-door collection and segregation, which improves the efficiency of recycling and social inclusion (Source: SwacH Pune-Journey of waste pickers). However, the city generates large amounts of waste (1000–2000 tonnes/day) putting pressure on the treatment systems. Kolhapur promotes a waste to resource approach where organic waste is processed for compost and biogas. Recent advances include decentralised composting, bulk waste generator rules, and a greater focus on circular economy practices.

2.1.3 Chhattisgarh (Ambikapur Model)

Ambikapur is a zerowaste city model, known for its complete segregation and decentralised waste processing by means of resource recovery centers. Waste is separated into various categories and locally processed, with revenue from recyclables. Women self help groups are playing a major role in showing the importance of community participation (Source: Chadha 2025, Princeton-Ambikapur model).

2.1.4 Kerala (Decentralized Model – Haritha Karma Sena)

Kerala implements a complete decentralised waste management system, where waste is treated at the house or community level. The Haritha Karma Sena (green task force) collects the non-biodegradable waste and ensures waste minimization through recycling. They also used digital platform like Haritha mithram for monitoring door to door collections, segregation and waste movement through MRFs and RRFs. Recently Kerala is working with Central undertakings like Bharat Petroleum Corporation Ltd (BPCL) for setting up large bio Compressed Natural/Bio Gas Plants that can cater to a large portion of municipal solid waste. Some recent developments include user-fee-based systems, increased financial sustainability and integration of local governance, making it one of the most scalable decentralised models in India (Source: Kerala LSGD-Solid waste management, Haritha Karma Sena & Haritha mithram e-governance portal).

2.1.5 Gujurat (Surat Model)

Surat has become a model city for cleanliness and has developed an efficient municipal system with scientific landfill management, regular waste collection and strong monitoring mechanisms. The city uses modern technologies for waste tracking and has come a long way in urban sanitation (Source: Surat Municipal Corporation-Solid Waste Management).

2.1.6 Odisha (Cuttack & Bhubaneswar-Emerging model)

Integrated Solid Waste Management (SWM) systems that consist of door-to-door collection, segregation, and material recovery facilities have been progressively introduced in cities such as Bhubaneswar and Cuttack. Plastic waste management initiatives by means of self-help groups and decentralized composting are also being encouraged (Source: OSPCB & Housing Urban department-SWM).

2.1.7 Uttar Pradesh (Varanasi-Technological cooperatives)

Varanasi (Uttar Pradesh) has witnessed remarkable changes in solid waste management with the implementation of modern and technological systems. High-capacity Waste to Energy (WtE) plants have been set up in the city that convert huge amounts of solid waste produced by municipalities into energy thus helping reduce the reliance on landfills and encouraging the use of resources sustainably. Also, the banks of River Ganga have been incorporated into an intelligent waste management system through the introduction of sensor-enabled smart bins that provide real-time monitoring of the waste generated in the area (Source: National Green Tribunal-Varanasi SWM).

2.2 Liquid Waste Management

India has made notable progress in liquid waste management through the adoption of decentralized treatment approaches, nature-based solutions, and policy-supported sanitation programs. Several cities and rural regions demonstrate how appropriate technological choices, institutional coordination, and community participation can significantly improve wastewater treatment efficiency and reduce environmental pollution. These case studies provide important lessons for identifying scalable and adaptable best practices suitable for river basin contexts.

2.2.1 Case Study-1: Odisha

Odisha has represented successful example of liquid waste transformation through FSSM (Faecal Sludge and Septage Management) and DEWATS (Decentralized Wastewater System) as illustrated in Fig. 1. Dhenkanal has successfully implemented FSTP'S (Faecal Sludge Treatment Plant) through decentralized clustering model partnering with UNICEF and the Centre for Policy Research this district leveraged FSTP to process sludge from neighboring gram panchayats through small cesspool emptier vehicle to navigate narrow lanes and ensure regular and affordable emptying service. The impact of this process is to eliminate indiscriminate dumping in local water ways and create a blueprint for scaling safe liquid waste management. Whereas, Bhubaneswar capital city of Bhubaneswar also has done a remarkable work by implementing DEWATS (Decentralized Wastewater System) the septage treatment process provides a prime technological case study which includes solid- liquid separation where raw septage goes through solid- liquid separation and is dried in sludge drying beds and then composted with green waste for soil conditioning then the liquid component flows by gravity into an Anaerobic Baffled Reactor (ABR) followed by Planted Gravel Filter(PGF) and a polishing pond. This effluent treated water from the polishing pond achieves high water quality and is directly recycled for irrigation and plantation.

Figure 1. Represent Faecal Sludge Treatment Plant (FSTP) to process sludge from neighboring gram panchayats through small cesspool emptier vehicle to navigate. (Source: Google)

2.2.2 Case Study-2: Indore

Indore represents one of the most successful urban examples of liquid waste transformation (Fig2). This city implemented mandatory source segregation along with decentralized sewage treatment infrastructure enabling treatment of approximately 367.8 MLD of wastewater by establishing treatment plants closer to the source of generation Indore reduced dependence on long sewer networks, minimized leakages, and improved treatment efficiency. Treated wastewater is reused for landscaping, industrial cooling, and other non-potable purposes demonstrating the potential of wastewater as a resource. The success of this model has been supported by strong municipal governance, institutional coordination, and active citizen participation, reinforced through national programs such as the Swachh Bharat Mission (Urban). (NIUA, 2020).

Figure 2. Represent Indore's Model of Water Conservation. (Source: National Institute of Urban Affairs, NIUA), 2020)

2.2.3 Case Study-3: Ujjain

Ujjain, where a community-led decentralized system has been implemented in Ravindra Nagar (Fig3). The locality uses reed bed–based constructed wetlands to treat approximately 13 kiloliters per day of domestic wastewater. The system achieved nearly 50% reduction in BOD, nitrates, and phosphates, demonstrating the effectiveness of plant-based treatment technologies in small settlements. Such nature-based solutions require low capital investment, minimal energy input, and simple maintenance making them suitable for peri-urban and small-town applications. (CSE, 2019).

Figure 3 Reed Bed–Based Decentralized Wastewater Treatment Ujjain (Ravindra Nagar) | Nature-based treatment system. (Source: Google)

2.2.4 Case Study-4: Alappuzha (Kerala)

The Alappuzha (Kerala) decentralized wastewater management model is widely recognized for its use of DEWATS (Decentralized Wastewater Treatment Systems) combined with household-level septic tanks and community-managed treatment units (Fig4). The system significantly reduced pollution entering canals and backwaters, improving local environmental conditions and public health outcomes. The model demonstrates how decentralized systems can be effectively implemented in dense settlements with high water tables and limited space for conventional sewer networks.

Figure 4 Represents Alappuzha (Kerala) decentralized wastewater management model. (Source: Google)

2.2.5 Case Study-5: Surat

Surat provides an example of large-scale wastewater reuse in an industrial urban setting (Fig5). Surat supplies tertiary-treated water to nearby industries through dedicated pipelines for non-potable industrial uses reducing dependency on freshwater resources. This includes gardening agriculture, lake rejuvenation and sewer cleaning. Surat Municipal Corporation reports that more than 30% of treated waste water is reused. (CPCB, 2020, Surat Municipal Corporation)

Figure 5 Represent Latest Advanced Robotic Technology for cleaning of Sewerage System Surat Municipal Corporation

2.2.6 Case Study-6: Pune

In Pune, structured faecal sludge and septage management (FSSM) systems have been introduced to manage wastewater in areas not connected to centralized sewer networks. Treatment facilities process sludge collected from septic tanks, preventing uncontrolled dumping and reducing groundwater contamination risks. The Pune model demonstrates the importance of addressing on-site sanitation systems as part of integrated liquid waste management planning. (MoHUA, 2019).

