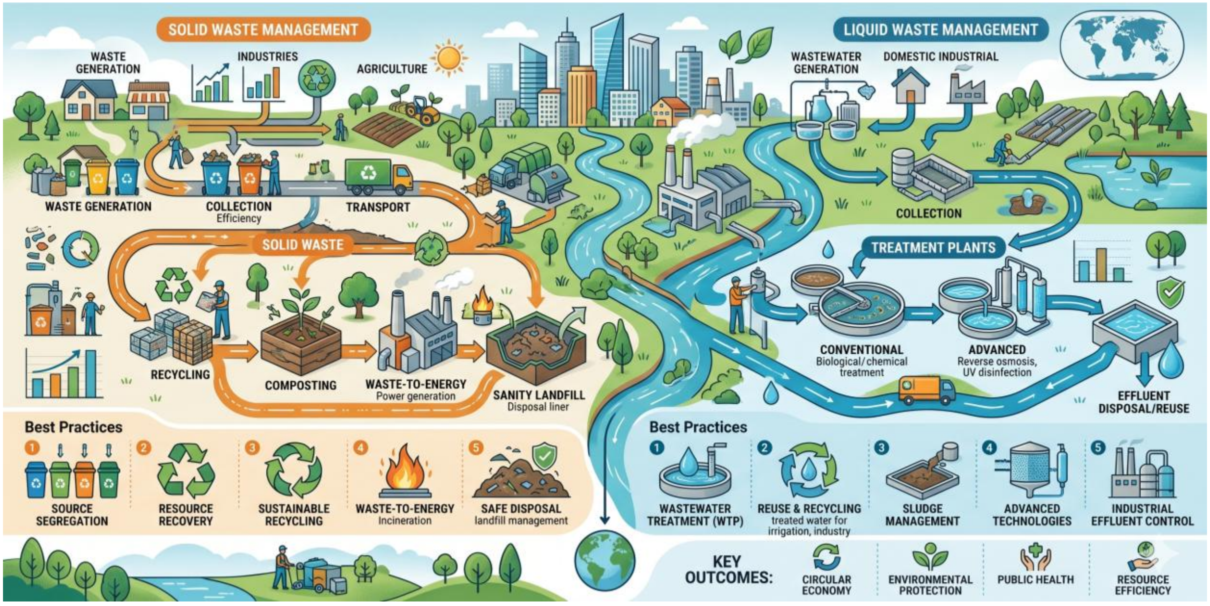
National River Conservation Directorate
Ministry of Jal Shakti,
Department of Water Resources,
River Development and Ganga Rejuvenation
Government of India

Mapping of Best Practices in Solid–Liquid Waste Management



March 2026

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Mapping of Best Practices in Solid–Liquid Waste Management

Cauvery River Basin

National River Conservation Directorate (NRCD)

The National River Conservation Directorate, functioning under the Department of Water Resources, River Development and 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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The Centres for Cauvery River Basin Management Studies (cCauvery) is a Brain Trust dedicated to River Science and River Basin Management. Established in 2024 by IISc Bengaluru and NIT Tiruchirappalli, under the supervision of cGanga at IIT Kanpur, the centre serves as a knowledge wing of the National River Conservation Directorate (NRCD). cCauvery is committed to restoring and conserving the Cauvery River and its resources through the collation of information and knowledge, research and development, planning, monitoring, education, advocacy, and stakeholder engagement.

www.ccauvery.org

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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.

www.cganga.org

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Team Members

Praveen C Ramamurthy, cCauvery, IISc Bengaluru
Shekhar M, cCauvery, IISc Bengaluru
Nagesh Kumar Dasika, cCauvery, IISc Bengaluru
Srinivas V V, cCauvery, IISc Bengaluru
Lakshminarayana Rao, cCauvery, IISc Bengaluru
Rajarshi Das Bhowmik, cCauvery, IISc Bengaluru
Bramha Dutt Vishwakarma, cCauvery, IISc Bengaluru
Debsunder Dutta, cCauvery, IISc Bengaluru
R Manjula, cCauvery, NIT Trichy
Nisha Radhakrishnan, cCauvery, NIT Trichy
S Saravanan, cCauvery, NIT Trichy
Aneesh Mathew, cCauvery, NIT Trichy
Laveti Satish, cCauvery, NIT Trichy
Prabu P, cCauvery, NIT Trichy
Vinod Tare, cGanga, IIT Kanpur

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.

Centres for Cauvery River Basin
Management Studies (cCauvery)
IISc Bengaluru (Lead Institute), NIT Tiruchirappalli (Fellow Institute)

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Abbreviations and Acronyms

ABR	Anaerobic Baffled Reactor
AI	Artificial Intelligence
AOP	Advanced Oxidation Process
CBG	Compressed Biogas
CETP	Common Effluent Treatment Plant
CRB	Cauvery River Basin
DEWATS	Decentralized Wastewater Treatment Systems
EPR	Extended Producer Responsibility
ERMF	Energy and Raw Materials Factory
FSSM	Fecal Sludge and Septage Management
FSTP	Fecal Sludge Treatment Plant
GIS	Geographic Information Systems
GOBARdhan	Galvanizing Organic Bio-Agro Resources Dhan
GPS	Global Positioning System
IoT	Internet of Things
IWMF	Integrated Waste Management Facility
KKPKP	Kagad Kach Patra Kashtakari Panchayat
MBR	Membrane Bioreactor
MF	Microfiltration
MRFs	Material Recovery Facilities
NEA	National Environment Agency
ODF	Open Defecation Free
PAYT	Pay-As-You-Throw
PMC	Pune Municipal Corporation
PUB	Public Utilities Board
RDF	Refuse-Derived Fuel
RFID	Radio Frequency Identification
RO	Reverse Osmosis
SATAT	Sustainable Alternative Towards Affordable Transportation
SBM	Swachh Bharat Mission
SBM-G	Swachh Bharat Mission-Gramin

SBM-U	Swachh Bharat Mission-Urban
SHG	Self-Help Group
SLRM	Solid and Liquid Resource Management
SLWM	Solid-Liquid Waste Management
STP	Sewage Treatment Plant
SWaCH	Solid Waste Collection and Handling
TWRP	Tuas Water Reclamation Plant
UASB	Upflow Anaerobic Sludge Blanket
UF	Ultrafiltration
UV	Ultraviolet
UNEP	United Nations Environment Programme
WtE	Waste-to-Energy
WHO	World Health Organization
ZLD	Zero-Liquid-Discharge

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1. Introduction

Solid and liquid waste management has emerged as one of the most critical environmental challenges worldwide. Rapid urbanization, industrial expansion, population growth, and changing consumption patterns have significantly increased the quantity and complexity of waste generated from households, industries, institutions, and agricultural activities (Gour & Singh, 2023; Hariyani et al., 2025). In many developing countries, inadequate collection, treatment, recycling, and disposal of waste have resulted in severe environmental degradation and public health concerns. Improper waste management practices contribute directly to water pollution, soil contamination, deterioration of air quality, greenhouse gas emissions, and ecosystem damage (Gour & Singh, 2023; Rathod et al., 2024).

River basins are particularly vulnerable to the impacts of poor waste management. Municipal solid waste, untreated sewage, industrial effluents, plastic waste, agricultural runoff, and livestock waste frequently enter rivers and associated water bodies. These pollutants degrade water quality, reduce ecological integrity, threaten aquatic biodiversity, and affect downstream users. The cumulative impacts become more pronounced in densely populated and economically active river basins where multiple sources of pollution coexist (Sawant et al., 2023; Onyemesili et al., 2022).

Solid-Liquid Waste Management (SLWM) refers to the systematic collection, segregation, transportation, treatment, resource recovery, reuse, and environmentally safe disposal of solid and liquid waste streams. Modern SLWM approaches emphasize waste minimization and resource recovery rather than simple disposal. The objective is to transform waste into valuable resources, including compost, bioenergy, recycled materials, treated water, and recovered nutrients. This approach aligns with the principles of sustainable development and circular economy (Raman et al., 2024).

Traditionally, waste management systems focused primarily on collection and disposal. However, growing environmental pressures and resource scarcity have encouraged a transition towards integrated waste management systems. These systems combine technological solutions, institutional frameworks, financial mechanisms, community participation, and environmental safeguards. The shift from a linear economy to a circular economy has further accelerated the adoption of innovative waste management practices worldwide (Anuardo et al., 2022; Hariyani et al., 2025).

In India, waste generation has increased substantially over the last two decades. Rapid urban growth has led to rising municipal solid waste generation, while expanding industrial and agricultural activities have increased wastewater and organic residue volumes (Hamdan et al., 2025). Despite significant improvements under national initiatives such as the Swachh Bharat Mission (SBM), challenges remain in ensuring effective treatment and safe disposal of waste across urban and rural areas (Varshney et al., 2025). Many settlements continue to face issues related to open dumping, inadequate sewage treatment, improper septage management, and insufficient recycling infrastructure.

The Swachh Bharat Mission-Gramin (SBM-G) Phase II has placed strong emphasis on SLWM as a key component of sustainable sanitation (Rajendran, 2025). The programme encourages villages and local institutions to adopt decentralized waste management systems, improve resource recovery, and achieve ODF Plus status (Kamble, 2025). Similar efforts are being implemented in urban areas through integrated municipal waste management programmes, wastewater treatment infrastructure, and resource recovery initiatives.

Several successful examples of waste management have emerged across India. Models such as the Solid and Liquid Resource Management (SLRM) Programme in Udupi (Jithendra & Godihal, 2023; Tiwari et al., 2024), the zero-waste approach of Ambikapur (Abraham et al., 2025; Bhatt & Mohapatra, 2023), the decentralized systems of Alappuzha (Bhatt & Mohapatra, 2023; Narayanan et al., 2023), and the integrated municipal waste management framework of Indore (Kotwani et al., 2025; Kumar & Kumar, 2024) have demonstrated that effective waste management can be achieved through community participation, technological innovation, and institutional commitment. These initiatives provide valuable lessons for replication in other regions.

Globally, many countries have adopted advanced waste management systems that integrate resource recovery, energy generation, wastewater recycling, and circular economy principles. Singapore has become a global leader in wastewater reuse through its NEWater Programme (Islam et al., 2024; Middha & Kumar, 2024). Sweden has developed efficient systems for nutrient recovery and waste-to-energy (WtE) conversion (Sindhøj & Cordeiro, 2025; Zueva et al., 2024). Germany has demonstrated successful implementation of advanced recycling and energy recovery technologies (Kullmann et al., 2022; Themelis, 2023). The Netherlands has pioneered circular approaches that view wastewater as a valuable resource rather than a waste product (van Leeuwen et al., 2018). These international experiences provide important insights for developing sustainable waste management strategies in river basins.

Technological advancements are transforming the waste management sector. Artificial intelligence (AI), Internet of Things (IoT), Geographic Information Systems (GIS), automation, advanced biological treatment processes, Decentralized Wastewater Treatment Systems (DEWATS), and resource recovery technologies are improving operational efficiency and environmental performance. Smart monitoring systems enable real-time tracking of waste collection and treatment operations. Resource recovery technologies facilitate the extraction of energy, nutrients, and reusable materials from waste streams. Nature-based solutions such as constructed wetlands and phytoremediation systems offer environmentally sustainable treatment alternatives.

The Cauvery River Basin (CRB) represents one of India's most important river systems. The basin supports millions of people and serves as a major source of water for domestic, agricultural, industrial, and ecological needs. The basin encompasses diverse landscapes, including forested catchments, agricultural regions, urban centers, industrial corridors, and deltaic ecosystems. Increasing population pressure and economic activities have led to substantial waste generation across the basin. Untreated sewage, industrial discharges, plastic waste, agricultural residues, and organic waste contribute significantly to water quality deterioration in various stretches of the river and its tributaries.

Given the diversity of environmental conditions and socio-economic characteristics within the basin, a single waste management solution may not be appropriate for all regions. Different zones require tailored interventions based on local conditions, infrastructure availability, waste characteristics, institutional capacity, and community participation. Therefore, identifying and mapping proven best practices is essential for designing effective basin-scale waste management strategies.

The present report focuses on the systematic assessment and mapping of national and international best practices in SLWM. The study examines successful case studies, innovative technologies, governance frameworks, and resource recovery approaches that have demonstrated measurable environmental and socio-economic benefits. The analysis seeks to identify scalable and adaptable solutions that can be implemented within the CRB to improve environmental quality and support sustainable development.

The primary objective of this report is to identify and map successful national and international best practices in solid and liquid waste management that can support sustainable river basin management. The report aims to evaluate innovative technologies, resource recovery approaches, and management frameworks for effective treatment, recycling, reuse, and safe disposal of waste streams. It further assesses the technical, environmental, economic, and institutional feasibility of these practices to determine their applicability within the CRB. Based on the analysis, the report seeks to identify scalable and adaptable waste management models for rural, urban, industrial, and agricultural areas, while developing basin-specific recommendations to reduce pollution loads, improve water quality, promote circular economy principles, and strengthen stakeholder participation for long-term environmental sustainability.

2. National Case Studies

2.1. Udupi Solid and Liquid Resource Management (SLRM) Model, Karnataka

2.1.1. Background

The SLRM model implemented in Udupi District, Karnataka, is recognized as one of India's pioneering decentralized rural waste management systems (Jithendra & Godihal, 2023). The initiative was developed under the SBM-G framework to address challenges associated with unsegregated waste disposal, open dumping, and environmental pollution in rural areas (Ministry of Jal Shakti, n.d.; Rajendran, 2025). The model follows a resource-recovery approach, treating waste as a valuable resource rather than a disposal burden. Udupi District established SLRM centers at the Gram Panchayat level to facilitate systematic collection, segregation, processing, and recovery of waste materials (Rajendran, 2025).

2.1.2. Key Features

The Udupi SLRM model incorporates a decentralized waste management system involving door-to-door waste collection, source segregation, resource recovery, and community participation (RDPR, 2020). Households segregate waste at source into biodegradable, recyclable, and domestic hazardous categories before collection. Waste is transported to village-level SLRM centers where secondary segregation and processing are undertaken (SBM-G, 2019). Recyclable materials are channeled to authorized recyclers, while biodegradable waste is processed through composting and related biological treatment methods (Ministry of Jal Shakti, n.d.). The model actively engages Self-Help Groups (SHGs) and local communities in waste collection and management activities, creating employment opportunities and strengthening local ownership (Kandpal & Saizen, 2022). Operational sustainability is supported through user charges collected by Gram Panchayats and local bodies (RDPR, 2020).

2.1.3. Achievements

The implementation of the SLRM model significantly improved waste segregation, resource recovery, and environmental sanitation across Udupi District. The initiative reduced open dumping, enhanced recycling rates, and strengthened decentralized waste management infrastructure (SBM-G, 2019). The establishment of material recovery facilities (MRFs) and SLRM centers enabled scientific handling of waste streams. It contributed to achieving Open Defecation Free (ODF) Plus objectives under the SBM (Ministry of Jal Shakti, n.d.).