In rural India, greywater constitutes a major proportion of liquid waste, with an estimated 15,000–18,000 MLD generated daily. Several villages have successfully implemented low-cost greywater management solutions such as soak pits, kitchen gardens, leach pits, and stabilization ponds. These systems help prevent water stagnation, reduce vector-borne diseases, and improve local sanitation conditions. National programs such as Swachh Bharat Mission (Gramin) and Jal Jeevan Mission have played a key role in promoting decentralized greywater management and strengthening awareness regarding safe disposal practices. These national experiences demonstrate that decentralized wastewater treatment systems provide practical solutions to bridge existing treatment gaps. Locating treatment units closer to the source reduces conveyance costs, minimizes infrastructure requirements, and allows flexible expansion based on population growth. Integration of industrial and domestic wastewater treatment further reduces pollutant loads entering rivers and groundwater systems (DDWS, 2021).

Despite these improvements, challenges remain in achieving universal wastewater treatment coverage. A considerable proportion of urban sewage still remains untreated and many rural areas lack structured drainage and treatment infrastructure. Addressing these gaps requires strengthening institutional capacity, increasing investment in decentralized technologies, and improving coordination among implementing agencies. Overall, national case studies indicate that successful liquid waste management depends on a combination of appropriate technology selection, decentralized infrastructure, strong governance, financial support mechanisms, and community participation. The integration of nature-based systems, resource recovery approaches, and policy-driven sanitation programs provides a strong foundation for developing scalable liquid waste management models applicable across different basin zones. (NITI Aayog, 2020).

3 International Case Studies

3.1 Solid Waste Management

3.1.1 Sweden (Waste to energy model)

Sweden boasts of one of the most efficient waste management systems, with about 1% of waste ending up in landfills. Recycled and processed waste generates electricity and heat at incineration plants. Latest developments in Sweden include development of carbon capture technology in the waste-to-energy plants and importing of waste from other nations to keep the energy generation going (Bolton et al., 2019).

3.1.2 Japan (Zero-Waste & Segregation Model)

Japan operates a very systematic system where multi-level segregation takes place in up to 20-40 categories. Zero-waste cities such as Kamikatsu have developed by maximizing recycling activities and minimizing waste to be deposited in landfills. Latest developments in Japan include use of artificial intelligence in waste-sorting and automation of recycling plants (Herrador et al., 2023).

3.1.3 Germany (Circular Economy & EPR Model)

The waste management model of Germany is based on extended producer responsibility, which means the producers take care of the disposing of their products after usage. The Green Dot system helps in recycling packaging materials. Latest developments in the country involve chemical recycling of plastic waste and circular economy innovations.

3.1.4 South Korea (Smart & Incentive-Based Model)

The system used in South Korea is the Pay-as-you-throw model, which charges individuals according to the amount of waste generated by them. Technological advances in this system include the use of radio-frequency identification bins, Internet of Things, and real-time waste tracking technologies (Park et al., 2018).

3.1.5 Singapore (High-Tech Urban Model)

As a result of land scarcity, Singapore depends heavily on waste to energy incineration technology, which helps to decrease the amount of waste by about 90%. The leftover ash is dumped into engineered landfills such as Semakau landfill. The latest developments include automation of waste collection and development of urban waste pipelines in smart residential areas (Syme et al., 2021).

3.1.6 United States (San Francisco – Zero Waste Model)

San Francisco is the leading urban area when it comes to waste management and recycling. It has mandatory recycling and composting laws and reaches over 80% diversion rates. The latest developments in San Francisco include AI-based sorting facilities, regulatory enforcement and composting facilities for agricultural purposes (Marfe et al.,2020).

3.1.7 China (Rapidly Evolving Model)

China recently introduced strict rules of segregation in major cities such as Shanghai. The latest developments include large-scale waste-to-energy facilities, AI-based sorting technologies and enforcement mechanisms (Li et al., 2025).

3.1.8 Slovenia (Ljubjana Model)

Ljubljana is considered the first "Zero Waste Capital" of Europe, as it has managed to implement an extremely efficient, preventive waste management system. The main principle of Ljubljana waste management system is "pre-cycling", which means that the citizens of the capital are encouraged to minimize the waste production through shopping without any packaging. One of the strengths of Ljubljana's waste management system is its convenient segregation infrastructure, where the recycling containers are more abundant than the garbage containers. In this way, people are encouraged to segregate their waste, which leads to one of the highest separate collection rates in the EU (Glavic et al., 2020; Muttil et al., 2026).

3.2 Liquid Waste Management

International experiences demonstrate that effective liquid waste management relies on integrating advanced treatment technologies with local environmental conditions, regulatory frameworks, and economic feasibility. Different countries have adopted context-specific approaches to wastewater treatment, reuse, and resource recovery, offering valuable insights for developing adaptable and scalable solutions suitable for basin-level implementation.

3.2.1 Case Study-1: Singapore

Countries facing significant water scarcity have demonstrated how wastewater can be transformed into a reliable alternative water resource. Singapore is a widely recognized example, where advanced membrane-based treatment systems are used to produce high-quality reclaimed water (NEWater) suitable for industrial use and indirect potable applications (Fig 6). Strong monitoring systems, stringent quality control standards, and long-term planning have enabled Singapore to significantly reduce dependence on imported water sources while ensuring water security. (PUB, Singapore's National Water Agency)

Figure 6 Represent Latest Advanced Robotic Technology for cleaning of Sewerage System Surat Municipal Corporation

3.2.2 Case Study-2: European countries

European countries such as Belgium and England have successfully implemented wastewater reuse strategies for industrial processes, agricultural irrigation, and other non-potable applications (Fig 7). These approaches help reduce pressure on freshwater resources, enhance water security, and promote circular water management practices. The reuse of treated greywater and reclaimed wastewater in urban systems has also contributed to improved water-use efficiency, reduced wastewater discharge volumes, and lower environmental pollution loads. Such initiatives demonstrate the potential of water reuse as a sustainable component of integrated wastewater management and resource conservation strategies (Lazarova et al., 2003).

Figure 7 Wastewater reuse and circular water management practices in Belgium and England.

3.2.3 Case Study-3: Italy

In Italy, wastewater management practices demonstrate the importance of developing flexible and specialized treatment systems for handling complex industrial effluents (Fig 8). Industrial clusters often generate wastewater with highly variable chemical and physical characteristics, necessitating customized treatment approaches that integrate physical, chemical, and biological processes. Advanced treatment configurations, including membrane bioreactors and chemical–physical treatment units, enhance treatment efficiency and ensure compliance with environmental discharge standards. The Italian experience highlights the need for adaptable and site-specific technological solutions capable of managing diverse waste streams while maintaining operational reliability and environmental sustainability (Collivignarelli et al., 2025).

Figure 8. Represent Italy's Industrial Wastewater Management

3.2.4 Case Study-4: Kuwait

In arid and semi-arid regions, wastewater management strategies must be carefully adapted to local climatic conditions and groundwater protection requirements. Kuwait provides a notable example where lined evaporation ponds are utilized for liquid waste management (Fig 9). These engineered lining systems prevent wastewater infiltration into underlying soil and aquifer systems, thereby safeguarding groundwater quality while facilitating controlled evaporation under high-temperature conditions. Such climate-responsive approaches demonstrate the importance of designing wastewater management systems that are tailored to regional environmental conditions, resource availability, and potential ecological risks (Al-Yaqout, 2003).

Figure 9. Kuwait's Lined Evaporation Ponds for Liquid Waste Management

3.2.5 Case Study-5: Northern Europe

Northern European countries such as Denmark and Finland illustrate how wastewater treatment facilities can evolve from conventional pollution control systems into integrated resource recovery centers (Fig 10). Advanced treatment plants in these countries recover valuable nutrients, particularly phosphorus and nitrogen, generate renewable energy through biogas production, and support circular economy principles. By transforming wastewater and sludge into reusable resources, these facilities enhance energy efficiency, reduce operational costs, and minimize the environmental footprint of wastewater treatment processes. Such approaches demonstrate the potential of resource-oriented wastewater management to contribute to both environmental sustainability and long-term resource security (Hosseinian et al., 2023).

Figure 10 Northern Europe resource recovery-oriented Wastewater treatment

Collectively, these international examples demonstrate that successful liquid waste management requires a balanced integration of technological innovation and context-specific implementation strategies. Advanced treatment technologies, including membrane filtration, biological treatment processes, bioremediation techniques, and sludge dewatering systems, can substantially enhance treatment efficiency, pollutant removal, and resource recovery potential. However, the long-term effectiveness of these solutions depends on adequate infrastructure planning, skilled operation and maintenance, financial viability, and strong institutional support. Global best practices emphasize the need for integrated approaches that combine technological advancements with supportive policy frameworks, economic feasibility, environmental sustainability, and stakeholder engagement. These lessons provide valuable insights for identifying adaptable and scalable solutions that can be tailored to basin-specific conditions and contribute to sustainable wastewater management and water resource protection (Singh et al., 2023).

4 Technological Innovations

4.1 Solid waste Management

The Mahanadi River Basin extends across substantial parts of Chhattisgarh and Odisha, encompassing rapidly urbanizing centres, industrial clusters, agricultural regions and smaller semi-urban settlements. Increasing urbanization, population growth, industrial development and changing consumption patterns have increased the generation of municipal, commercial and industrial solid waste across the basin. Consequently, technological innovations in solid waste management (SWM) are increasingly important for improving collection, segregation, resource recovery, treatment and environmentally safe disposal, while also reducing the risk of waste-derived pollution entering the Mahanadi and its tributaries.

Recent studies have demonstrated the potential of GIS, remote sensing, spatial analysis and data-driven approaches for identifying waste-management hotspots, optimizing infrastructure locations and assessing environmental impacts within the Mahanadi basin (Das, 2025a; Das, 2025b). These technologies are particularly relevant for a basin-scale approach because solid-waste management interventions need to account for differences in urban density, waste generation, industrial activity, land availability and proximity to rivers and drainage networks.

In the Chhattisgarh portion of the Mahanadi basin, major urban and industrial centres such as Raipur, Durg–Bhilai, Bilaspur, Korba, Dhamtari, Mahasamund, Raigarh and Janjgir-Champa generate substantial quantities of municipal and industrial solid waste. The technological approach in the state has increasingly shifted from conventional collection and disposal towards door-to-door collection, source segregation, decentralized processing, material recovery, integrated solid waste management and legacy-waste remediation. Chhattisgarh has reported extensive coverage of door-to-door collection and source segregation, supported by composting, SLRM/MRF facilities and integrated solid-waste management infrastructure.

In Raipur, one of the largest urban centres in the basin, technological interventions include structured door-to-door collection, waste transportation systems, source segregation, processing and scientific disposal. The availability of city-level solid-waste datasets covering collection efficiency, segregation, processing, disposal, equipment and vehicles provides opportunities for data-driven and GIS-based SWM planning. (Raipur Municipal Corporation) GIS and multi-criteria decision-analysis approaches have also been demonstrated for identifying suitable landfill locations in the Raipur urban region, illustrating the potential of spatial decision-support systems for environmentally compatible waste infrastructure planning.

Bilaspur represents another important example where technology can support optimization of the entire waste-management chain. GIS-based and mathematical optimization approaches have been applied for transfer-station location planning, integrating source separation, transportation networks, landfill locations and economic considerations. (ScienceDirect) The state has also identified Raipur and Bilaspur for integrated solid waste management infrastructure, including scientific landfill and processing systems.

In Durg–Bhilai and Korba, the technological focus is particularly important because of the interaction between municipal waste and intensive industrial activities. These areas require integrated systems combining material recovery, composting, scientific landfilling, construction and demolition waste management, industrial waste management and environmental monitoring. Korba, in particular, is a major coal and power-generation centre, while the Durg–Bhilai region is dominated by steel and associated industries. Therefore, technological interventions should emphasize segregation of municipal and industrial waste streams, resource recovery, treatment of process-related residues and strict control of leachate and contaminated runoff.

Dhamtari, Mahasamund and other smaller urban centres can benefit from decentralized and low-cost technologies such as composting, vermicomposting, decentralized organic-waste processing, small-scale biogas systems, SLRM centres and localized material recovery facilities. Such systems can reduce transportation requirements and minimize the quantity of untreated organic waste reaching disposal sites. Earlier implementation of composting and vermicomposting systems in municipalities such as Dhamtari, Korba and Durg demonstrates the applicability of decentralized treatment technologies in the state.

An important technological intervention across Chhattisgarh is the remediation of legacy waste through biomining. Legacy dumpsites can act as long-term sources of leachate, litter, odour, particulate matter and other contaminants, particularly where they are located near drainage channels or water bodies. Biomining involves excavation, screening and segregation of old waste into recoverable materials, combustible fractions, soil-like fractions and rejects, thereby reducing the volume of accumulated waste and enabling reclamation of dumpsite land. State-level monitoring has reported biomining activities at multiple dumpsites, along with extensive progress in clearing legacy waste.

For the Mahanadi basin, GIS and remote sensing have additional value in identifying dumpsites and waste-processing facilities located close to rivers, tributaries, drains and flood-prone areas. Such spatial databases can be integrated with drainage networks, land-use maps and water-quality monitoring stations to identify potential pathways of solid-waste-derived pollution into the river system. This approach is particularly relevant in Chhattisgarh because the Mahanadi basin includes extensive urban and industrial areas as well as major tributary systems such as the Seonath, Hasdeo, Mand, Kelo, Pairi and Jonk.

The Odisha portion of the Mahanadi basin includes important urban and industrial centres such as Cuttack, Sambalpur, Angul, Jharsuguda, Boudh, Sonepur and parts of Nayagarh and Khordha. Rapid urbanization and industrialization have increased pressure on existing SWM systems, particularly around major urban centres and industrial clusters. Technological innovations are therefore being introduced to improve collection, transportation, segregation, resource recovery and scientific disposal.

In Cuttack and Khordha, including Bhubaneswar, smart-city and urban-management initiatives have supported the adoption of GPS-enabled collection vehicles, digital monitoring systems, route optimization and decentralized waste-processing facilities. Material Recovery Facilities (MRFs) and mechanized or semi-mechanized segregation systems can improve recovery of recyclable materials and reduce the quantity of waste requiring final disposal.