2.1.4. Relevance to the CRB

The Udupi SLRM model demonstrates how decentralized infrastructure, community participation, and resource recovery can improve waste management performance in rural areas (SBM-G, 2019). Similar approaches can be adopted in gram panchayats across the CRB to reduce waste leakage into rivers and streams, improve environmental sanitation, and promote circular economy principles.

2.2. Indore Integrated Solid Waste Management Model, Madhya Pradesh

2.2.1. Background

Indore, the largest city in Madhya Pradesh, has emerged as a national benchmark in urban solid waste management through sustained implementation of integrated waste management practices under the Swachh Bharat Mission-Urban (SBM-U). Prior to the transformation, the city faced challenges related to open waste dumping, inadequate segregation, and inefficient collection systems. To address these issues, the Indore Municipal Corporation adopted a comprehensive approach encompassing source segregation, door-to-door collection, scientific processing, resource recovery, public participation, and technology-enabled monitoring systems (SBM-U, 2020). The city's sustained efforts have led to its consistent ranking as India's cleanest city in the Swachh Survekshan assessment framework.

2.2.2. Key Features

The Indore model is built upon universal door-to-door waste collection, ensuring coverage of all households, commercial establishments, and institutional premises within the city limits. Waste generators are required to segregate waste at source into wet, dry, sanitary, domestic hazardous, and other designated categories before collection (SBM-U, 2020). The city has established a network of MRFs and transfer stations where recyclable materials are sorted and channeled to authorized recycling industries. Biodegradable waste is processed through composting and biomethanation facilities, while construction and demolition waste is separately collected and recycled (CPCB, n.d.). The municipality employs Global Positioning System (GPS)-enabled collection vehicles and digital monitoring systems to ensure operational efficiency and accountability (Kotwani et al., 2025). Strong citizen engagement, awareness campaigns, and enforcement measures have played a crucial role in maintaining high levels of compliance and public participation.

2.2.3. Achievements

Indore has consistently ranked first in the Swachh Survekshan rankings due to its effective waste management practices and citywide cleanliness initiatives. The city has achieved near-universal source segregation and scientific processing of municipal solid waste, significantly reducing dependence on landfill disposal (SBM-U, 2020). The closure and remediation of the legacy waste dumpsite at Devguradia is regarded as one of the largest successful biomining and landfill reclamation projects in India. The city's integrated approach has resulted in improved environmental quality, enhanced resource recovery, and strengthened urban sanitation systems (CPCB, n.d.).

2.2.4. Relevance to the CRB

The Indore model provides valuable lessons for major urban centers within the CRB, including Mysuru, Tiruchirappalli, Salem, Erode, and rapidly growing peri-urban areas. The model demonstrates the importance of source segregation, scientific processing infrastructure, digital monitoring systems, citizen participation, and institutional commitment in achieving sustainable urban waste management outcomes. Adoption of similar practices can reduce solid waste leakage into river systems, improve urban environmental quality, and support basin-wide pollution reduction objectives.

2.3. Ambikapur Zero-Waste Model, Chhattisgarh

2.3.1. Background

Ambikapur, a municipal corporation in Surguja District, Chhattisgarh, transformed its waste management system through a decentralized, community-driven approach under the SBM-U. Prior to the intervention, the city faced challenges associated with open dumping, poor waste collection, and inadequate processing infrastructure (Fig. 1). To address these issues, the Ambikapur Municipal Corporation adopted a decentralized solid waste management model centered on source segregation, door-to-door collection, resource recovery, and women’s participation through SHGs. The model gained national recognition for eliminating the city's landfill, converting waste into economic resources, and generating sustainable livelihoods for women (MoHUA, n.d.).

Fig. 1. Ambikapur scenario before launch of zero waste model

2.3.2. Key Features

The Ambikapur model (Fig. 2) is based on 100% door-to-door collection and mandatory source segregation of waste into wet, dry, and domestic hazardous categories before collection (MoHUA, n.d.). The city established a network of SLRM Centers, where waste is brought for secondary segregation and resource recovery. These centers are operated by women's SHGs, which undertake sorting, processing, and sale of recyclable materials. Biodegradable waste is processed into compost, while recyclable materials such as plastics, paper, glass, and metals are recovered and sold through authorized recycling channels (SBM-U, 2020). The municipality also introduced user charges and awareness campaigns to strengthen financial sustainability and public participation (MoHUA, n.d.).

Fig. 2. Ambikapur model – achieving zero waste status:(a) the waste treatment – process re-engineered, (b) garbage clinics (the core), (c) inorganic waste treatment into 156 categories, (d) recyclables after segregation, (e) recyclables for sale with price, (f) organic waste treatment, (g) remediation of dumpsite into sanitary park

2.3.3. Achievements

According to official reports, Ambikapur became one of India's first cities to successfully eliminate a legacy dumpsite through systematic waste recovery and landfill reclamation (MoHUA, n.d.). The city achieved near-complete waste segregation and processing, substantially reducing the quantity of waste requiring final disposal. The operation of SLRM centers by women-led SHGs generated employment and livelihood opportunities while strengthening community ownership of waste management activities. The city's success earned national recognition in the Swachh Survekshan and established Ambikapur as a model for decentralized municipal waste management (MoHUA, n.d.).

2.3.4. Relevance to the CRB

The Ambikapur model demonstrates the effectiveness of decentralized resource recovery centers, community participation, and women-led waste management systems in achieving sustainable waste management outcomes. The model is particularly relevant for medium-sized towns and municipalities within the CRB, where centralized infrastructure may be financially challenging. Replicating similar approaches can improve waste segregation, reduce waste leakage into river systems, create local employment opportunities, and strengthen circular-economy practices across the basin.

2.4. Alappuzha Decentralized Waste Management Model, Kerala

2.4.1. Background

Alappuzha Municipality in Kerala adopted a decentralized waste management approach following the closure of its centralized waste disposal facility at Sarvodayapuram in 2012 due to environmental and public health concerns. Rather than establishing another large, centralized landfill or treatment facility, the municipality promoted household-level and community-level waste processing systems. The strategy was based on the principles of waste minimization, source segregation, decentralized treatment, and community participation. The model subsequently gained national and international recognition as an innovative approach to urban solid waste management and was recognized by the United Nations Environment Programme (UNEP) as a successful example of sustainable waste management practices (UNEP, n.d.; Government of Kerala, 2018).

2.4.2. Key Features

The Alappuzha model emphasizes decentralized management of biodegradable waste at the source through household biogas plants, pipe compost systems, ring compost units, and community composting facilities (Government of Kerala, 2018). Households are encouraged to segregate waste into biodegradable and non-biodegradable categories before treatment and collection. Biodegradable waste is processed within individual households or community facilities, thereby reducing the need for transportation and centralized processing infrastructure (UNEP, n.d.). Non-biodegradable waste is collected periodically at designated collection centers and transferred to authorized recycling agencies (Suchitwa Mission, n.d.). The municipality actively promotes citizen participation, awareness campaigns, and technical support for the installation and maintenance of decentralized treatment systems.

2.4.3. Achievements

The decentralized approach significantly reduced the quantity of waste requiring transportation and disposal while minimizing environmental impacts associated with centralized dumping facilities (UNEP, n.d.). Thousands of household composting and biogas units were installed across the municipality, resulting in substantial diversion of organic waste from the municipal waste stream (Suchitwa Mission, n.d.). The model contributed to improved urban sanitation, reduced greenhouse gas emissions from waste transportation and disposal, and enhanced public participation in waste management activities. Alappuzha's achievements led to its recognition by national and international organizations as a successful example of decentralized waste management (UNEP, n.d.).

2.4.4. Relevance to the CRB

The Alappuzha model offers valuable lessons for small towns, peri-urban settlements, and semi-urban regions of the CRB where land availability and financial resources may limit the feasibility of large, centralized facilities. Promoting household composting, community biogas systems, and decentralized organic waste treatment can substantially reduce waste generation, transportation costs, and pollution loads entering rivers and water bodies. The model is particularly suitable for settlements with a high proportion of biodegradable waste and strong community participation.

2.5. GOBARdhan Initiative: Waste-to-Wealth Model, India

2.5.1. Background

The Galvanizing Organic Bio-Agro Resources Dhan (GOBARdhan) initiative was launched by the Government of India in 2018 under the SBM-G to promote the scientific management of cattle dung, agricultural residues, biodegradable waste, and organic waste streams (Fig. 3). The programme seeks to transform organic waste into valuable resources such as biogas, compressed biogas (CBG), bio-slurry, and organic manure, thereby supporting rural sanitation, renewable energy generation, and sustainable agriculture (DDWS, n.d.). The initiative aligns with the principles of circular economy and waste-to-wealth by converting waste streams into productive resources while reducing environmental pollution and greenhouse gas emissions (Ministry of Jal Shakti, n.d.).

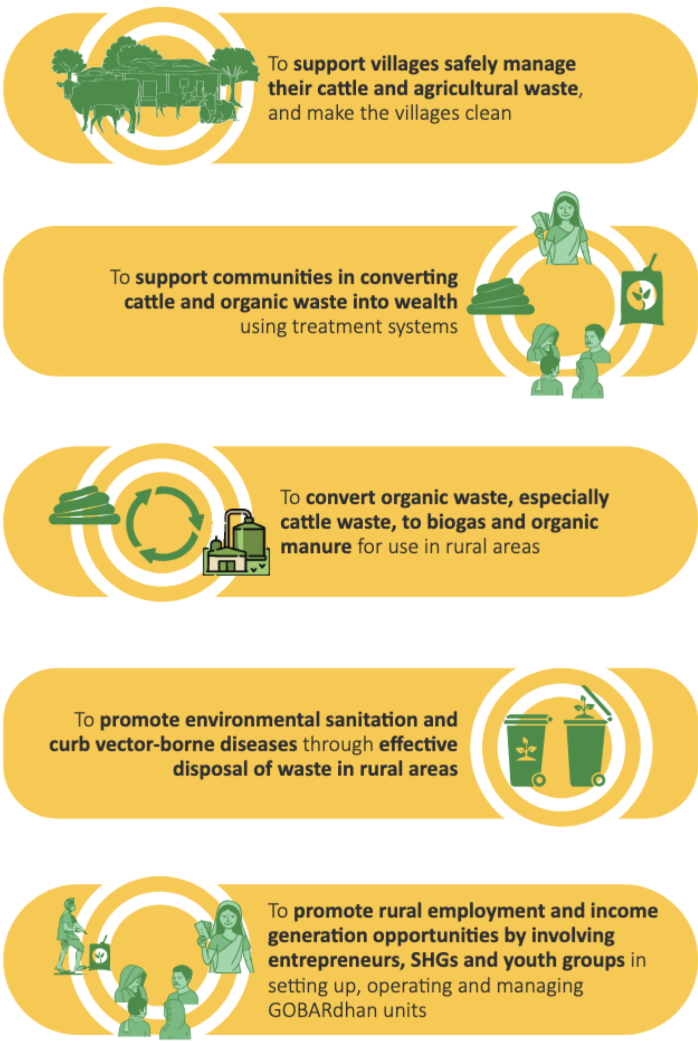

Fig. 3. Objectives of GOBARdhan

(**Source:** https://swachhbharatmission.ddws.gov.in/sites/default/files/communication-material/gobardhan.pdf)

2.5.2. Key Features

The GOBARdhan initiative promotes the establishment of community-based and cluster-level biogas and CBG plants utilizing cattle dung, agricultural residues, food waste, and other biodegradable organic waste materials (DDWS, n.d.). The programme supports the scientific collection, treatment, and processing of organic waste through anaerobic digestion technologies to generate renewable energy and nutrient-rich organic fertilizers (Ministry of Jal Shakti, n.d.). The initiative encourages convergence between gram panchayats, farmers, dairy cooperatives, private investors, and local institutions to establish sustainable waste management systems. The generated bio-slurry is utilized as an organic soil amendment. At the same time, biogas and CBG can be used for cooking, electricity generation, and as transportation fuels (Ministry of Petroleum and Natural Gas, 2023).

2.5.3. Achievements

The GOBARdhan initiative has emerged as a key component of rural waste management and resource recovery under SBM-G Phase II. According to the Department of Drinking Water and Sanitation, numerous biogases and CBG projects have been sanctioned and operationalized across various states, contributing to improved waste management, renewable energy production, and the generation of organic fertilizer (DDWS, n.d.). The programme supports reducing open dumping of organic waste, mitigating methane emissions, and enhancing rural livelihoods through value addition and resource recovery (Ministry of Jal Shakti, n.d.). Furthermore, GOBARdhan has been integrated with the Sustainable Alternative Towards Affordable Transportation (SATAT) initiative to promote CBG production at a larger scale (MoPNG, 2023). Fig. 4 represents the key benefits of the GOBARdhan initiative.

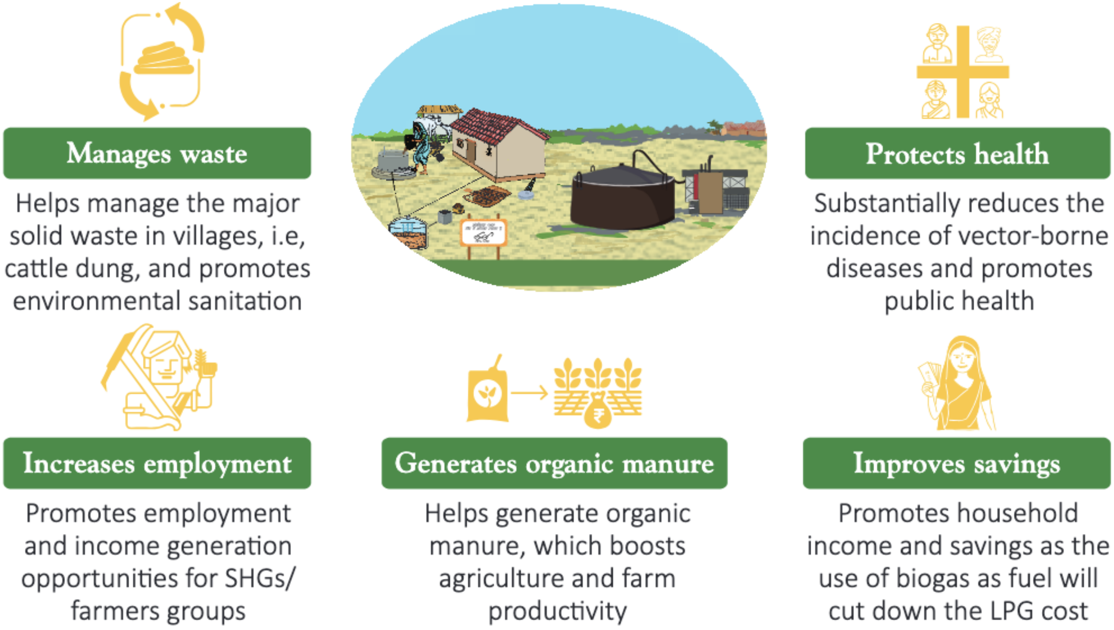

Fig. 4. Benefits of GOBARdhan

(**Source:** https://swachhbharatmission.ddws.gov.in/sites/default/files/communication-material/gobardhan.pdf)

2.5.4. Relevance to the CRB

The GOBARdhan model is highly relevant to the CRB due to extensive agricultural activities, a large livestock population, dairy farming, and the availability of organic biomass resources across the basin. The establishment of village-level and cluster-level biogas plants can significantly reduce organic waste accumulation, prevent direct discharge of livestock waste into rivers and streams, and generate renewable energy for rural communities. The utilization of bio-slurry as organic manure can improve soil health and reduce dependence on chemical fertilizers. The model is particularly suitable for agricultural regions of Karnataka and Tamil Nadu, where livestock-based economies and intensive farming systems generate substantial quantities of biodegradable waste.