In Sambalpur and Jharsuguda, where industrial activity is prominent, integrated waste-management approaches are particularly important. Technologies such as composting, material recovery, plastic recycling, scientific landfill management and legacy-waste remediation can be combined with stronger monitoring of industrial and hazardous waste streams. In Sambalpur, for example, the municipal corporation initiated the process for biomining legacy waste at the A. Katapali dumpsite through an RFP issued in 2024 (Sambalpur Municipal Corporation, 2024).

Angul, characterized by mining, power generation and heavy industrial activity, requires a differentiated technological approach involving industrial waste characterization, waste minimization, resource recovery, scientific disposal, landfill engineering and environmental monitoring. GIS and remote sensing can support identification of waste-disposal hotspots and assessment of their relationship with drainage networks and surface-water resources (Das et al., 2025a).

In smaller and semi-urban districts such as Boudh and Sonepur, decentralized SWM technologies are more appropriate because of comparatively lower waste generation and limited economies of scale for large centralized facilities. Community composting, vermicomposting, decentralized organic-waste treatment, small material-recovery centres and local resource-recovery systems can provide cost-effective solutions while reducing the transportation and disposal burden.

Across both Chhattisgarh and Odisha, several emerging technologies have significant potential for strengthening solid-waste management and protecting the Mahanadi River system. Biomining and dumpsite remediation are particularly important for reducing the long-term environmental impacts of legacy waste. Similarly, MRFs, decentralized composting, plastic recovery and resource-recovery systems can increase material recovery and reduce dependence on landfilling.

The adoption of IoT-enabled smart bins, GPS-based vehicle tracking, RFID-based collection systems, digital weighing systems and real-time SWM dashboards can further improve operational efficiency in larger urban centres. These systems can provide information on collection routes, vehicle performance, waste quantities and service gaps, allowing municipal authorities to move towards data-driven waste management.

Another important technological application is GIS-based basin-scale waste-pollution mapping. A common geospatial platform can integrate the locations of dumpsites, MRFs, composting plants, landfills, waste-processing facilities, industrial waste-generating units, river channels, tributaries, drains and water-quality monitoring stations. Such integration can help identify areas where poorly managed solid waste may directly or indirectly affect surface-water quality.

Technologies for river and drain interception, including floating waste barriers, trash booms, trash skimmers and mechanical surface-cleaning systems, can also be deployed at selected locations where solid waste frequently enters the Mahanadi or its tributaries. However, these should be considered supplementary measures rather than substitutes for source segregation, collection and scientific waste management.

Overall, technological innovation in solid waste management across the Mahanadi basin should follow a need-based and location-specific approach. Large urban centres such as Raipur, Bhubaneswar, Cuttack, Bilaspur and Sambalpur can benefit from smart collection, digital monitoring, mechanized processing and integrated waste-management systems. Industrial centres such as Korba, Durg–Bhilai, Raigarh, Angul and Jharsuguda require stronger integration of municipal, industrial and hazardous-waste management with environmental monitoring. Smaller towns and rural settlements are better suited to decentralized composting, material recovery and community-based resource-recovery systems.

For effective protection of the Mahanadi, these technologies should ultimately be integrated into a basin-scale solid-waste management framework, linking waste generation and treatment data with GIS-based environmental monitoring, river-water quality, drainage networks and pollution hotspots. Such an integrated approach can help shift SWM from a conventional collection-and-disposal model towards a resource-recovery, pollution-prevention and river-protection model across both Chhattisgarh and Odisha.

4.2 Liquid waste Management:

4.2.1 Emerging and Proven Technologies in Liquid Waste Management

Technological innovations play a crucial role in enhancing the efficiency, sustainability, and adaptability of liquid waste management systems. Recent advancements have focused on decentralized wastewater treatment technologies, nature-based solutions, faecal sludge management, and smart monitoring systems that improve pollutant removal efficiency, facilitate resource recovery, and reduce operational costs. These innovations support the transition from conventional waste disposal practices toward integrated, resilient, and circular wastewater management approaches, thereby contributing to improved environmental protection and sustainable water resource management (Sha et al., 2024).

4.2.2 Decentralized Wastewater Treatment Systems (DEWATS)

Decentralized Wastewater Treatment Systems (DEWATS) provide a practical and environmentally sustainable approach for managing wastewater close to the source of generation. Unlike conventional centralized sewage treatment plants, these are designed to treat domestic, institutional, and small-scale industrial wastewater ranging from approximately 1 to 1,000 cubic meters per day making them suitable for small communities, residential complexes, commercial establishments, and industrial clusters. DEWATS systems are particularly beneficial in areas where centralized sewer infrastructure is either unavailable or economically unviable these systems operate primarily on gravity flow principles and biological treatment processes reducing the need for complex mechanical equipment.

Key advantages of DEWATS include:

- Cost-effectiveness: Comparatively low construction and operational costs.
- Low maintenance requirements: Minimal mechanical components reduce operational complexity.
- Energy efficiency: Systems generally function without continuous electricity input.
- High treatment performance: Capable of removing a significant proportion of organic pollutants and suspended solids.

The treatment process typically consists of a multi-stage sequence that combines physical and biological treatment mechanisms:

- Primary Settling (Sediment Removal): Wastewater first enters a settling chamber where heavier suspended solids settle at the bottom separating from the liquid fraction.
- Anaerobic Baffled Reactors (Biological Treatment): The partially clarified wastewater flows through a series of chambers where anaerobic microorganisms degrade organic matter in oxygen-free conditions.
- Filtration Units: Wastewater passes through filter media such as sand, gravel, or charcoal, which physically remove remaining suspended particles while supporting microbial activity.
- Polishing Units or Ponds: Final treatment occurs through exposure to sunlight and atmospheric oxygen, helping to reduce pathogen levels and improve effluent quality for safe discharge or reuse. DEWATS are widely recognized as effective and sustainable solutions for decentralized sanitation planning, especially in peri-urban and rural areas where conventional sewerage infrastructure is limited or unavailable (Varma et al., 2022).

4.2.3 Nature Based Solutions (NBS)

Nature-based solutions (NBS) are increasingly being adopted as sustainable and low-cost alternatives for wastewater treatment. Techniques such as constructed wetlands, root-zone treatment systems, and reed bed filtration utilize natural processes involving plants, soil, and microbial communities to remove pollutants from wastewater.

Root-zone treatment: This system allow wastewater to pass through planted beds where plant roots, microorganisms, and soil media work together to remove organic matter, nutrients, and pathogens. Constructed wetlands are engineered systems designed to replicate natural wetland functions, enabling effective filtration, sedimentation, and biological degradation of contaminants.

Reed bed: This system uses specific wetland vegetation that enhances filtration and nutrient uptake improving overall water quality. These approaches require low energy input, minimal maintenance and provide additional environmental benefits such as biodiversity enhancement and landscape improvement.

Nature-based treatment systems are particularly suitable for small settlements, institutional campuses, and environmentally sensitive areas where conventional treatment technologies may not be feasible due to economic, technical, or environmental constraints (Vymazal, 2018).

4.2.4 Industrial Wastewater Treatment Technologies

Industrial wastewater often contains complex pollutants including heavy metals, chemicals, oils, and organic compounds requiring multi-stage treatment processes to ensure safe discharge or reuse. Treatment systems typically include:

- Preliminary and primary treatment for removal of suspended solids and oil residues
- Secondary biological treatment for degradation of organic matter
- Tertiary treatment processes such as advanced filtration, chemical precipitation, membrane separation, or adsorption for removal of dissolved pollutants

Common industrial wastewater treatment methods include sedimentation, coagulation–flocculation, biological treatment reactors, activated carbon adsorption, and advanced membrane technologies. These treatment systems effectively remove physical, chemical, and biological contaminants, enabling industries to comply with environmental discharge regulations while significantly reducing pollution loads on receiving water bodies (Kato & Kansha, 2024).

4.2.5 Faecal Sludge Treatment Plants (FSTP)

Faecal sludge treatment is a critical component of liquid waste management, particularly in areas that rely on on-site sanitation systems such as septic tanks and pit latrines. Standardized Faecal Sludge Treatment Plants (FSTPs), developed in accordance with Central Pollution Control Board (CPCB) guidelines, are increasingly being adopted for the safe treatment and disposal of septage. Faecal sludge typically contains a high moisture content, often exceeding 80–90%, making dewatering an essential preliminary treatment process. Dewatering reduces sludge volume, facilitates subsequent treatment and disposal, and enhances overall management efficiency. Technologies such as drying beds, geotextile dewatering systems, and mechanical dewatering equipment are commonly employed in FSTPs to improve sludge handling and treatment performance. Effective faecal sludge management minimizes groundwater contamination, prevents illegal dumping, and improves public health and sanitation conditions, particularly in densely populated urban areas and informal settlements (Manga et al., 2024).

4.2.6 Digital Monitoring and Smart Technologies

The integration of digital technologies is transforming wastewater management practices by enhancing system monitoring, operational efficiency, and decision-making processes. Advanced sensors, remote monitoring systems, and artificial intelligence (AI)-based tools are increasingly being employed to detect leakages, monitor water quality parameters, optimize treatment performance, and reduce operational costs. Smart monitoring technologies enable real-time assessment of system performance, early identification of operational failures, and efficient allocation of resources. These innovations facilitate data-driven planning, improve the reliability of wastewater treatment infrastructure, and support the development of more resilient and sustainable water management systems (Lowe et al., 2022)

4.2.7 Transition Towards Resource Recovery

Technological innovations are gradually shifting the focus of wastewater management from conventional waste disposal to resource recovery and circular water management. Treated wastewater can be reused for irrigation, industrial processes, groundwater recharge, and landscaping, thereby reducing dependence on freshwater resources. Furthermore, the recovery of valuable nutrients such as nitrogen and phosphorus, along with energy generation through biogas production, contributes to more sustainable and resource-efficient wastewater management practices. These approaches support long-term environmental protection, promote circular economy principles, and enhance the resilience of water resource systems (Kundu et al., 2022).

Advancements in wastewater treatment technologies, faecal sludge management, digital monitoring systems, and resource recovery are driving the transition toward more efficient and sustainable wastewater management. The integration of these approaches enhances pollution control, improves treatment performance, and promotes water reuse and resource recovery in line with circular economy principles.

5 Scalable Models for Basin Application

5.1 Solid Waste Management

For successful management of solid waste in the Mahanadi basin, scalable models must consider the diversity of regions-urban, semi-urban, industrial, and rural. A decentralized waste management model is highly beneficial because waste will be processed at the source or community level through composting, biogas plants, and small Material Recovery Facilities (MRFs). This reduces transportation costs and prevents waste accumulation near riverbanks. In urban centers, a hybrid model combining centralized and decentralized systems can be implemented. Centralized facilities such as waste-to-energy plants and scientific landfills can handle non-recyclable waste, while decentralized units manage organic and recyclable waste locally. This ensures efficiency and reduces landfill dependency.

An integrated waste management strategy needs to be employed in industrial regions. It requires the integration of municipal and industrial waste treatment with the provision of proper monitoring systems. It needs the expansion of technologies like effluent treatment plants (ETPs), hazardous waste management, and recycling facilities to protect the Mahanadi River.

First, a river-centered waste management framework is necessary, which entails use of floating waste barriers, cleaning equipment of the surface of the rivers, as well as strict regulation of dumping along the banks of rivers. Such a framework will address the specific environmental problems posed by the basin directly. Also, a community-centered framework involving use of self-help groups (SHGs), local authorities and other similar institutions can be implemented in rural and semi-urban settings. Such a framework ensures sustainability through participation, employment opportunities, and cost-saving operations. The applicability of these two frameworks in the Mahanadi basin depends on several factors such as economic feasibility, availability of infrastructure, social acceptance, and environmental appropriateness. Decentralized approaches are feasible in rural and semi-urban settings because they are cheap, require little infrastructure, and easy to implement. Also, they fit in the context of SHGs and similar local institutions.

Urban areas have higher financial and technical capacity, making them suitable for advanced technologies such as smart waste management systems, GPS tracking, and waste-to-energy plants. However, these systems require strong governance, skilled manpower, and continuous maintenance, which can pose challenges if not properly managed.

In the industrial zones, it is possible to install integrated waste management systems provided there is strict regulation of the activities and cooperation between the industries and the local government. Presence of the pollution control boards and industrial infrastructure makes this feasible but compliance with regulations is an important aspect.

Social acceptance is another critical factor. Public participation in waste segregation and reduction is essential for the success of any model. Awareness programs, incentives, and strict enforcement mechanisms are necessary to ensure behavioral change.

Environmental feasibility is especially necessary in the Mahanadi basin. Technologies must be selected carefully to avoid further ecological damage. For example, waste-to-energy plants must comply with emission standards, while landfill sites must be designed to prevent leachate contamination of the river. Overall, a context-specific and flexible approach, rather than a one-size-fits-all model, is essential for successful implementation in the basin.

5.2 Liquid waste Management

The selection of scalable liquid waste management models for basin-level implementation requires consideration of population density, settlement patterns, wastewater generation rates, land availability, institutional capacity, environmental sensitivity, and economic feasibility. Lessons from national and international case studies indicate that no single wastewater management approach is suitable for all locations. Instead, a combination of centralized, decentralized, nature-based, and resource recovery-oriented systems should be adopted based on local conditions. For effective basin-wide implementation, the following scalable models are proposed.

5.2.1 Decentralized Wastewater Treatment Model for Rural and Peri-Urban Areas

In rural villages, peri-urban settlements, and small towns where centralized sewerage systems are economically unviable, Decentralized Wastewater Treatment Systems (DEWATS) combined with nature-based treatment technologies offer a practical solution. These systems can treat domestic wastewater close to the source of generation using anaerobic baffled reactors, settling tanks, constructed wetlands, reed beds, and polishing ponds. The treated effluent may be reused for irrigation, landscaping, and groundwater recharge. Such systems require relatively low capital investment, minimal energy consumption, and simple operation and maintenance, making them highly suitable for widespread implementation across rural basin zones. The successful experiences of Ujjain and Alappuzha demonstrate the effectiveness of decentralized wastewater treatment in reducing environmental pollution while improving sanitation outcomes (Sha et al., 2024).

5.2.2 Cluster-Based Wastewater Management Model for Medium-Sized Urban Settlements

For medium-sized towns and rapidly growing urban centers, a cluster-based wastewater management approach is recommended. Under this model, several adjacent communities or wards are connected to localized treatment facilities rather than relying on a single centralized treatment plant. This approach reduces conveyance costs, minimizes infrastructure requirements, and allows phased expansion as population and wastewater generation increase. The model integrates decentralized treatment units with local sewer networks and can incorporate treated wastewater reuse for urban landscaping, construction activities, and industrial applications. Such systems provide operational flexibility while ensuring adequate treatment coverage in expanding urban areas (Jung et al.2018).