2.6. Pune SWaCH Cooperative Model, Maharashtra

2.6.1. Background

The Solid Waste Collection and Handling (SWaCH) Cooperative was established in Pune, Maharashtra, in 2007 as India's first wholly owned cooperative of self-employed waste pickers and waste collectors. The initiative emerged from collaboration among the Pune Municipal Corporation (PMC), the Kagad Kach Patra Kashtakari Panchayat (KKPKP), and local communities to address challenges in waste collection, segregation, recycling, and livelihood security for informal waste workers. The model formally integrated waste pickers into the municipal waste management system, transforming them into service providers responsible for door-to-door waste collection and resource recovery (PMC, n.d.; SWaCH, n.d.). Fig. 5 illustrates the major activities and service components implemented under the Pune SWaCH cooperative model, highlighting community-based waste collection, recycling, composting, e-waste management, awareness programmes, and resource recovery initiatives that support inclusive and sustainable municipal solid waste management in Pune.

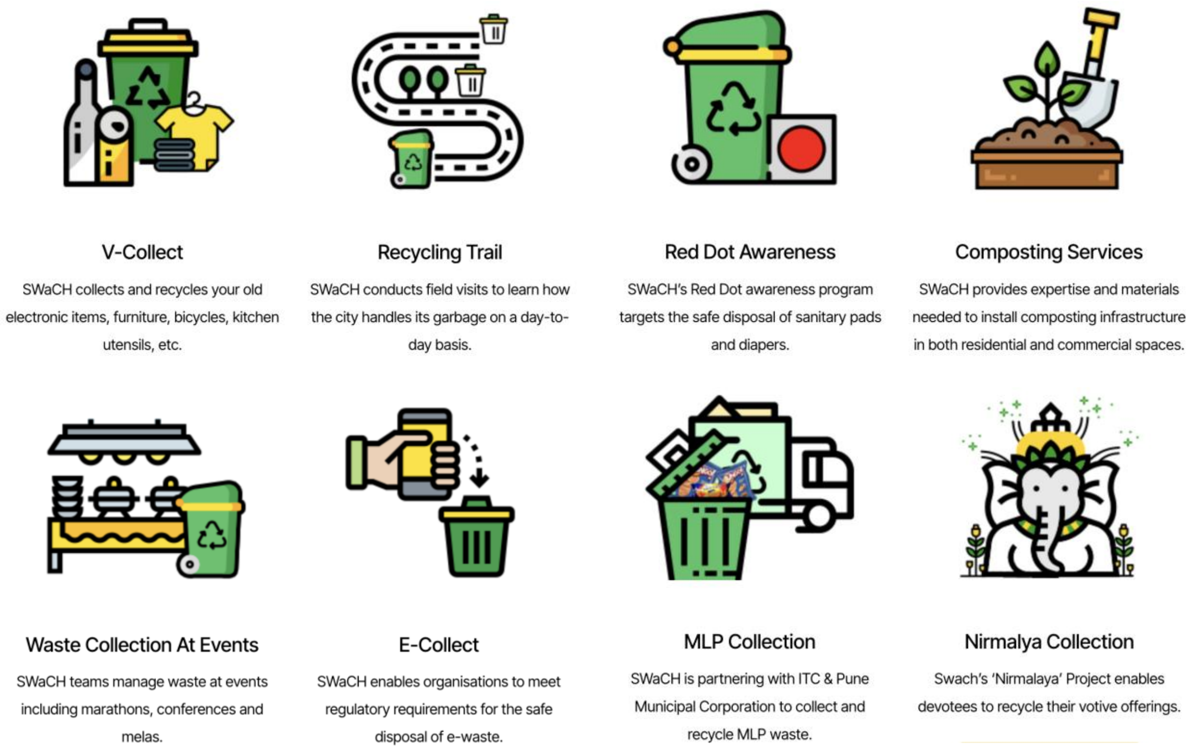

Fig. 5. Key components and service activities of the Pune SWaCH cooperative model, Maharashtra

(**Source:** https://swachcoop.com/)

2.6.2. Key Features

The Pune SWaCH model operates on the principle of door-to-door collection of segregated waste directly from households, commercial establishments, and institutions (SWaCH, n.d.). Waste generators are encouraged to segregate waste into wet, dry, sanitary, and domestic hazardous categories before collection (PMC, n.d.). Unlike conventional municipal collection systems, SWaCH members collect user fees directly from households, reducing financial burden on the municipal corporation while ensuring livelihood security for workers (MoHUA, n.d.). Recyclable materials are recovered and sold through authorized recycling networks, while biodegradable waste is promoted for composting and decentralized treatment (SWaCH, n.d.). The model emphasizes social inclusion, occupational safety, capacity building, and environmental sustainability by formally recognizing waste pickers within the urban waste management framework.

2.6.3. Achievements

The SWaCH Cooperative has become one of the world's largest waste picker-owned cooperatives, providing waste collection services to a significant proportion of Pune's households and commercial establishments (SWaCH, n.d.). The model has enhanced source segregation, increased recycling rates, reduced waste sent to disposal facilities and generated stable livelihoods for thousands of waste workers (MoHUA, n.d.). The integration of informal waste pickers into formal waste management systems has also improved social security, labor dignity, and occupational conditions for marginalized communities. The success of SWaCH has been recognized nationally and internationally as an innovative and inclusive approach to sustainable urban waste management.

2.6.4. Relevance to the CRB

The Pune SWaCH model demonstrates the importance of integrating informal waste workers into formal waste management systems. Many cities and towns within the CRB already depend on informal recycling networks for waste recovery. Adopting a similar cooperative framework can improve source segregation, increase recycling rates, reduce waste leakage into rivers and drainage systems, and create sustainable livelihood opportunities for waste workers. The model is particularly suitable for urban centers such as Mysuru, Bengaluru, Salem, Tiruchirappalli, Erode, and Karur, where large quantities of recyclable waste are generated daily.

2.7. Panaji Decentralized Waste Management Model, Goa

2.7.1. Background

The City of Panaji, Goa, is recognized as one of India's leading examples of decentralized municipal solid waste management. The city initiated systematic waste management reforms in the early 2000s in response to growing concerns about open dumping, rising waste generation, and environmental degradation associated with tourism and urbanization. Supported by the Government of Goa and technical agencies, Panaji adopted a decentralized waste management strategy emphasizing source segregation, door-to-door collection, material recovery, composting, and citizen participation. The model has been widely cited as a successful example of urban waste management that minimizes reliance on landfill while maximizing resource recovery (CCP, 2021).

2.7.2. Key Features

The Panaji model is based on mandatory segregation of waste at source into biodegradable, recyclable, sanitary, and domestic hazardous waste categories before collection (CCP, 2021). The city operates an extensive door-to-door collection system, ensuring regular collection of segregated waste from households, commercial establishments, hotels, restaurants, and institutions (MoHUA, n.d.). Organic waste is treated through decentralized composting and bio gasification facilities, while dry recyclable waste is routed to MRFs for sorting and recycling (Government of Goa, 2021). The city has also implemented strict enforcement mechanisms, awareness campaigns, and user participation programmes to improve compliance with waste segregation regulations (CCP, 2021). Tourism establishments and commercial generators are required to follow waste management regulations and promote responsible waste disposal practices.

2.7.3. Achievements

Panaji has achieved high levels of source segregation and waste recovery through sustained community engagement and effective municipal governance. The decentralized approach has significantly reduced the volume of waste requiring transportation and final disposal, while improving recycling efficiency and environmental performance (Government of Goa, 2021). The city has been recognized nationally for its innovative waste management practices. It serves as a model for other urban local bodies seeking to transition from landfill-dependent systems to resource recovery-oriented waste management (CCP, 2021). The initiative has also contributed to improved urban cleanliness and environmental sustainability in a city that generates significant tourism-related waste.

2.7.4. Relevance to the CRB

The Panaji model offers valuable lessons for urban centers and tourist destinations within the CRB. Cities such as Mysuru, Srirangapatna, Talakaveri, Shivanasamudra, Hogenakkal, Tiruchirappalli, and other tourism-intensive areas can benefit from decentralized waste treatment systems, mandatory source segregation, and strengthened citizen participation mechanisms. The model demonstrates how effective governance, decentralized infrastructure, and strict enforcement can significantly reduce waste leakage into rivers, lakes, and drainage networks while enhancing resource recovery and environmental sustainability.

3. International Case Studies

3.1. Singapore NEWater Programme and Integrated Water Management System

3.1.1. Background

Singapore is internationally recognized for its advanced water and wastewater management framework, which has transformed treated wastewater into a strategic water resource. Due to limited freshwater availability and a high reliance on imported water, Singapore adopted an integrated water resources management approach that emphasizes water conservation, wastewater treatment, water reuse, and resource recovery. The Public Utilities Board (PUB), Singapore's National Water Agency, developed the NEWater programme as a key component of the country's long-term water security strategy. Introduced in 2003, NEWater involves the production of high-quality reclaimed water from treated municipal wastewater through advanced purification processes (Tortajada & Joshi, 2013).

3.1.2. Key Features

The NEWater system (Fig. 6) utilizes a multi-barrier treatment process consisting of microfiltration (MF), reverse osmosis (RO), and ultraviolet (UV) disinfection to produce ultra-clean reclaimed water that exceeds World Health Organization (WHO) drinking water quality standards. The reclaimed water is primarily supplied to industries requiring high-purity water and is also blended with reservoir water for indirect potable reuse. Singapore's water management framework integrates wastewater collection, treatment, reuse, stormwater management, and environmental protection under a single institutional structure managed by PUB. The system is supported by advanced monitoring technologies, extensive public awareness programmes, and strong regulatory frameworks to ensure safety and reliability.

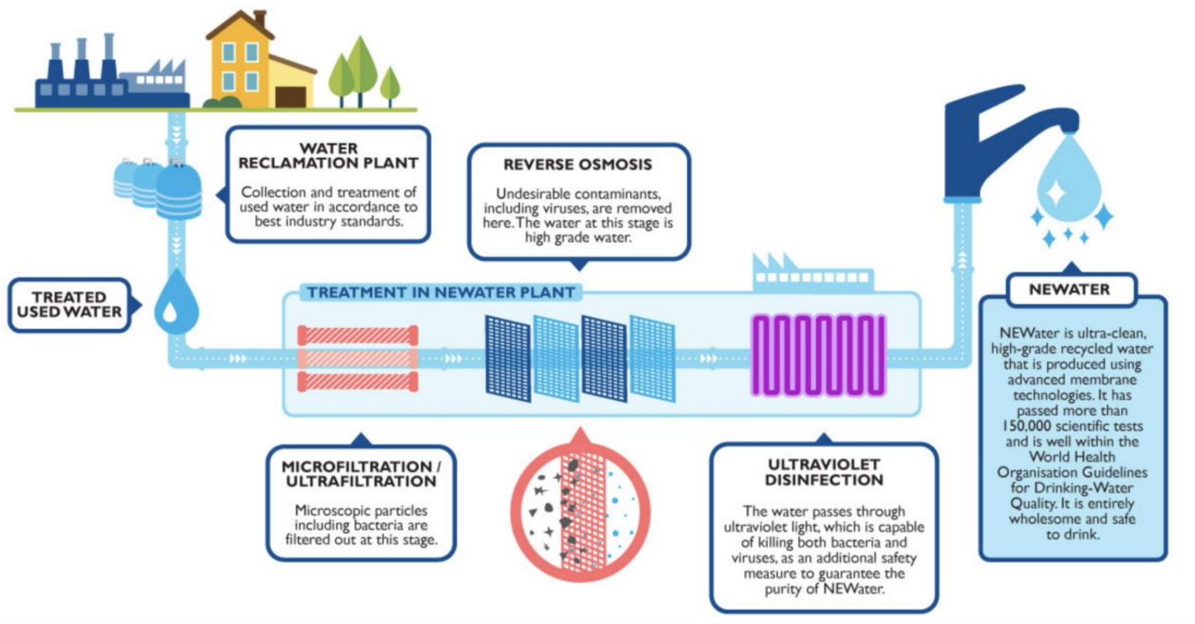

Fig. 6. Schematic representation of the Singapore NEWater water reclamation and reuse system

(**Source:** https://greennetwork.asia/gna-knowledge-hub/newater-singapores-recycled-water/)

3.1.3. Achievements

The NEWater programme currently meets a significant portion of Singapore's water demand and has become a cornerstone of the nation's water sustainability strategy. The initiative has reduced dependence on imported water, enhanced water security, and improved resilience against climate variability and drought conditions (Tortajada & Joshi, 2013). Singapore's integrated water management approach has received international recognition as one of the most successful examples of urban water recycling and resource recovery. The programme demonstrates how wastewater can be transformed from an environmental liability into a valuable resource through technological innovation and effective governance.

3.1.4. Relevance to the CRB

The Singapore model provides important lessons for urban and industrial regions of the CRB facing increasing water stress and growing wastewater generation. Cities such as Bengaluru, Mysuru, Tiruchirappalli, Salem, and Erode, as well as industrial clusters in the basin, can adopt advanced wastewater recycling and reuse systems to reduce freshwater withdrawals and improve water-use efficiency. Treated wastewater can be utilized for industrial processes, landscaping, groundwater recharge, and non-potable applications, thereby reducing pressure on river water resources. The model highlights the importance of integrated governance, advanced treatment technologies, and long-term planning in achieving sustainable water resource management.

3.2. Tuas Nexus Integrated Waste and Water Resource Recovery Facility, Singapore

3.2.1. Background

Tuas Nexus (Fig. 7) is one of the world's first large-scale integrated facilities combining solid waste management and wastewater treatment within a single infrastructure framework. Developed by Singapore's National Environment Agency (NEA) and PUB, the facility was designed to enhance resource efficiency, optimize land utilization, and support Singapore's transition towards a circular economy. The project integrates the Tuas Water Reclamation Plant (TWRP) with the Integrated Waste Management Facility (IWMF), creating synergies between wastewater treatment, sludge management, WtE processes, and resource recovery systems (NEA, 2023).

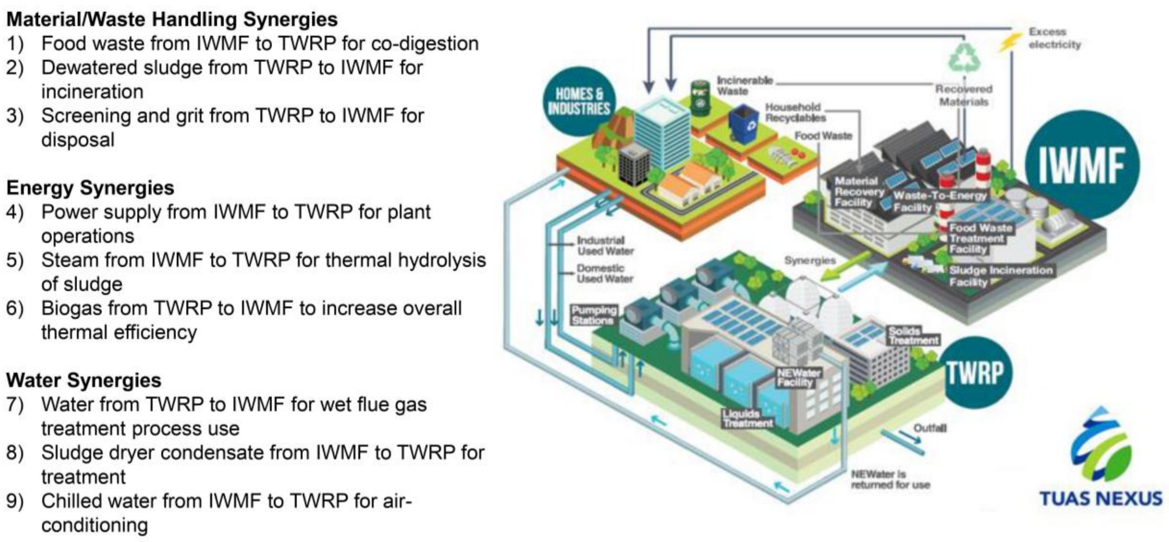

Fig. 7. Tuas Nexus integrated waste and water resource recovery facility

(Source: https://www.nea.gov.sg/our-services/waste-management/waste-management-infrastructure/integrated-waste-management-facility)

3.2.2. Key Features

Tuas Nexus combines municipal wastewater treatment and solid waste processing within a unified resource recovery ecosystem. The TWRP treats used water through advanced treatment technologies and produces treated water for reuse under Singapore's national water recycling programme. Sludge generated during wastewater treatment is co-digested with food waste in centralized anaerobic digesters to maximize biogas production (NEA, 2023). The IWMF incorporates advanced WtE technologies that convert non-recyclable municipal solid waste into electricity while significantly reducing the volume of waste requiring disposal (NEA, 2023). The facility also incorporates resource recovery systems for energy generation, nutrient recovery, and efficient management of residual materials.

3.2.3. Achievements

According to the NEA, Tuas Nexus is expected to significantly reduce land requirements for waste and wastewater infrastructure by integrating multiple treatment processes within a single site (NEA, 2023). The co-digestion of food waste and sewage sludge enhances biogas production and improves energy recovery efficiency compared to conventional standalone treatment systems. The integrated facility contributes to Singapore's long-term goals of reducing landfill dependency, increasing resource recovery, improving water security, and achieving greater energy efficiency (NEA, 2023). The project is widely regarded as a global benchmark for integrated resource recovery and circular economy-based infrastructure development.

3.2.4. Relevance to the CRB

The Tuas Nexus model provides valuable insights for developing integrated waste and wastewater management systems in major urban and industrial centers across the CRB. Cities such as Bengaluru, Mysuru, Tiruchirappalli, Salem, and Erode, as well as industrial clusters, can benefit from co-treatment approaches involving sewage sludge, food waste, and other organic waste streams. Integrated resource recovery facilities can support renewable energy generation, reduce waste disposal requirements, improve wastewater management, and enhance circular economy outcomes. The model demonstrates the potential benefits of combining traditionally separate waste and wastewater sectors into a unified resource management framework.

3.3. Sweden Circular WtE and Resource Recovery Model

3.3.1. Background

Sweden is widely recognized as a global leader in circular-economy practices, waste management, and resource recovery. Over several decades, the country has developed an integrated waste management system that prioritizes waste prevention, reuse, recycling, biological treatment, and energy recovery. Landfilling of municipal waste has been progressively reduced through strict environmental regulations, economic instruments, and investment in advanced waste treatment infrastructure. Sweden's waste management strategy is guided by the European Union Waste Framework Directive and national circular economy policies, which promote the recovery of materials, nutrients, and energy from waste streams (Avfall Sverige, 2024; European Commission, n.d.).

3.3.2. Key Features

The Swedish waste management system follows a waste hierarchy that prioritizes prevention, reuse, recycling, and recovery before disposal (European Commission, n.d.). Municipal solid waste is segregated at source into multiple fractions, including food waste, paper, plastics, metals, glass, textiles, and hazardous waste (Avfall Sverige, 2024). Organic waste is treated through composting and anaerobic digestion, producing biogas and nutrient-rich digestate that can be utilized in agriculture (Waste management in Sweden, n.d.). Non-recyclable combustible waste is processed in highly efficient WtE facilities, generating electricity and district heating for residential and commercial consumers (IEA Bioenergy, 2023). Advanced emission control systems ensure compliance with stringent environmental standards and minimize atmospheric pollution (EEA, 2016).

3.3.3. Achievements

Sweden has achieved one of the lowest landfill disposal rates in the world, with less than 1% of municipal waste sent to landfills (Avfall Sverige, 2024). A substantial proportion of municipal waste is either recycled or converted into energy through WtE facilities, contributing significantly to national renewable energy production (IEA Bioenergy, 2023). Biogas produced from food waste and sewage sludge is increasingly utilized as a renewable transportation fuel, supporting climate mitigation objectives (Waste management in Sweden, n.d.). The country's integrated approach has reduced greenhouse gas emissions, improved resource efficiency, and strengthened the transition toward a circular economy (EEA, 2016).

3.3.4. Relevance to the CRB

The Swedish model provides valuable lessons for urban and industrial regions within the CRB, where increasing waste generation poses challenges for sustainable management. Cities such as Bengaluru, Mysuru, Salem, Erode, Tiruchirappalli, and industrial clusters can adopt source segregation systems, anaerobic digestion facilities, WtE technologies, and resource recovery approaches to reduce reliance on landfills and enhance resource utilization. The integration of food waste treatment, biogas production, energy recovery, and nutrient recycling can significantly reduce pollution, generate renewable energy, and advance circular economy development within the basin.

3.4. Netherlands Circular Wastewater and Nutrient Recovery Model

3.4.1. Background

The Netherlands is recognized as a global leader in circular water management and wastewater resource recovery. Faced with increasing pressures on water resources, nutrient sustainability, and environmental protection, Dutch water authorities and wastewater utilities have adopted the concept of transforming wastewater treatment plants into resource recovery facilities. Rather than viewing wastewater as a waste stream to be disposed of, the Dutch approach considers it a valuable source of water, energy, nutrients, and raw materials. This transformation has been driven by the Dutch Water Authorities (Waterschappen), the Energy and Raw Materials Factory (ERMF) programme, and national circular economy policies aimed at maximizing resource recovery while minimizing environmental impacts (STOWA, 2022; Dutch Water Authorities, 2023).

3.4.2. Key Features

The Dutch model promotes the recovery of valuable resources from municipal and industrial wastewater through advanced treatment and circular economy approaches (Dutch Water Authorities, 2023). Wastewater treatment plants are increasingly designed to recover phosphorus, nitrogen, cellulose, bioplastics precursors, and energy from sewage and sludge streams (STOWA, 2022). Anaerobic digestion of sewage sludge is widely employed to generate biogas, which is used for electricity and heat production within treatment facilities (European Commission, n.d.). Several wastewater treatment plants have achieved energy-neutral or energy-positive operation through efficient energy recovery systems. The Netherlands has also pioneered phosphorus recovery technologies such as struvite precipitation, enabling the production of fertilizers from wastewater-derived nutrients (Witek-Krowiak et al., 2022).

3.4.3. Achievements

The Dutch wastewater sector has successfully demonstrated the technical and economic feasibility of resource recovery at large scales. Numerous wastewater treatment facilities now recover significant quantities of phosphorus and energy while reducing operational costs and environmental impacts (STOWA, 2022). The ERMF programme has enabled wastewater utilities to convert recovered resources into marketable products, supporting circular economy objectives (Dutch Water Authorities, 2023). The integration of nutrient recovery, energy generation, and water reuse have contributed to improved sustainability, reduced greenhouse gas emissions, and enhanced resource efficiency across the Dutch water sector (European Commission, n.d.).

3.4.4. Relevance to the CRB

The Netherlands model offers important lessons for wastewater management and pollution control within the CRB. Urban centers and industrial clusters generate substantial quantities of wastewater and sewage sludge that can be recovered as resources rather than disposed of. Technologies for phosphorus recovery, biogas generation, sludge valorization, and treated wastewater reuse can support sustainable water management while reducing nutrient pollution in rivers and reservoirs. The model is particularly relevant for large sewage treatment plants (STPs), common effluent treatment plants (CETPs), and industrial wastewater treatment facilities operating within the basin. Adoption of similar approaches can contribute to the development of the circular economy, resource conservation, and long-term basin sustainability.

3.5. Germany WtE and Recycling Model

3.5.1. Background

Germany is widely regarded as one of the world's most advanced countries in municipal solid waste management, recycling, and resource recovery. Over the past three decades, the country has developed a comprehensive waste management framework based on the principles of waste prevention, recycling, resource recovery, and circular economy. The German waste management system is supported by stringent environmental legislation, including the Circular Economy Act (Kreislaufwirtschaftsgesetz, KrWG), the Packaging Act, and strict landfill regulations. Since the implementation of the Landfill Ordinance in 2005, untreated municipal waste has been prohibited from disposal in landfills, significantly increasing recycling and energy recovery rates (Federal Environment Agency, 2023; EEA, 2026).

3.5.2. Key Features

Germany follows a hierarchical waste management approach prioritizing waste prevention, reuse, recycling, recovery, and disposal as the last option. Households and commercial establishments are required to segregate waste into multiple streams, including paper, plastics, glass, bio-waste, residual waste, and packaging materials (Jalalipour et al., 2025). The country operates an extensive network of recycling facilities supported by the Extended Producer Responsibility (EPR) system, under which producers share responsibility for the collection and recycling of packaging waste. Organic waste is separately collected and processed through composting and anaerobic digestion facilities. In contrast, non-recyclable combustible waste is treated in highly efficient WtE plants that generate electricity and district heating (CEWEP, n.d.). Advanced emission control technologies ensure compliance with some of the world's strictest environmental standards.

3.5.3. Achievements

Germany has achieved one of the highest municipal waste recycling rates globally, with a substantial proportion of municipal waste being recycled or recovered for energy generation. The landfill disposal of untreated municipal waste has been virtually eliminated since the introduction of strict landfill restrictions in 2005 (Jalalipour et al., 2025). WtE facilities contribute significantly to renewable and low-carbon energy production while reducing the volume of waste requiring final disposal (CEWEP, n.d.). The country's integrated approach has enhanced resource efficiency, reduced greenhouse gas emissions, and promoted circular economy development across multiple sectors.

3.5.4. Relevance to the CRB

The German model offers valuable lessons for urban and industrial regions of the CRB, where increasing waste generation and limited landfill availability pose significant challenges. Adoption of source segregation systems, EPR mechanisms, advanced recycling infrastructure, and WtE technologies can substantially reduce waste disposal requirements and environmental pollution. Large urban centers such as Bengaluru, Mysuru, Salem, Erode, and Tiruchirappalli can particularly benefit from integrated recycling and energy recovery systems. The model also demonstrates the importance of strong regulatory frameworks, institutional coordination, and private sector participation in achieving sustainable waste management outcomes.

3.6. Kamikatsu Zero-Waste Town Model, Japan

3.6.1. Background

Kamikatsu, a small town in Tokushima Prefecture, Japan, is internationally recognized for its pioneering Zero Waste Policy, formally adopted through the Zero Waste Declaration in 2003. Faced with rising waste management costs, stricter environmental regulations on small incinerators, and the absence of resources to construct a new large-scale incineration facility, the town adopted a community-driven approach emphasizing waste reduction, reuse, recycling, and resource recovery. The Zero Waste Declaration established a long-term goal of eliminating waste destined for landfill and incineration through extensive source segregation and material recovery practices. Over time, Kamikatsu developed one of the world's most recognized zero-waste systems, achieving recycling rates exceeding 80% and becoming an international model for sustainable waste management and circular economy implementation (Government of Japan, 2019; Shenyoputro et al., 2023; Zero Waste Town Kamikatsu, 2024).

3.6.2. Key Features

The Kamikatsu model relies heavily on source segregation and citizen participation. Residents are required to separate waste into multiple categories, including paper, plastics, metals, textiles, glass, electronics, and other recyclable materials before delivery to community collection centers. The town operates a Zero Waste Centre, where materials are sorted, stored, reused, recycled, or prepared for further processing (Zero Waste Town Kamikatsu, 2024). Dedicated reuse programmes allow residents to exchange and reuse household items, thereby reducing waste generation. Extensive awareness campaigns, environmental education initiatives, and community participation programmes support high compliance with segregation and recycling practices. The model emphasizes behavioral change as a critical component of sustainable waste management.

3.6.3. Achievements

Kamikatsu has achieved one of the highest waste diversion rates in the world, with a substantial proportion of municipal waste being reused, recycled, or recovered rather than disposed of through conventional methods. The town has significantly reduced landfill requirements and minimized dependence on incineration through intensive source segregation and material recovery efforts. The initiative has also strengthened environmental awareness and community ownership of waste management activities. Kamikatsu is frequently cited as a leading example of how local communities can successfully implement circular economy principles through active citizen engagement and decentralized resource recovery systems (Zero Waste Town Kamikatsu, 2024).

3.6.4. Relevance to the CRB

The Kamikatsu model offers valuable lessons for rural settlements, small towns, eco-sensitive regions, and tourism destinations within the CRB. Areas located in the Western Ghats, upper catchments, and environmentally sensitive zones can benefit from community-based waste segregation, reuse initiatives, and decentralized recycling systems. The model demonstrates that behavioral change, public participation, and local ownership can significantly improve waste management outcomes while reducing environmental impacts. Adoption of similar approaches can help reduce waste leakage into rivers, streams, reservoirs, and protected ecosystems across the basin.