5.2.3 Faecal Sludge and Septage Management (FSSM) Model

In areas dependent on septic tanks and on-site sanitation systems, dedicated Faecal Sludge Treatment Plants (FSTPs) should be established to ensure safe collection, transportation, treatment, and disposal of septage. Standardized treatment facilities incorporating dewatering units, drying beds, and biological stabilization processes can significantly reduce environmental and public health risks. The Pune experience demonstrates that integrating FSSM within basin sanitation planning is essential for achieving comprehensive wastewater management coverage, particularly in settlements lacking sewer networks.

The adoption of these scalable wastewater management models facilitates basin-wide wastewater management by aligning treatment strategies with local settlement patterns, infrastructure availability, environmental sensitivity, and socio-economic conditions. Their effective implementation can significantly reduce the discharge of untreated wastewater, improve receiving water quality, enhance public health outcomes, and promote the reuse of treated effluent and recovery of valuable resources. Furthermore, the integration of decentralized treatment systems, cluster-based wastewater management, and faecal sludge management into basin planning enhances climate resilience, supports circular water management principles, and establishes an adaptable framework that can be replicated across diverse river basins for sustainable, inclusive, and long-term sanitation management.

6 Adaptability And Feasibility Analysis

6.1 Liquid waste Management

Evaluation of adaptability and feasibility is essential to determine whether identified liquid waste management practices can be successfully implemented across different basin zones. While technological solutions may demonstrate effectiveness under controlled conditions, their long-term success depends on their ability to respond to changing environmental, social, regulatory, and economic conditions. This section assesses the flexibility, scalability, and practicality of selected technologies and management approaches to ensure sustainable implementation.

6.1.1 Adaptability of Liquid Waste Management Systems

Adaptability refers to the capacity of a liquid waste management system to adjust to future changes in wastewater characteristics, population growth, climatic variability, and regulatory requirements.

Systems that are adaptable are more resilient, cost-effective in the long term, and capable of sustaining performance under varying operational conditions.

Key Factors Influencing Adaptability

1. Waste Variability: Wastewater quantity and quality can vary significantly due to population fluctuations, seasonal changes, industrial activities, and land-use patterns. Effective treatment systems must be capable of handling variations in flow volume, pollutant load (BOD, COD), nutrient concentrations, and presence of toxic substances. Modular and flexible treatment units improve adaptability by allowing operational adjustments without major infrastructure modifications.

2. Scalability: Scalability is the ability of a system to expand or adjust capacity in response to population growth, urban expansion, or seasonal demand variations. Decentralized treatment systems generally demonstrate greater scalability compared to centralized systems, as additional treatment units can be added incrementally without requiring major redesign of existing infrastructure.

3. Technological Flexibility: Technologically adaptable systems allow integration of improved treatment processes, automation tools, and monitoring systems as they become available. The incorporation of digital monitoring technologies, smart sensors, and renewable energy components enhances operational efficiency and ensures long-term sustainability. Systems that allow phased technological upgrades reduce the need for complete infrastructure replacement.

4. Climate and Environmental Resilience: Liquid waste management systems must remain functional under climate variability including extreme rainfall events, flooding, drought conditions, and temperature fluctuations. Nature-based solutions such as constructed wetlands, stabilization ponds, and biofiltration systems often demonstrate higher resilience due to their ability to operate under variable environmental conditions with minimal mechanical dependency.

5. Regulatory Adaptation: Environmental regulations governing wastewater discharge and reuse are continuously evolving and often becoming more stringent over time. Therefore, adaptable treatment systems should be capable of meeting future discharge standards, water reuse guidelines, and environmental compliance requirements. Advanced treatment technologies and modular system designs enhance the flexibility of wastewater infrastructure and support compliance with changing regulatory frameworks (Spiller et al., 2015).

6.1.2 Feasibility Analysis of Liquid Waste Management Systems

Feasibility analysis assesses whether a proposed liquid waste management system is practical, sustainable, and suitable for implementation under specific local conditions. It considers technical reliability, economic viability, environmental sustainability, social acceptance, and institutional support.

Key Dimensions of Feasibility

1. Technical Feasibility: Technical feasibility evaluates whether the selected technology is reliable, proven, and suitable for local wastewater characteristics and climatic conditions. Availability of trained personnel for operation and maintenance is also an important consideration, as complex systems may require specialized technical expertise.

2. Economic Feasibility: Economic feasibility considers capital investment requirements, operational costs, maintenance expenses, and long-term financial sustainability. Cost-effective systems with lower energy consumption and minimal operational complexity are generally more viable. Opportunities for cost recovery through wastewater reuse, resource recovery, user charges, or tariff mechanisms improve financial sustainability.

3. Environmental Feasibility: Environmentally feasible systems minimize pollution loads, reduce greenhouse gas emissions, and limit sludge generation. Technologies that enable resource recovery, water reuse, and nutrient recycling contribute to improved environmental outcomes and support circular economy principles.

4. Social Feasibility: Community acceptance plays an important role in successful implementation of liquid waste management systems. Systems must be socially acceptable, hygienic, safe, and compatible with local land-use patterns. Public awareness, willingness to participate, and availability of suitable land influence implementation success.

5. Institutional and Legal Feasibility: Institutional feasibility evaluates alignment of proposed systems with government policies, regulatory frameworks, and administrative capacity. Clear roles and responsibilities for implementation, monitoring, and maintenance are necessary to ensure long-term functionality. Coordination among local authorities, regulatory agencies, and service providers is essential for effective governance.

Overall, adaptability and feasibility assessment helps identify solutions that are not only technically effective but also practically implementable under basin-specific socio-economic and environmental conditions. This evaluation supports the selection of appropriate models that can be successfully scaled and sustained over the long term (Lizot et al., 2020).

7 Recommendations and Role of Stakeholders

7.1 Solid Waste Management

Effective solid waste management in the Mahanadi basin requires coordinated efforts from multiple stakeholders, including government agencies, local bodies, communities, industries, and private sectors.

Government authorities at the state and municipal levels should focus on policy implementation, infrastructure development, and regulatory enforcement. They must ensure proper funding, monitoring, and maintenance of waste management systems. Urban local bodies (ULBs) play a key role in waste collection, segregation, and processing.

Communities and citizens are central to the success of SWM systems. Their role includes waste segregation at source, participation in awareness programs, and adoption of sustainable practices. Self-help groups can be actively involved in waste collection, recycling, and composting activities, especially in rural areas.

Industries, particularly in districts like Angul and Jharsuguda, must adopt sustainable waste management practices and comply with environmental regulations. The implementation of Extended Producer Responsibility (EPR) can ensure that producers take responsibility for post-consumer waste, especially plastics.

The private sector can contribute through technology provision, investment, and public-private partnerships (PPPs). NGOs and research institutions can support awareness campaigns, capacity building, and innovation in waste management practices.

The Mahanadi basin can be divided into distinct zones, each requiring tailored strategies:

- **Urban Zone:** Implementation of smart waste management systems, waste-to-energy plants, and advanced recycling facilities. Strict enforcement of segregation rules and digital monitoring systems should be prioritized.
- **Industrial Zone:** Adoption of integrated waste management systems, including hazardous waste treatment, ETPs, and continuous pollution monitoring. Strong regulatory enforcement is essential.
- **Semi-Urban Zone:** Combination of decentralized composting units and small-scale recycling facilities. Community participation and awareness programs should be strengthened.
- **Rural Zone:** Promotion of low-cost decentralized solutions such as composting, vermiculture, and biogas plants. SHG-based models can ensure sustainability and local employment.
- **Riverbank / Sensitive Zone:** Installation of floating waste barriers, strict prohibition of dumping, regular river cleaning operations, and GIS-based monitoring of pollution hotspots.