3.7. South Korea Food Waste Recycling and Resource Recovery Programme

3.7.1. Background

South Korea has developed one of the world's most advanced food waste management systems in response to increasing urbanization, limited landfill space, and environmental concerns associated with organic waste disposal (Lee et al., 2024). During the 1990s, large amounts of food waste were disposed of in landfills, leading to leachate generation, greenhouse gas emissions, and environmental degradation. To address these challenges, the Government of South Korea introduced a series of policy reforms, including mandatory source segregation, landfill restrictions, volume-based waste fee systems, and food waste recycling programmes. These measures were implemented under the Framework Act on Resource Circulation and related waste management regulations, transforming food waste from an environmental burden into a valuable resource (KECO, n.d.; OECD, 2021).

3.7.2. Key Features

The South Korean model is based on mandatory segregation of food waste at source, ensuring that organic waste is collected separately from other municipal waste streams (Ministry of Environment, 2023). The country has implemented a Pay-As-You-Throw (PAYT) system, under which households and commercial establishments pay waste management fees according to the quantity of food waste generated (OECD, 2021). In several cities, smart collection systems using Radio Frequency Identification (RFID) technology are employed to accurately measure food waste generation and promote waste reduction. Collected food waste is processed through composting, animal feed production, anaerobic digestion, and biogas generation facilities, enabling recovery of nutrients and renewable energy (KECO, n.d.). Strong public awareness campaigns and robust regulatory enforcement mechanisms support high compliance rates nationwide.

3.7.3. Achievements

South Korea has achieved one of the highest food waste recycling rates globally through the implementation of integrated policy, technology, and resource recovery measures (Ministry of Environment, 2023). The diversion of food waste from landfills has significantly reduced environmental pollution, greenhouse gas emissions, and disposal costs. Resource recovery facilities generate valuable products such as compost, animal feed, and renewable energy while supporting circular economy objectives (KECO, n.d.). The success of the programme has made South Korea a global reference for the sustainable management of biodegradable municipal waste.

3.7.4. Relevance to the CRB

The South Korean model offers important lessons for managing organic and food waste across the CRB's urban and peri-urban areas. A significant proportion of municipal solid waste generated in Indian cities consists of biodegradable material, much of which is currently disposed of through unsustainable practices. Adoption of source segregation, user-based charging systems, decentralized organic waste treatment, and biogas generation facilities can substantially reduce waste disposal requirements and environmental pollution. The model is particularly relevant for cities such as Bengaluru, Mysuru, Salem, Erode, Tiruchirappalli, and rapidly growing urban centers where food waste management remains a major challenge. Integration of organic waste recycling with energy recovery and compost production can support circular economy initiatives while reducing pollution loads entering rivers and drainage networks.

4. Technological Innovations in Solid–Liquid Waste Management

Technological innovation has become a critical enabler of sustainable solid and liquid waste management worldwide. Increasing waste generation, rapid urbanization, industrial growth, resource depletion, and environmental degradation have necessitated the adoption of advanced technologies that move beyond conventional waste collection and disposal practices. Modern waste management systems increasingly focus on resource recovery, circular economy principles, renewable energy generation, wastewater reuse, nutrient recovery, and digital monitoring, transforming waste streams into valuable economic and environmental resources.

Globally, technological advancements have improved the efficiency of waste segregation, recycling, biological treatment, wastewater treatment, and environmental monitoring systems. Countries such as Singapore, Germany, Sweden, the Netherlands, Japan, and South Korea have successfully integrated innovative technologies into their waste management frameworks to maximize resource recovery and minimize environmental impacts (Agamuthu & Babel, 2023). Similarly, several Indian initiatives, including the Udupi SLRM model, the GOBARdhan programme, Indore's integrated waste management system, and DEWATS implemented under the SBM, demonstrate the growing importance of technology-driven solutions in addressing waste management challenges (MoHUA, n.d.; Ministry of Jal Shakti, n.d.).

The CRB faces multiple waste management challenges arising from rapid urban expansion, industrial activities, agricultural intensification, tourism, and population growth. Untreated sewage, municipal solid waste, industrial effluents, agricultural residues, and livestock waste continue to contribute to water quality deterioration across several stretches of the basin. Technological innovations offer significant opportunities to reduce pollution loads, improve resource recovery, enhance wastewater reuse, and strengthen environmental sustainability. The following sections review key technological innovations in solid and liquid waste management and assess their relevance for implementation within the CRB.

4.1. Technology Classification Framework

Technologies used in solid and liquid waste management can be broadly categorized based on their primary function, treatment approach, and resource recovery potential. Understanding these categories is important for selecting suitable interventions across different environmental, socio-economic, and institutional settings within a river basin. Table 1 presents a broad classification of technologies relevant to integrated solid–liquid waste management.

Table 1. Classification of major solid–liquid waste management technologies

Sr. No.	Technology Category	Major Technologies	Primary Application
1.	**Waste Collection and Monitoring**	IoT sensors, GPS tracking, RFID systems, smart bins	Collection efficiency and monitoring
2.	**Waste Segregation and Material Recovery**	MRFs, optical sorting, AI-based sorting	Recycling and resource recovery
3.	**Organic Waste Management**	Composting, vermicomposting, anaerobic digestion, bio methanation	Organic waste treatment and energy recovery
4.	**WtE Technologies**	Incineration, Refuse-Derived Fuel (RDF), gasification, pyrolysis	Energy generation from residual waste
5.	**Wastewater Treatment Technologies**	STPs, Membrane Bioreactors (MBRs), DEWATS, Upflow Anaerobic Sludge Blanket (UASB) reactors	Liquid waste treatment
6.	**Wastewater Reuse Technologies**	RO, ultrafiltration (UF), UV disinfection	Water recycling and reuse
7.	**Nutrient Recovery Technologies**	Struvite recovery, ammonia recovery, sludge valorization	Resource recovery
8.	**Fecal Sludge Management Technologies**	Fecal Sludge Treatment Plants (FSTPs), drying beds, co-treatment facilities	Septage treatment

9.	**Nature-Based Solutions**	Constructed wetlands, phytoremediation, bio-retention systems	Ecological treatment and restoration
10.	**Digital and Smart Technologies**	GIS, AI, Remote Sensing (RS), digital twins	Planning, monitoring, and decision support

The technological selection process depends on several factors, including waste quantity and composition, population density, land availability, financial resources, institutional capacity, environmental sensitivity, and regulatory requirements (Agamuthu & Babel, 2023). For example, decentralized systems such as composting, biogas plants, DEWATS, and constructed wetlands are often more suitable for rural and peri-urban areas. In contrast, large urban centers may require advanced recycling facilities, wastewater recycling plants, and digital monitoring systems.

An integrated waste management system typically combines multiple technologies rather than relying on a single treatment approach. Successful examples from Singapore, Sweden, Germany, and India demonstrate that combining source segregation, resource recovery, biological treatment, wastewater reuse, and digital technologies can significantly improve environmental performance and operational efficiency (IEA Bioenergy, 2023). Consequently, the selection of technologies for the CRB should be guided by local conditions, pollution sources, infrastructure availability, and long-term sustainability objectives.

4.2. Advanced Waste Segregation and Material Recovery Technologies

Waste segregation and material recovery are essential components of sustainable solid waste management. The effectiveness of recycling, composting, biomethanation, and WtE systems depends largely on source segregation and efficient sorting processes. Poor segregation leads to contamination of recyclable materials, reduced recovery rates, increased disposal costs, and greater reliance on landfills. Consequently, advanced segregation and material recovery technologies play a crucial role in supporting circular economy objectives by recovering valuable resources from waste streams (Agamuthu & Babel, 2023; EEA, 2026).

Source segregation remains the most important step, requiring waste generators to separate biodegradable, recyclable, sanitary, hazardous, and residual waste before collection (CPCB, n.d.). MRFs are then used to sort and process collected waste through technologies such as conveyor systems, trommel screens, magnetic separators, eddy-current separators, and optical sorters (EEA, 2026). Modern facilities increasingly incorporate AI and machine vision systems to improve sorting accuracy and recovery efficiency.

Countries such as Germany, Sweden, and Singapore have successfully implemented advanced segregation and recycling systems that achieve high resource recovery rates while minimizing landfill disposal (European Commission, n.d.; Avfall Sverige, 2024). In India, cities such as Indore, Ambikapur, and Udupi have demonstrated the effectiveness of Material Recovery Facilities and decentralized resource recovery centers in improving recycling performance and reducing environmental pollution (MoHUA, n.d.).

Advanced segregation and material recovery technologies improve recycling efficiency, reduce reliance on landfills, and enhance resource recovery. However, their success depends on public participation, compliance with source segregation, and the availability of recycling markets. Establishment of MRFs also requires investment, technical expertise, and operational capacity.

Within the CRB, improper waste disposal and inadequate segregation contribute significantly to pollution of rivers, reservoirs, and drainage systems. Establishing centralized and decentralized Material Recovery Facilities can improve recycling rates and reduce waste leakage into water bodies. Urban centers such as Bengaluru, Mysuru, Salem, Erode, Tiruchirappalli, and Karur can benefit from advanced MRFs. At the same time, rural areas can adopt decentralized resource recovery centers, such as the Udupi SLRM model. Such interventions can strengthen circular economy practices and support basin-wide pollution reduction.

4.3. Anaerobic Digestion and Biogas Technologies

Anaerobic digestion is a widely adopted technology for managing biodegradable waste while generating renewable energy and recovering nutrients. It is particularly suitable for treating food waste, livestock manure, agricultural residues, sewage sludge, and other organic waste streams. The technology supports circular economy principles by converting waste into valuable products such as biogas and organic fertilizers (IEA Bioenergy, 2023).

Anaerobic digestion is a biological process in which microorganisms decompose organic matter in the absence of oxygen, producing biogas rich in methane and carbon dioxide. The process also generates nutrient-rich digestate that can be used as an organic fertilizer and soil conditioner. Biogas can be utilized for cooking, heating, electricity generation, or upgraded to CBG for transportation applications (IEA Bioenergy, 2023).

Globally, anaerobic digestion is extensively used in Germany, Sweden, the Netherlands, and Singapore for organic waste treatment, renewable energy generation, and resource recovery (European Biogas Association, 2023). In India, initiatives such as the GOBARdhan Scheme and SATAT programme promote the conversion of cattle dung, agricultural residues, and organic waste into biogas and organic fertilizers (Ministry of Jal Shakti, n.d.; MoPNG, 2023).

The technology offers several benefits, including reduced organic waste volumes, renewable energy generation, nutrient recovery, and greenhouse gas mitigation. It also reduces odors and environmental pollution associated with conventional waste disposal methods (Badsha et al., 2025; Chojnacka & Moustakas, 2024; IEA Bioenergy, 2023). However, successful implementation requires reliable feedstock supply, proper segregation of organic waste, technical expertise, and regular maintenance.

The CRB has significant potential for anaerobic digestion due to its extensive agricultural activities, livestock population, dairy sector, and urban settlements. Large quantities of cattle dung, crop residues, food waste, market waste, and sewage sludge can serve as feedstocks for biogas production. Community-scale biogas plants in rural areas and municipal biogas methanation facilities in urban centers such as Bengaluru, Mysuru, Salem, Erode, and Tiruchirappalli can reduce organic pollution loads while generating renewable energy and organic fertilizers. Integration with STPs and fecal sludge management systems can further enhance resource recovery and support sustainable basin-wide waste management.

4.4. WtE Technologies

WtE technologies convert non-recyclable waste into useful forms of energy such as electricity, heat, steam, or fuel. They are increasingly adopted as part of integrated waste management systems because they reduce waste volumes while recovering energy from residual waste streams (CEWEP, n.d.). Countries such as Germany, Sweden, Japan, and Singapore have successfully implemented WtE facilities to reduce reliance on landfills and enhance resource recovery (IEA Bioenergy, 2023).

The most widely used WtE technology is mass-burn incineration, where waste is combusted under controlled conditions to generate heat and electricity. Other technologies include the production of RDF, gasification, and pyrolysis. RDF utilizes combustible fractions of municipal waste such as plastics, paper, and textiles as fuel for cement kilns and industrial boilers, while gasification and pyrolysis convert waste into syngas, bio-oil, and char (CPCB, n.d.; IEA Bioenergy, 2023).

Countries such as Sweden and Germany have achieved significant reductions in landfill disposal through advanced WtE infrastructure combined with effective source segregation and recycling systems (Avfall Sverige, 2024; Jalalipour et al., 2025). In India, WtE projects have been implemented in cities such as Delhi, Hyderabad, and Indore to recover energy from municipal waste and reduce landfill burden.

WtE technologies can reduce waste volumes by 70–90%, extend landfill life, and generate renewable energy from residual waste streams (European Commission, n.d.). However, their performance depends on waste composition, calorific value, and effective segregation. High capital costs, operational requirements, air emission control, and ash management remain important challenges, particularly in developing regions (CPCB, n.d.).

In the CRB, WtE technologies can complement existing waste management systems in major urban centers such as Bengaluru, Mysuru, Salem, Erode, and Tiruchirappalli. However, WtE should be considered only after maximizing source segregation, recycling, composting, biomethanation, and material recovery. Given the high biodegradable content of municipal waste in the basin, composting and anaerobic digestion are often more suitable for organic waste. At the same time, WtE facilities can be used for treating residual combustible waste fractions.

4.5. DEWATS

DEWATS are increasingly recognized as effective solutions for wastewater management in rural areas, peri-urban settlements, institutions, residential complexes, and small towns where centralized sewerage systems are often economically or technically unfeasible. DEWATS treat wastewater close to the point of generation using low-energy, robust, and locally adaptable treatment processes, thereby reducing dependence on extensive sewer networks and lowering operational costs (Varma et al., 2022).

A typical DEWATS system combines physical, biological, and natural treatment processes, including sedimentation tanks, anaerobic baffled reactors (ABRs), anaerobic filters, constructed wetlands, planted gravel filters, and polishing ponds. These systems effectively remove suspended solids, organic matter, nutrients, and pathogens while requiring minimal energy and maintenance (Muzioreva et al., 2022). Treated wastewater can be reused for irrigation, landscaping, groundwater recharge, and other non-potable purposes.

DEWATS have been successfully implemented across Asia, Africa, and Latin America for decentralized sanitation and wastewater treatment. In India, the technology has been adopted in residential complexes, educational institutions, tourism facilities, industrial campuses, and rural communities to reduce untreated wastewater discharge into water bodies.

The major advantages of DEWATS include low capital and operational costs, simple operation, reduced energy requirements, and flexibility for phased implementation. These systems can achieve substantial reductions in biochemical oxygen demand, chemical oxygen demand, suspended solids, and pathogen concentrations (Muzioreva et al., 2022). However, adequate land availability, periodic maintenance, and regular monitoring are necessary to ensure long-term performance.

DEWATS are highly relevant to the CRB, where many villages, small towns, tourism centers, and peri-urban settlements lack adequate sewerage infrastructure. Adoption of DEWATS can significantly reduce wastewater pollution entering rivers, streams, and tributaries while providing affordable sanitation solutions. Integration with constructed wetlands, wastewater reuse systems, and fecal sludge management infrastructure can further strengthen pollution control and support sustainable river basin management.