7.2 Liquid Waste Management:

Based on the assessment of national and international best practices, technological innovations, and feasibility considerations. The following recommendations are proposed to improve the effectiveness, sustainability, and scalability of liquid waste management systems. These recommendations aim to support integrated river basin management while reducing environmental pollution and improving resource efficiency.

- Improving Sewage and Effluent Treatment Infrastructure: Efficient functioning of Sewage Treatment Plants (STPs) and Effluent Treatment Plants (ETPs) is critical for reducing pollution loads. Periodic technical audits, performance evaluation, and timely maintenance of treatment facilities should be undertaken to ensure optimal operational efficiency and compliance with prescribed standards.
- Promoting Decentralized Wastewater Treatment Systems: Decentralized wastewater treatment approaches such as DEWATS, constructed wetlands, and cluster-level treatment units should be encouraged particularly in small towns, peri-urban areas, residential complexes, and institutions. These systems reduce infrastructure costs, improve local treatment capacity, and minimize conveyance losses.

- Encouraging Reuse of Treated Wastewater: Reuse of treated wastewater should be promoted for non-potable applications such as irrigation, landscaping, industrial cooling, construction activities, and groundwater recharge. Resource recovery approaches reduce pressure on freshwater sources and support circular water economy principles.
- Capacity Building and Technical Training: Regular training programs should be conducted for municipal staff, plant operators, engineers, and technical personnel to improve operational efficiency of treatment systems. Skill development initiatives enhance the reliability and sustainability of wastewater management infrastructure.
- Integration of Digital Monitoring Systems: Deployment of online monitoring systems and smart sensors linked to regulatory agencies can improve compliance tracking, detect operational failures, and ensure timely corrective actions. Digital monitoring enhances transparency and supports data-driven decision-making.
- Increasing Public Awareness and Community Participation: Awareness campaigns should be conducted to promote responsible sanitation practices, wastewater reuse, and water conservation. Community participation is essential for improving acceptance of decentralized systems and ensuring proper utilization of sanitation infrastructure.

7.3 Role of Stakeholders

The successful implementation of basin-scale liquid waste management requires strong institutional coordination supported by regulatory frameworks, technical guidelines, and participatory governance mechanisms. Policies such as the National Urban Sanitation Policy, FSSM Policy, AMRUT Guidelines, and environmental regulations provide a structured framework for defining stakeholder responsibilities and ensuring sustainable wastewater management across urban, peri-urban, and rural landscapes. Effective liquid waste management requires coordinated efforts among multiple stakeholders across policy, planning, implementation, monitoring, and community engagement levels.

➢ **Central Pollution Control Board (CPCB)**

The CPCB plays a central role in establishing national regulatory frameworks for wastewater management. Key responsibilities include:

- Formulating wastewater discharge standards and technical guidelines
- Providing regulatory direction for treatment technologies
- Coordinating with State Pollution Control Boards

- Monitoring compliance at national level and supporting policy development

➢ **State Pollution Control Board (SPCB)**

SPCBs are responsible for implementation and enforcement of wastewater regulations at the state level. Their key functions include:

- Granting Consent to Establish (CTE) and Consent to Operate (CTO)
- Monitoring compliance of industries and municipal treatment facilities
- Conducting inspections and environmental audits
- Initiating legal action against non-compliant entities

➢ **Urban Local Bodies (ULBs) and Municipal Corporations**

Urban local bodies play a critical role in planning and managing urban wastewater infrastructure. Their responsibilities include:

- Development, operation, and maintenance of sewerage systems
- Establishment and management of STPs and decentralized treatment systems
- Implementation of wastewater reuse initiatives
- Ensuring safe collection and conveyance of sewage

➢ **Industries**

Industries are responsible for treatment of industrial effluents prior to discharge. Key responsibilities include:

- Installation and operation of Effluent Treatment Plants (ETPs)
- Compliance with discharge standards and environmental regulations
- Adoption of zero liquid discharge (ZLD) practices where required
- Submission of compliance and monitoring data to regulatory authorities

➢ **Community and Citizens**

Community participation is essential for ensuring effective implementation and sustainability of wastewater management systems. Citizens contribute through:

- Responsible use of sanitation and sewerage infrastructure
- Acceptance and promotion of treated wastewater reuse
- Reporting illegal discharges, blockages, and system failures
- Supporting decentralized sanitation initiative

➢ **Private Sector and PPP Operators**

Private sector participation enhances technical expertise, innovation, and financial efficiency. Their contributions include:

- Design, construction, and operation of STPs, ETPs, and FSTPs
- Provision of advanced and energy-efficient treatment technologies
- Supporting performance-based operation and maintenance models

➢ **NGOs and Academic Institutions**

Research institutions and civil society organizations support innovation, capacity building, and knowledge dissemination. Their role includes:

- Conducting awareness and training programs.
- Supporting implementation of decentralized and nature-based solutions.
- Providing technical research inputs and pilot studies.
- Facilitating stakeholder engagement and community participation.

These recommendations and stakeholder roles provide a structured framework for improving liquid waste management practices through coordinated institutional mechanisms, technological adoption, and community participation. The integration of regulatory compliance, decentralized systems, and resource recovery approaches can significantly contribute to improved river health and sustainable basin management (Kudaibergenova et al., 2025).

References

1. Bolton, K. and Rousta, K., 2019. Solid waste management toward zero landfill: A Swedish model. In *Sustainable resource recovery and zero waste approaches* (pp. 53-63). Elsevier.
2. Das, A., 2025a. Water pollution and water quality assessment and application of criterion impact loss (CILOS), geographical information system (GIS), artificial neural network (ANN) and decision-learning technique in river water quality management: An experiment on the Mahanadi catchment, Odisha, India. *Desalination and Water Treatment*, *321*, p.100969.
3. Das, A., 2025b. A data-driven approach utilizing machine learning (ML) and geographical information system (GIS)-based time series analysis with data augmentation for water quality assessment in Mahanadi River Basin, Odisha, India. *Discover Sustainability*, *6*(1), p.555.
4. Glavic, P., Szilagyi, A., Karouti, I., Kostoulas, A., Hernaez, O., Dolinsky, M., Schonfelder, T., Ruzicka, P., Stawecka, G., Karadimas, D. and Sousa Rocha, C., 2020. Education for zero waste and circular economy sector in Europe.
5. Herrador, M., de Jong, W., Nasu, K. and Granrath, L., 2023. The rising phenomenon of circular cities in Japan. Case studies of Kamikatsu, Osaki and Kitakyushu. *Science of the Total Environment*, *894*, p.165052.
6. Khan, S., Ali, B., Alharbi, A.A., Alotaibi, S. and Alkhathami, M., 2024. Efficient IoT-assisted waste collection for urban smart cities. *Sensors*, *24*(10), p.3167.
7. Kumar, A. and Agrawal, A., 2020. Recent trends in solid waste management status, challenges, and potential for the future Indian cities–A review. *Current Research in Environmental Sustainability*, *2*, p.100011.
8. Li, Q. and Yan, B., 2025. Research On The Effectiveness Of Urban Waste Sorting İn The New Era: A Case Study of Shanghai. *CHINESE STUDIES Учредители: Scientific Research Publishing, Inc.*, *14*(01), pp.42-53.
9. Marfe, G., Di Stefano, C. and Hermann, A., 2020. Zero waste management as key factor for sustainable development. In *Hazardous waste management and health risks* (pp. 159-192). Bentham Science Publishers.
10. Mazzoli, E., Parashar, A., D'Odorico, P. and Branca, G., 2024. Greening the city: A holistic assessment of waste management alternatives in India. *Science of the Total Environment*, *955*, p.176894.
11. Meena, M.D., Dotaniya, M.L., Meena, B.L., Rai, P.K., Antil, R.S., Meena, H.S., Meena, L.K., Dotaniya, C.K., Meena, V.S., Ghosh, A. and Meena, K.N., 2023. Municipal solid waste:

Opportunities, challenges and management policies in India: A review. *Waste Management Bulletin*, *1*(1), pp.4-18.

12. Muttil, N. and Juwana, I., 2026, March. Advancing Zero-Waste Goals: A Global Review of Strategies, Policies and Performance. In *Journal of Physics: Conference Series* (Vol. 3196, No. 1, p. 012013). IOP Publishing.

13. Park, S., 2018. Factors influencing the citizen cost burden in managing the volume-based waste fee system in South Korea. *Waste Management*, *82*, pp.285-291.

14. Syme, R., 2021. A review of domestic waste management policy and law in Singapore. *Asia Pacific Journal of Environmental Law*, *24*(1), pp.90-119.

15. Kudaibergenova, R. M., Bolatbek, A. B., Spanov, M. U., Baibazarova, E. A., Orynbayev, S. A., Murzakasymova, N. S., & Kabdushev, A. A. (2025). State Regulation and Strategic Management of Water Resources and Wastewater Treatment at the Regional Level: Institutional and Technological Solutions. *Water, 18*(1), 63.

16. Al-Yaqout, A. F. (2003). Assessment and analysis of industrial liquid waste and sludge disposal at unlined landfill sites in arid climate. *Waste Management, 23*(9), 817–824.

17. Central Pollution Control Board. (2020). *Status of water supply, wastewater generation and treatment in Class I cities & Class II towns of India*. CPCB.

18. Central Pollution Control Board. (2021). *Performance evaluation of sewage treatment plants in India*. CPCB.

19. Centre for Science and Environment. (2019). *Decentralized wastewater treatment systems: Lessons from Indian cities*. CSE.

20. Collivignarelli, M., Bellazzi, S., Calabria, L. M. R., Sordi, M., Crotti, B., & Abbá, A. (2025). Operational criteria and challenges in management of liquid waste treatment facility based on chemical–physical processes and membrane biological reactor in thermophilic conditions: A case study. *Sustainability, 17*(1).

21. Department of Drinking Water and Sanitation. (2021). *Greywater management guidelines under SBM-G*. Government of India.

22. Hosseinian, A., Pettersson, A., Ylä-Mella, J., & Pongrácz, E. (2023). Phosphorus recovery methods from secondary resources, assessment of overall benefits and barriers with focus on the Nordic countries. *Journal of Material Cycles and Waste Management, 25*(2), 737–756.

23. Kato, S., & Kansha, Y. (2024). Comprehensive review of industrial wastewater treatment techniques. *Environmental Science and Pollution Research*.

24. Kudaibergenova, R. M., Bolatbek, A. B., Spanov, M. U., Baibazarova, E. A., Orynbayev, S. A., Murzakasymova, N. S., & Kabdushev, A. A. (2025). State regulation and strategic management of water resources and wastewater treatment at the regional level: Institutional and technological solutions. *Water, 18*(1), 63.

25. Kundu, D., Dutta, D., Samanta, P., Dey, S., Sherpa, K., Kumar, S., & Dubey, B. (2022). Valorization of wastewater: A paradigm shift towards circular bioeconomy and sustainability. *Science of the Total Environment, 857*, 159467.

26. Lazarova, V., Hills, S., & Birks, R. (2003). Using recycled water for non-potable urban uses: A review with particular reference to toilet flushing. *Water Science and Technology: Water Supply, 3*(4), 69–77.

27. Lizot, M., Goffi, A. S., Thesari, S., Trojan, F., Afonso, P., & Ferreira, P. F. V. (2020). Multi-criteria methodology for selection of wastewater treatment systems with economic, social, technical and environmental aspects. *Environment, Development and Sustainability, 22*(6), 5395–5417.

28. Lowe, M., Qin, R., & Mao, X. (2022). A review on machine learning, artificial intelligence, and smart technology in water treatment and monitoring. *Water, 14*(9), 1384.

29. Manga, M., Muoghalu, C. C., Brandoni, C., Fitzsimons, L., Reade, A., Salzberg, A., & Brown, J. (2024). From sludge to resource recovery: Geotextiles for efficient dewatering and sustainable utilization of faecal sludge. *Energy, Ecology and Environment*.

30. Ministry of Housing and Urban Affairs. (2019). *National policy on faecal sludge and septage management*. Government of India.

31. Ministry of Housing and Urban Affairs. (2021). *India's urban sanitation success stories*. Government of India.

32. Ministry of Housing and Urban Affairs. (2022). *Swachh Bharat Mission (Urban) 2.0 framework*. Government of India.

33. National Institute of Urban Affairs. (2020). *Best practices compendium on urban sanitation*. NIUA.

34. NITI Aayog. (2020). *Composite water management index*. Government of India.

35. PUB, Singapore's National Water Agency. (n.d.). *NEWater*. PUB.

36. Sha, C., Shen, S., Zhang, J., Zhou, C., Lu, X., & Zhang, H. (2024). A review of strategies and technologies for sustainable decentralized wastewater treatment. *Water, 16*(1).

37. Silva, J. (2023). Wastewater treatment and reuse for sustainable water resources management: A systematic literature review. *Sustainability*.

38. Singh, B. J., Chakraborty, A., & Sehgal, R. (2023). A systematic review of industrial wastewater management: Evaluating challenges and enablers. *Journal of Environmental Management, 345*, 118882.

39. Spiller, M., Vreeburg, J., Leusbrock, I., & Zeeman, G. (2015). Flexible design in water and wastewater engineering—Definitions, literature and decision guide. *Journal of Environmental Management, 149*, 271–281.

40. U.S. Environmental Protection Agency. (n.d.). *Water reuse and recycling: Singapore NEWater case study*. EPA.

41. Varma, V. G., Jha, S., Raju, L. H. K., Kishore, R. L., & Ranjith, V. (2022). A review on decentralized wastewater treatment systems in India. *Chemosphere, 308*, 136312.

42. Vymazal, J. (2018). Constructed wetlands for wastewater treatment: A review. *Water, 10*(5), 530.

43. World Bank. (2018). *Wastewater management in coastal cities of India*. World Bank.

44. Sha, C., Shen, S., Zhang, J., Zhou, C., Lu, X., & Zhang, H. (2024). A review of strategies and technologies for sustainable decentralized wastewater treatment. *Water*, *16*(20), 3003

45. Jung, Y. T., Narayanan, N. C., & Cheng, Y. L. (2018). Cost comparison of centralized and decentralized wastewater management systems using optimization model. *Journal of environmental management*, *213*, 90-97.