4.6. Advanced Wastewater Recycling and Reuse Technologies

Advanced wastewater recycling and reuse technologies enable the treatment of municipal and industrial wastewater to standards suitable for various non-potable and portable applications, thereby reducing dependence on freshwater resources and improving water security (Maher et al., 2025). As water scarcity and urbanization intensify, wastewater is increasingly recognized as a valuable resource rather than a waste product.

Modern wastewater reuse systems employ advanced treatment technologies, including MF, UF, MBRs, RO, UV disinfection, and advanced oxidation processes (AOPs). These technologies effectively remove suspended solids, dissolved contaminants, nutrients, pathogens, and trace pollutants, producing high-quality reclaimed water suitable for industrial use, groundwater recharge, landscape irrigation, and other applications.

Globally, Singapore's NEWater programme is one of the most successful examples of wastewater reuse, supplying high-quality reclaimed water for industrial and municipal purposes through advanced membrane treatment and disinfection processes. Israel, Australia, and several European countries have also adopted large-scale wastewater reuse programmes to enhance water security and reduce pressure on freshwater resources (OECD, 2021; European Commission, n.d.).

In India, wastewater reuse is gaining importance in cities such as Bengaluru, Chennai, and Hyderabad, where treated wastewater is increasingly used for industrial cooling, landscaping, construction activities, and groundwater recharge (Goyal & Kumar, 2021).

Wastewater recycling offers several benefits, including reduced freshwater abstraction, improved water availability, lower pollutant discharge, and enhanced climate resilience. However, advanced treatment systems require substantial investment, skilled operation, continuous monitoring, and regular maintenance. Public acceptance of recycled water can also be a challenge, particularly for potable reuse applications (European Commission, n.d.).

For the CRB, wastewater recycling presents a significant opportunity to address growing water demand and seasonal water scarcity. Urban centers such as Bengaluru, Mysuru, Salem, Erode, and Tiruchirappalli generate substantial volumes of wastewater that can be treated and reused for industrial operations, urban landscaping, agriculture, groundwater recharge, and other non-potable uses. Adoption of wastewater reuse technologies can reduce freshwater withdrawals from the Cauvery River while improving water quality and supporting sustainable basin-wide water management.

4.7. Nutrient Recovery Technologies

Nutrient recovery technologies focus on recovering valuable nutrients, particularly nitrogen and phosphorus, from wastewater, sewage sludge, fecal sludge, animal manure, and organic waste streams. These technologies support circular economy objectives by converting waste into useful agricultural inputs while reducing environmental pollution (European Commission, n.d.; STOWA, 2022).

One of the most widely adopted nutrient recovery methods is struvite precipitation, which recovers phosphorus and ammonium as magnesium ammonium phosphate crystals that can be used as slow-release fertilizers (STOWA, 2022). Other technologies include ammonia stripping, ion exchange, membrane separation, and biological nutrient recovery systems that enable the recovery and reuse of nitrogen compounds (European Commission, n.d.). Nutrient-rich biosolids and digestate generated from wastewater treatment and anaerobic digestion can also be utilized as organic fertilizers and soil conditioners.

Several countries, including the Netherlands, Sweden, and Germany, have integrated nutrient recovery into wastewater treatment and resource recovery programmes. The Netherlands' ERMF initiative is a notable example, promoting the recovery of phosphorus, nitrogen, and other valuable resources from wastewater treatment facilities (Dutch Water Authorities, 2023).

Nutrient recovery technologies offer significant environmental and economic benefits by reducing nutrient discharge into water bodies, minimizing eutrophication risks, and reducing dependence on synthetic fertilizers. However, their implementation often requires advanced treatment infrastructure, technical expertise, and market demand for recovered products.

The CRB has considerable potential for nutrient recovery, given the large volumes of wastewater, sewage sludge, livestock waste, and agricultural residues generated across the region. Recovery of phosphorus and nitrogen from STPs, fecal sludge treatment facilities, and anaerobic digestion systems can reduce nutrient pollution while providing valuable fertilizers for agriculture. Integration of nutrient recovery with wastewater treatment, biogas production, and resource recovery systems can support sustainable agriculture, improve water quality, and strengthen circular economy practices within the basin.

4.8. Fecal Sludge and Septage Management (FSSM) Technologies

FSSM has become an essential component of sanitation management in areas that rely on on-site sanitation systems such as septic tanks, pit latrines, and twin-pit toilets. Improper handling and disposal of fecal sludge can contaminate surface water and groundwater, leading to environmental pollution and public health risks.

FSSM includes the collection, transportation, treatment, resource recovery, and safe disposal or reuse of fecal sludge and septage. Common treatment technologies include sludge drying beds, planted drying beds, settling-thickening tanks, co-treatment at STPs, geotextile dewatering systems, mechanical dewatering units, and composting or co-composting systems (Muzioreva et al., 2022). These technologies are typically integrated within FSTPs to achieve effective treatment and resource recovery.

Several countries across Asia, Africa, and Latin America have adopted FSSM programmes to improve sanitation and reduce environmental pollution. In India, cities such as Devanahalli, Wai, Tiruchirappalli, and Warangal have successfully implemented decentralized FSSM systems, demonstrating cost-effective alternatives to conventional sewerage infrastructure (MoHUA, n.d.).

FSSM technologies offer significant environmental and public health benefits by reducing pathogen transmission, groundwater contamination, and direct discharge of untreated waste into rivers and water bodies. Resource recovery through composting and nutrient recycling further supports circular economy objectives and sustainable agriculture. However, effective implementation requires regular desludging services, institutional coordination, regulatory oversight, public awareness, and long-term operation and maintenance arrangements (Muzioreva et al., 2022).

FSSM is highly relevant to the CRB, where many rural communities, peri-urban settlements, and small towns continue to depend on septic tanks and other on-site sanitation systems. Establishment of FSTPs, scheduled desludging services, and co-treatment facilities at existing STPs can significantly reduce pollution loads entering rivers and tributaries.

Integration of FSSM with composting, nutrient recovery, and wastewater management systems can further enhance environmental sustainability and support basin-wide sanitation improvements.

4.9. Nature-Based Solutions and Green Infrastructure

Nature based solutions and green infrastructure are sustainable approaches that utilize natural processes to treat wastewater, manage stormwater, improve water quality, recover nutrients, and restore degraded ecosystems. Compared to conventional treatment systems, these approaches generally require lower energy inputs and provide additional environmental benefits such as biodiversity conservation, carbon sequestration, and climate resilience (Muzioreva et al., 2022).

Common nature-based technologies include constructed wetlands, phytoremediation systems, floating treatment wetlands, riparian buffer zones, bio-retention systems, rain gardens, and waste stabilization ponds. Among these, constructed wetlands are the most widely adopted for wastewater treatment, utilizing natural processes such as sedimentation, filtration, microbial degradation, and plant uptake to remove pollutants (Muzioreva et al., 2022).

Nature-based solutions have been successfully implemented worldwide for municipal wastewater treatment, agricultural runoff management, wetland restoration, and river rejuvenation. Countries such as the Netherlands, the United States, Australia, and several European nations have integrated green infrastructure into water resource and river basin management programmes (European Commission, n.d.). In India, constructed wetlands and phytoremediation systems have been increasingly used for wastewater treatment, lake restoration, and pollution control (CPCB, n.d.).

The major advantages of nature-based solutions include low operational costs, minimal energy requirements, improved ecosystem services, and enhanced climate resilience. These systems are effective in removing suspended solids, nutrients, pathogens, and certain heavy metals from wastewater and runoff. However, they often require larger land areas and regular maintenance to ensure sustained performance.

Nature-based solutions have significant potential in the CRB, particularly for managing wastewater, agricultural runoff, and non-point source pollution. Constructed wetlands can provide decentralized treatment for villages, institutions, and peri-urban settlements, while riparian buffer zones can reduce sediment and nutrient transport into rivers and reservoirs. Floating treatment wetlands can improve water quality in eutrophied lakes and reservoirs. Integration of these approaches with river rejuvenation, watershed management, and wastewater treatment programmes can significantly enhance ecological sustainability and water quality throughout the basin.

4.10. AI, GIS, RS, IoT, and Digital Twins Technologies

Digital technologies are transforming the planning, monitoring, and management of solid–liquid waste systems by enabling data-driven, efficient, and adaptive decision-making. Technologies such as AI, GIS, RS, IoT, and Digital Twins are increasingly used to improve waste collection, wastewater management, pollution monitoring, and resource recovery (Agamuthu & Babel, 2023).

AI and machine learning support waste generation forecasting, route optimization, automated waste sorting, predictive maintenance, and treatment process optimization. IoT-based sensors provide real-time monitoring of waste bins, sewer networks, treatment plants, and water quality parameters, enabling rapid response to operational issues (Agamuthu & Babel, 2023). GIS and RS technologies support spatial analysis, hotspot identification, site suitability assessment, infrastructure planning, and environmental monitoring (Szafarczyk & Agbasi, 2025).

Several countries have successfully integrated digital technologies into waste management systems. Singapore utilizes smart monitoring and predictive analytics for wastewater treatment and water reuse, while European cities employ AI-assisted collection systems and IoT-enabled smart waste bins to improve operational efficiency (EEA, 2026). In India, digital technologies are increasingly being adopted under Smart Cities Mission projects and urban sanitation programmes.

The major benefits of digital technologies include improved operational efficiency, real-time monitoring, enhanced regulatory compliance, better forecasting, and data-driven decision-making. However, implementation requires investments in infrastructure, skilled personnel, data management systems, and long-term technical support.

For the CRB, digital technologies can significantly strengthen waste management and environmental monitoring. GIS and RS can support pollution hotspot mapping, site selection for treatment facilities, and watershed monitoring. IoT-enabled monitoring stations can provide real-time water quality information, while AI models can assist in forecasting waste generation, predicting pollution, and optimizing treatment. Integration of these technologies within a basin-wide decision-support system can enhance planning, compliance monitoring, and sustainable management of solid and liquid waste across the basin.

4.11. Technology Suitability Assessment for the CRB

The CRB encompasses diverse geographical, socio-economic, and environmental settings, ranging from the forested headwaters of the Western Ghats to densely populated urban centers, industrial corridors, intensive agricultural regions, and the deltaic plains of Tamil Nadu. Consequently, a single technological solution cannot effectively address the wide range of solid and liquid waste management challenges encountered across the basin. Instead, successful waste management requires adopting context-specific technologies that reflect local waste characteristics, settlement patterns, infrastructure availability, environmental sensitivity, institutional capacity, and economic feasibility (Agamuthu & Babel, 2023).

The review of national and international best practices demonstrates that integrated waste management systems are most effective when multiple complementary technologies are combined within a circular economy framework. Therefore, a technology suitability assessment is essential to identify the most appropriate interventions across the CRB's different zones and to guide future planning, investment, and implementation strategies.

For technology assessment purposes, the CRB may be broadly classified into four functional zones (Table 2):

1. **Upper Catchment and Eco-Sensitive Zone**: Western Ghats, Kodagu, Talakaveri, forested and high-rainfall regions.
2. **Rural and Agricultural Zone**: Villages, agricultural landscapes, livestock-dominated areas, and small rural settlements.
3. **Urban and Industrial Zone**: Bengaluru Metropolitan Region, Mysuru, Salem, Erode, Tiruppur, Karur, Tiruchirappalli, and industrial clusters.
4. **Lower Basin and Delta Zone**: Irrigation-intensive regions, wetlands, reservoirs, tanks, and deltaic ecosystems.

Each zone exhibits distinct waste generation patterns, environmental risks, and infrastructure requirements, necessitating tailored technological interventions.

Table 2. Technology suitability assessment for the CRB

Sr. No.	Technology	Upper Catchment	Rural & Agricultural Areas	Urban Areas	Industrial Areas	Delta & Wetland Areas
1.	**Source Segregation and MRFs**	Moderate	High	Very High	High	High
2.	**Composting and Vermicomposting**	High	Very High	Moderate	Low	High
3.	**Anaerobic Digestion and Biogas**	High	Very High	High	Moderate	High
4.	**WtE**	Low	Low	High	High	Low
5.	**DEWATS**	Very High	Very High	Moderate	Low	High
6.	**Wastewater Recycling and Reuse**	Low	Moderate	Very High	Very High	Moderate
7.	**Nutrient Recovery Systems**	Moderate	High	High	High	High
8.	**Fecal Sludge Management**	High	Very High	High	Low	Moderate
9.	**Constructed Wetlands**	Very High	High	Moderate	Moderate	Very High

10.	**Riparian Buffers and Green Infrastructure**	Very High	High	Moderate	Moderate	Very High
11.	**GIS, AI, IoT, and Digital Technologies**	High	High	Very High	Very High	High

4.11.1. Recommended Technology Packages

4.11.1.1. Upper Catchment and Eco-Sensitive Areas

The upper reaches of the CRB include ecologically sensitive regions characterized by forests, steep slopes, biodiversity hotspots, and tourism activities. In these areas, low-impact and environmentally compatible technologies should be prioritized. Decentralized waste management systems, composting, biogas plants, DEWATS, constructed wetlands, and riparian restoration measures are particularly suitable due to their low energy requirements and ecological compatibility.

WtE facilities and large centralized treatment systems are generally less appropriate because of limited waste quantities, land-use constraints, and ecological sensitivities. Instead, community-based resource recovery centers and nature-based solutions should form the foundation of waste management strategies.

4.11.1.2. Rural and Agricultural Areas

Rural regions constitute a substantial portion of the CRB and generate significant quantities of livestock waste, crop residues, domestic wastewater, and biodegradable municipal waste. Anaerobic digestion, composting, vermicomposting, FSSM systems, DEWATS, and nutrient recovery technologies are highly suitable for these areas due to the availability of organic feedstocks and agricultural reuse opportunities.

The integration of GOBARdhan-type biogas systems with village sanitation programmes can simultaneously address waste management, renewable energy generation, and organic fertilizer production. Constructed wetlands and DEWATS can further reduce pollution loads entering local streams and tributaries.

4.11.1.3. Urban and Industrial Areas

Urban centers and industrial clusters generate large quantities of municipal solid waste, sewage, industrial effluents, and commercial waste streams. Consequently, these areas require more advanced technological solutions, including MRFs, automated segregation systems, wastewater recycling plants, nutrient recovery systems, smart monitoring platforms, and advanced treatment infrastructure.

Wastewater reuse should be prioritized in cities experiencing water stress, particularly Bengaluru, Mysuru, Salem, Erode, Tiruppur, Karur, and Tiruchirappalli. Industrial areas should adopt zero-liquid-discharge (ZLD) systems, advanced effluent treatment technologies, and resource recovery approaches to minimize environmental impacts and improve resource efficiency.

4.11.1.4. Lower Basin and Delta Region

The lower CRB and delta region support intensive agriculture, fisheries, wetlands, and ecologically sensitive aquatic ecosystems. Water quality protection is therefore of paramount importance. Nature-based solutions such as constructed wetlands, riparian buffers, phytoremediation systems, and floating treatment wetlands are particularly suitable for controlling nutrient pollution and improving ecosystem health.

Wastewater reuse, nutrient recovery, and agricultural recycling of organic waste products can also support sustainable resource management within the delta. Technologies that minimize nutrient discharge and enhance water conservation should be prioritized to protect downstream ecosystems and maintain agricultural productivity.

4.11.2. Strategic Implications for Basin Planning

The technology suitability assessment indicates that the CRB should adopt a hybrid management framework combining centralized and decentralized systems according to local conditions. Urban centers require advanced treatment and resource recovery infrastructure, whereas rural and environmentally sensitive areas can benefit from decentralized and nature-based solutions. Digital technologies such as GIS, RS, IoT, and AI should serve as cross-cutting tools supporting planning, monitoring, compliance assessment, and decision-making across all basin zones.

Rather than relying solely on waste treatment, future interventions should emphasize resource recovery, wastewater reuse, nutrient recycling, renewable energy generation, and circular economy principles. Such an integrated approach can substantially reduce pollution loads, improve water quality, enhance resource efficiency, and strengthen long-term environmental sustainability throughout the CRB.

5. Scalable Models for the CRB

The review of national and international best practices demonstrates that successful solid–liquid waste management systems are characterized by integrated planning, source segregation, resource recovery, wastewater treatment, stakeholder participation, and effective governance mechanisms. However, direct replication of existing models is often constrained by differences in socio-economic conditions, waste characteristics, infrastructure availability, institutional capacity, and environmental settings. Therefore, scalable and adaptable models tailored to the specific conditions of the CRB are required.

The CRB encompasses diverse landscapes including the Western Ghats, rural agricultural regions, rapidly urbanizing centers, industrial clusters, and ecologically sensitive deltaic ecosystems (Table 3). Consequently, different management models are needed for different basin zones. The following scalable models have been developed by integrating lessons from the Udupi SLRM Model, Ambikapur Zero-Waste Model, Singapore NEWater Programme, Tuas Nexus Facility, Sweden's Circular Economy Framework, Netherlands Resource Recovery Systems, and other successful national and international initiatives.

Table 3. Scalable solid–liquid waste management models for different zones of the CRB

Sr. No.	Model	Target Areas	Key Components
1.	**Model I: Decentralized Rural Solid–Liquid Waste Management Model**	a) Villages b) Gram Panchayats c) Rural growth centers	**Solid Waste** a) Household-level source segregation b) Door-to-door collection c) Village Resource Recovery Centers (RRCs)

		d) Upper catchment settlements e) Eco-sensitive regions	d) Composting and vermicomposting units e) Community biogas plants f) Plastic collection and recycling systems **Liquid Waste** a) Household soak pits b) Greywater treatment systems c) DEWATS d) Constructed wetlands e) Community wastewater reuse systems **Expected Outcomes** a) Reduction in open dumping b) Improved village sanitation c) Renewable energy generation d) Reduced river pollution e) Local employment generation **Best Practice References** a) Udupi SLRM Model b) GOBARdhan Initiative

			c) Kamikatsu Zero-Waste Model
2.	**Model II: Small Town Circular Waste Management Model**	a) Population: 20,000–100,000 b) Taluk headquarters c) Emerging urban centers	**Solid Waste** a) Source segregation b) Decentralized MRFs c) Composting facilities d) Biomethanation plants e) Plastic recovery centers **Liquid Waste** a) FSSM systems b) FSTPs c) DEWATS d) Decentralized STPs **Digital Systems** a) GPS-enabled waste collection b) GIS-based monitoring **Expected Outcomes** a) Improved sanitation b) Increased recycling c) Reduced untreated wastewater discharge d) Enhanced resource recovery **Best Practice References** a) Ambikapur

			b) Panaji c) Devanahalli FSSM Model
3.	**Model III: Integrated Urban Circular Economy Model**	a) Bengaluru b) Mysuru c) Salem d) Erode e) Tiruchirappalli	**Solid Waste** a) Advanced Material Recovery Facilities b) Automated sorting systems c) RDF production d) WtE facilities e) Circular economy initiatives **Liquid Waste** a) Large STPs b) Wastewater recycling c) Nutrient recovery systems d) Sludge-to-energy facilities **Smart Technologies** a) IoT-enabled monitoring b) AI-assisted waste forecasting c) GIS-based decision support **Expected Outcomes** a) High recycling rates

			b) Reduced landfill dependency c) Increased water reuse d) Renewable energy generation **Best Practice References** a) Indore b) Singapore NEWater c) Sweden Circular Waste Model d) Germany Recycling Framework
4.	**Model IV: Industrial Cluster ZLD Model**	a) Tiruppur b) Erode c) Karur d) Bengaluru industrial clusters e) Textile and manufacturing corridors	**Key Components** a) CETPs b) ZLD systems c) Wastewater recycling d) Sludge management e) Resource recovery f) Continuous online monitoring **Expected Outcomes** a) Reduced industrial pollution b) Improved compliance c) Reduced freshwater abstraction d) Circular water economy

			Best Practice References a) Singapore Industrial Water Reuse b) Netherlands Resource Recovery Systems
5.	**Model V: Delta and Wetland Protection Model**	a) Lower CRB b) Delta districts c) Wetlands d) Reservoirs e) Irrigation command areas	**Pollution Control** a) Nutrient recovery systems b) Constructed wetlands c) Floating treatment wetlands d) Riparian buffer zones **Agricultural Measures** a) Compost utilization b) Recycled wastewater irrigation c) Agricultural runoff management **Ecosystem Restoration** a) Wetland rehabilitation b) Biodiversity enhancement c) Riverbank stabilization **Expected Outcomes** a) Reduced eutrophication b) Improved water quality

			c) Enhanced ecosystem health d) Sustainable agriculture **Best Practice References** a) Netherlands Circular Water Model b) Nature-Based Solutions in Europe

5.1. Integrated Basin-Wide Resource Recovery Framework

The five scalable models should not operate independently but should function as interconnected components of a basin-wide circular economy framework. Organic waste generated in rural and urban areas can support biogas production and composting. Treated wastewater can be reused for industrial and agricultural purposes. Nutrients recovered from wastewater and sludge can be recycled into agricultural production systems. Recyclable materials can be returned to industrial supply chains through Material Recovery Facilities and recycling industries.

Digital technologies, including GIS, RS, IoT, and AI, should be integrated across all models to support monitoring, planning, compliance assessment, and decision-making. Such an integrated framework can transform waste streams into valuable resources while significantly reducing pollution loads entering the Cauvery River system.

5.2. Key Success Factors for Scaling Across the Basin

a) Strong institutional coordination
b) Basin-wide monitoring framework
c) Public participation and awareness
d) Sustainable financing mechanisms
e) Public–private partnerships
f) Circular economy incentives

g) Capacity building programmes

h) Digital governance systems

i) Regulatory enforcement and compliance monitoring

6. Adaptability and Feasibility Analysis

The successful implementation of solid–liquid waste management interventions depend not only on technological performance but also on their adaptability to local conditions and long-term feasibility. Technologies and management models that perform effectively in one geographical or socio-economic setting may not necessarily be suitable for another. Therefore, a systematic assessment of technical, economic, environmental, social, institutional, and regulatory feasibility is essential before large-scale implementation within the CRB.

The CRB is characterized by substantial spatial variability in population density, urbanization levels, industrial development, agricultural intensity, infrastructure availability, and ecological sensitivity. The upper catchment regions are dominated by forests and tourism activities, whereas the middle basin contains rapidly growing urban and industrial centers. The lower basin and delta regions support intensive agriculture and ecologically important wetlands. Consequently, waste management solutions must be adapted to local conditions while maintaining basin-wide sustainability objectives.

6.1. Technical Feasibility Analysis

Technical feasibility refers to the suitability of a technology or management approach under local environmental, infrastructural, and operational conditions. Technologies selected for the CRB must be capable of handling local waste characteristics, climatic conditions, settlement patterns, and pollution sources while maintaining reliable long-term performance.

6.1.1. Rural and Agricultural Areas

Technologies such as composting, vermicomposting, anaerobic digestion, DEWATS, constructed wetlands, and fecal sludge management systems are technically feasible in rural areas due to the availability of organic feedstocks, lower wastewater volumes, and relatively low infrastructure requirements. These technologies are simple to operate, require limited energy inputs, and can be managed at the community level.

6.1.2. Urban Areas

Large urban centers such as Bengaluru, Mysuru, Salem, Erode, and Tiruchirappalli possess the technical capacity to support advanced MRFs, wastewater recycling systems, nutrient recovery technologies, and smart monitoring platforms. However, successful implementation requires efficient segregation systems, reliable utility services, skilled manpower, and institutional coordination.

6.1.3. Industrial Areas

Industrial clusters have the technical capability to implement advanced effluent treatment technologies, wastewater reuse systems, resource recovery facilities, and ZLD systems. Existing industrial infrastructure and regulatory oversight provide a strong foundation for adopting advanced treatment technologies.

6.1.4. Ecologically Sensitive Areas

In upper catchment and environmentally sensitive regions, decentralized and nature-based technologies are technically more appropriate than large, centralized facilities. Constructed wetlands, DEWATS, and community resource recovery centers can provide effective pollution control while minimizing ecological disturbances.

6.2. Economic Feasibility Analysis

Financial viability remains one of the most important determinants of successful waste management implementation. The economic feasibility of proposed interventions depends on capital investment requirements, operation and maintenance costs, revenue generation potential, funding availability, and long-term sustainability.

6.2.1. Low-Cost Technologies

The following technologies generally require relatively low investment and operational costs:

- Composting and vermicomposting
- Community biogas systems
- DEWATS
- Constructed wetlands
- Riparian buffer systems
- Village Resource Recovery Centers

These technologies are particularly suitable for rural areas and small towns where financial resources may be limited.

6.2.2. Moderate-Cost Technologies

Technologies requiring moderate levels of investment include:

- Material Recovery Facilities
- FSTPs
- Biomethanation facilities
- DEWATS
- Smart collection and monitoring systems

These interventions are suitable for municipal implementation through public funding, user charges, and public–private partnerships.

6.2.3. High-Cost Technologies

The following technologies involve significant capital and operational expenditures:

- WtE facilities
- Advanced wastewater recycling plants
- RO systems
- Nutrient recovery systems
- ZLD facilities
- Digital twin platforms

Such technologies are generally feasible only in large urban centers and industrial clusters where economies of scale and resource recovery opportunities justify investments.

6.3. Environmental Feasibility Analysis

Environmental feasibility assesses the extent to which proposed interventions contribute to pollution reduction, ecosystem protection, resource conservation, and climate resilience.

6.3.1. High Environmental Benefits

The following technologies provide substantial environmental benefits:

- Anaerobic digestion

- Composting
- Wastewater reuse
- Constructed wetlands
- Nutrient recovery
- Riparian restoration
- Floating treatment wetlands

These technologies directly reduce pollution loads entering rivers, reservoirs, lakes, and wetlands while supporting resource recovery and ecosystem restoration.

6.3.2. Moderate Environmental Benefits

- Material Recovery Facilities
- Fecal sludge management systems
- Digital monitoring technologies
- Smart waste collection systems

These interventions primarily improve management efficiency and reduce environmental risks.

6.3.3. Potential Environmental Concerns

WtE facilities and advanced industrial treatment systems require careful environmental safeguards due to potential air emissions, residual ash generation, and energy consumption. Strict monitoring and regulatory compliance are necessary to ensure environmental sustainability.

6.4. Social Feasibility Analysis

Social acceptance is critical for the successful adoption of waste management systems. Public participation, behavioral change, awareness, and stakeholder engagement significantly influence long-term effectiveness.

6.4.1. High Social Acceptability

The following interventions generally receive strong community acceptance:

- Source segregation programmes
- Composting

- Community biogas plants
- Resource recovery centers
- Constructed wetlands
- Village sanitation initiatives

These systems often generate visible local benefits including cleaner environments, employment opportunities, and improved public health.

6.4.2. Moderate Social Acceptability

- Fecal sludge treatment facilities
- Material Recovery Facilities
- Wastewater reuse programmes

These interventions may require awareness campaigns and stakeholder consultations to address concerns regarding odor, aesthetics, and reuse practices.

6.4.3. Lower Social Acceptability

- WtE facilities
- Landfills
- Large industrial waste treatment facilities

Such projects often face public resistance due to concerns regarding emissions, environmental impacts, and land acquisition issues.

6.5. Institutional and Governance Feasibility

Institutional capacity is often the determining factor between successful and unsuccessful waste management programmes. Effective implementation requires coordination among multiple stakeholders including government agencies, urban local bodies, gram panchayats, industries, civil society organizations, academic institutions, and local communities.

6.5.1. Existing Strengths

The CRB benefits from:

- SBM infrastructure
- Urban local body networks

- Existing sewage treatment facilities
- Active Pollution Control Boards
- River basin management initiatives
- Growing private-sector participation

6.5.2. Existing Challenges

Several institutional barriers continue to constrain implementation:

- Fragmented governance structures
- Limited technical expertise
- Inadequate operation and maintenance capacity
- Weak monitoring and enforcement mechanisms
- Financial constraints
- Limited inter-state coordination

Strengthening institutional frameworks and establishing basin-wide coordination mechanisms will therefore be essential for scaling successful interventions.

6.6. Technology Feasibility Matrix

Table 4 summarizes the feasibility assessment of major solid–liquid waste management technologies for the CRB based on five key criteria: technical feasibility, economic feasibility, environmental benefits, social acceptance, and overall suitability. The assessment indicates that source segregation, composting/vermicomposting, anaerobic digestion, DEWATS, and constructed wetlands exhibit the highest overall suitability due to their proven effectiveness, strong environmental benefits, relatively low operational requirements, and adaptability across diverse basin conditions.

Technologies such as wastewater reuse, nutrient recovery, FSSM, MRFs, and AI/GIS/IoT-based systems also demonstrate high potential for basin-wide implementation, particularly in urban, peri-urban, and industrial areas where adequate infrastructure and institutional capacity are available. These technologies support resource recovery, pollution reduction, and improved operational efficiency but may require additional financial investment and technical expertise.

In contrast, WtE technologies show comparatively lower feasibility because of their high capital costs, dependence on well-segregated waste streams, operational complexity, and environmental compliance requirements. Overall, the matrix suggests that a combination of decentralized treatment systems, resource recovery approaches, nature-based solutions, and digital monitoring technologies provides the most practical and sustainable pathway for improving solid–liquid waste management and reducing pollution loads across the CRB.

Table 4. Feasibility assessment of major technologies for the CRB

Sr. No.	**Technology**	**Technical Feasibility**	**Economic Feasibility**	**Environmental Benefits**	**Social Acceptance**	**Overall Suitability**
1.	**Source Segregation**	High	High	High	High	Very High
2.	**Material Recovery Facilities**	High	Moderate	High	High	High
3.	**Composting/ Vermicomp - sting**	High	High	High	High	Very High
4.	**Anaerobic Digestion**	High	Moderate	Very High	High	Very High
5.	**WtE**	Moderate	Moderate	Moderate	Moderate	Moderate
6.	**DEWATS**	High	High	High	High	Very High
7.	**Wastewater Reuse**	High	Moderate	Very High	Moderate	High
8.	**Nutrient Recovery**	Moderate	Moderate	High	Moderate	High
9.	**FSSM**	High	Moderate	High	High	High
10.	**Constructed Wetlands**	High	High	Very High	High	Very High
11.	**AI/GIS/IoT Technologies**	High	Moderate	High	High	High

6.7. Priority Technologies for Basin-Wide Implementation

Based on the feasibility assessment, the following technologies emerge as the most suitable for widespread implementation across the CRB:

a) **Tier 1 (Highest Priority)**

- Source segregation and resource recovery
- Composting and vermicomposting
- Anaerobic digestion and biogas systems
- DEWATS
- Fecal sludge management
- Constructed wetlands and nature-based solutions

b) **Tier 2 (Medium Priority)**

- Material Recovery Facilities
- Wastewater reuse systems
- Nutrient recovery technologies
- GIS, AI, and IoT-based monitoring systems

c) **Tier 3 (Selective Application)**

- WtE facilities
- ZLD systems
- Advanced resource recovery technologies

These technologies should be implemented selectively in large urban centers and industrial corridors where technical and economic conditions are favorable.

The feasibility assessment demonstrates that no single technology can effectively address the diverse waste management challenges of the CRB. Instead, a combination of decentralized and centralized approaches tailored to local conditions is required. Rural and ecologically sensitive regions are best served by community-based and nature-based solutions, whereas urban and industrial areas require advanced treatment, recycling, and resource recovery infrastructure.

Among all evaluated technologies, source segregation, anaerobic digestion, DEWATS, fecal sludge management, wastewater reuse, and nature-based solutions exhibit the highest overall feasibility and scalability. Their implementation, supported by strong governance mechanisms, stakeholder participation, digital monitoring systems, and sustainable financing models, can substantially reduce pollution loads, improve water quality, enhance resource recovery, and contribute to the long-term sustainability of the CRB.

7. Recommendations and Role of Stakeholders

The successful implementation of solid–liquid waste management interventions within the CRB requires a coordinated approach involving government agencies, urban local bodies, Gram Panchayats, industries, academic institutions, civil society organizations, and local communities. The review of national and international best practices indicates that sustainable waste management systems are achieved through a combination of technological innovation, institutional coordination, regulatory enforcement, stakeholder participation, and resource recovery approaches. Given the diverse environmental, socio-economic, and infrastructural characteristics of the basin, recommendations must be tailored to specific basin zones while maintaining an integrated basin-wide management framework.

7.1. Basin-Specific Recommendations for Different Basin Zones

The CRB comprises diverse environmental and socio-economic settings, including forested catchments, agricultural landscapes, urban centres, industrial corridors, and ecologically sensitive delta regions. As a result, waste management challenges and priorities vary significantly across different parts of the basin. Table 5 presents zone-specific recommendations by identifying key challenges and corresponding interventions to support effective solid–liquid waste management, pollution reduction, resource recovery, and sustainable river basin management.

Table 5. Zone-wise recommendations for SLWM in the CRB

Sr. No.	**Zone**	**Coverage Areas**	**Key Challenges**	**Recommended Interventions**
1.	**Upper Catchment and Eco-Sensitive Zone**	a) Talakaveri and Kodagu region b) Western Ghats landscapes c) Forested catchments d) Hill stations and tourism destinations e) Environmentally sensitive tributaries	a) Tourism-related waste generation b) Plastic pollution c) Inadequate wastewater treatment d) Ecological sensitivity e) Seasonal population fluctuations	**Solid Waste Management** a) Mandatory source segregation at household and commercial levels b) Establishment of village-level Resource Recovery Centers (RRCs) c) Plastic-free tourism zones. d) Decentralized composting and vermicomposting systems e) Community biogas plants for biodegradable waste **Liquid Waste Management** a) DEWATS

				b) Constructed wetlands c) Greywater reuse systems d) Eco-friendly sanitation facilities at tourism locations **Ecosystem Protection** a) Riparian buffer restoration b) Riverbank stabilization measures c) Strict prohibition of waste disposal in streams and forest areas d) Periodic monitoring of sensitive water bodies **Priority Stakeholders** a) Forest Department b) Tourism Department

				c) Gram Panchayats d) Karnataka State Pollution Control Board e) Local communities f) Eco-development committees
2.	**Rural and Agricultural Zone**	a) Agricultural villages b) Livestock-dominated regions c) Rural growth centers d) Irrigated command areas	a) Livestock waste disposal b) Agricultural runoff c) Open dumping of solid waste d) Inadequate sanitation infrastructure e) Septage management issues	**Solid Waste Management** a) Village-level segregation systems b) Composting and vermicomposting units c) Cluster-based Resource Recovery Centers d) Plastic collection and recycling networks **Organic Waste Management** a) GOBARdhan-based biogas plants

				b) Community biomethanation facilities c) Agricultural residue management systems d) Organic fertilizer production **Liquid Waste Management** a) Soak pits and greywater management b) DEWATS c) FSSM d) Waste stabilization ponds **Agricultural Pollution Management** a) Nutrient management plans b) Buffer strips along watercourses

				c) Promotion of organic farming d) Precision fertilizer application **Priority Stakeholders** a) Gram Panchayats b) Rural Development Departments c) Agriculture Department d) Animal Husbandry Department e) Farmer Producer Organizations (FPOs) f) SHGs
3.	**Urban and Peri-Urban Zone**	a) Bengaluru b) Mysuru c) Salem d) Erode e) Tiruchirappalli f) Emerging urban centers	a) Increasing municipal waste generation b) Landfill dependency c) Sewage management gaps	**Liquid Waste Management** a) Expansion of sewage treatment capacity b) Wastewater recycling and reuse

			d) Plastic waste accumulation e) Resource recovery limitations	c) Nutrient recovery systems d) Sludge-to-energy programmes **Smart Technologies** a) GPS-enabled collection systems b) GIS-based planning platforms c) AI-based waste forecasting d) IoT-enabled monitoring systems **Institutional Measures** a) User-fee-based service models b) Public–Private Partnerships (PPPs) c) Performance-based monitoring systems

				Priority Stakeholders a) Urban Local Bodies (ULBs) b) Municipal Corporations c) State Urban Development Departments d) Private waste management operators e) Resident Welfare Associations f) Pollution Control Boards
4.	**Industrial Corridor Zone**	a) Tiruppur textile cluster b) Erode industrial areas c) Karur textile industries d) Bengaluru industrial corridors e) Manufacturing and processing clusters	a) Industrial wastewater discharge b) Hazardous waste generation c) High freshwater demand d) Sludge management issues e) Compliance monitoring	**Industrial Wastewater Management** a) ZLD systems b) Upgradation of CETPs c) Water recycling and reuse d) Real-time effluent monitoring **Resource Recovery**

				a) Industrial symbiosis initiatives b) Sludge valorization c) Recovery of chemicals and salts d) Energy recovery systems **Compliance and Governance** a) Continuous Online Monitoring Systems (OCEMS) b) Environmental audits c) Third-party compliance assessments d) Strengthened enforcement mechanisms **Priority Stakeholders** a) Industries b) Industrial Associations

				c) Pollution Control Boards d) State Industries Departments e) CETP Operators f) Research Institutions
5.	**Lower Basin and Delta Zone**	a) Cauvery Delta districts b) Wetlands and floodplains c) Reservoir command areas d) Estuarine ecosystems	a) Nutrient enrichment b) Agricultural runoff c) Wastewater discharge d) Wetland degradation e) Water quality deterioration	**Water Quality Protection** a) Constructed wetlands b) Floating treatment wetlands c) Nutrient recovery systems d) Riparian buffer restoration **Agricultural Management** a) Treated wastewater reuse b) Precision nutrient management c) Organic manure utilization d) Controlled fertilizer application

				Ecosystem Restoration a) Wetland rehabilitation programmes b) Biodiversity conservation initiatives c) Floodplain restoration d) Sediment management measures **Priority Stakeholders** a) Water Resources Departments b) Agriculture Departments c) Wetland Authorities d) Local Bodies e) Research Institutions f) Community Organizations

7.2. Role of Key Stakeholders

Effective implementation of solid–liquid waste management interventions in the CRB requires active participation and coordination among multiple stakeholders. Government agencies provide policy direction, regulatory oversight, and financial support, while local bodies are responsible for service delivery and infrastructure management. Industries play a critical role in pollution control, resource recovery, and compliance with environmental regulations. Academic institutions contribute through research, innovation, capacity building, and technical support, whereas civil society organizations and local communities facilitate awareness generation, behavioural change, and community participation. The roles and responsibilities of major stakeholders are summarized in Table 6.

Table 6. Stakeholder roles for implementation of basin-wide SLWM interventions

Sr. No.	Stakeholders	Role
1.	**Central Government Agencies**	a) Policy formulation and regulatory guidance b) Funding support through national programmes c) Development of technical standards and guidelines d) Monitoring of basin-wide implementation
2.	**State Governments**	a) Programme implementation and coordination b) Capacity building and institutional strengthening c) Enforcement of environmental regulations d) Financial support and incentive mechanisms
3.	**Urban Local Bodies and Gram Panchayats**	a) Service delivery and infrastructure management b) Waste collection and segregation programmes c) Community mobilization d) Monitoring and reporting
4.	**Industries**	a) Compliance with environmental regulations b) Adoption of cleaner production technologies c) Waste minimization and resource recovery d) Participation in circular economy initiatives

5.	**Academic and Research Institutions**	a) Technology development and innovation b) Monitoring and evaluation studies c) Capacity-building programmes d) Decision-support system development
6.	**Civil Society Organizations and Communities**	a) Public awareness and behavioral change b) Community participation c) Citizen monitoring and accountability d) Local resource management initiatives

7.3. Strategic Basin-Wide Recommendations

a) Establish a CRB Solid–Liquid Waste Management Coordination Framework to facilitate inter-state coordination and basin-wide planning.

b) Achieve 100% source segregation across all urban and rural local bodies within the basin.

c) Prioritize resource recovery over disposal through composting, biomethanation, recycling, wastewater reuse, and nutrient recovery.

d) Promote decentralized treatment systems in rural and environmentally sensitive regions.

e) Expand wastewater recycling and reuse programmes in water-stressed urban and industrial centers.

f) Strengthen FSSM systems in areas lacking sewerage infrastructure.

g) Integrate GIS, RS, AI, and IoT technologies into basin-wide monitoring and decision-support systems.

h) Promote nature-based solutions for river rejuvenation, wetland restoration, and pollution control.

i) Strengthen public-private partnerships and innovative financing mechanisms.

j) Develop a basin-wide circular economy roadmap linking waste management, water resources, agriculture, energy, and environmental sustainability.

The CRB requires a diversified and integrated waste management strategy that recognizes the unique characteristics of different basin zones while maintaining a common framework centered on pollution prevention, resource recovery, circular economy principles, and environmental sustainability. Successful implementation will depend on strong stakeholder collaboration, adaptive governance, technological innovation, and long-term commitment to protecting the ecological integrity and water security of one of India's most important river basins.

8. Conclusion

The review of national and international best practices demonstrates that effective solid–liquid waste management requires an integrated approach combining source segregation, resource recovery, wastewater treatment, stakeholder participation, technological innovation, and strong governance mechanisms. Successful models such as the Udupi SLRM Model, Indore Solid Waste Management Model, Pune SWaCH Cooperative, Singapore NEWater Programme, and various resource recovery initiatives highlight the potential of circular economy principles in reducing environmental pollution while generating social and economic benefits. For the CRB, no single solution can address the diverse waste management challenges across urban, rural, industrial, agricultural, and ecologically sensitive regions. A combination of decentralised treatment systems, Material Recovery Facilities, anaerobic digestion, faecal sludge management, wastewater reuse, nature-based solutions, and digital monitoring technologies offers the most suitable pathway for sustainable basin-wide implementation. Adoption of these scalable models can significantly reduce pollution loads entering rivers and water bodies, improve resource efficiency, enhance water security, and support renewable energy generation. The successful implementation of these interventions will require coordinated action among government agencies, local bodies, industries, research institutions, civil society organisations, and local communities. With sustained commitment, adequate investment, and effective governance, the CRB can transition towards a resilient, resource-efficient, and environmentally sustainable solid–liquid waste management framework that contributes to long-term river health, ecological integrity, and socio-economic development.

9. Significance of the Report

This report provides a comprehensive assessment of national and international best practices in solid–liquid waste management and evaluates their applicability within the CRB. It serves as a strategic reference for policymakers, government agencies, local bodies, industries, and researchers by identifying proven, scalable, and adaptable solutions for managing waste across diverse urban, rural, industrial, and agricultural settings. The report highlights integrated approaches that combine source segregation, recycling, resource recovery, wastewater treatment, faecal sludge management, nature-based solutions, and digital technologies to reduce pollution and improve environmental sustainability. It also supports informed decision-making by assessing the technical feasibility, environmental benefits, economic viability, and institutional requirements of different waste management interventions. By promoting circular-economy principles and resource recovery, the report outlines pathways to convert waste into valuable resources, including treated water, renewable energy, compost, recycled materials, and nutrients. Ultimately, the report contributes to river conservation, improved water quality, climate resilience, and sustainable development within the CRB.

References

1. Abraham, M., Atiq, A., Pandey, S., Prasad, G. and Dkhar, N.B., 2025. Management: Indian and Global Case. Efficient and Enhanced Management of Plastic Waste in India: Case Studies from Vapi and Surat, p.147.
2. Agamuthu, P. and Babel, S., 2023. Waste management developments in the last five decades: Asian perspective. Waste Management & Research, 41(12), pp.1699-1716.
3. Anuardo, R.G., Espuny, M., Costa, A.C.F. and Oliveira, O.J., 2022. Toward a cleaner and more sustainable world: A framework to develop and improve waste management through organizations, governments and academia. Heliyon, 8(4).
4. Avfall Sverige, 2024. Swedish Waste Management 2024. Malmö: Avfall Sverige. Available at: https://www.avfallsverige.se/media/ca2fijue/swedish-waste-management-2024.pdf (Accessed: 11/02/2026).
5. Badsha, M.M., Maheer, U., Omar, F.M., Ramli, A., Balakrishnan, V., Hamed, Y., Arafath, M.A. and Hossain, M.S., 2025. Sustainable approaches on innovative utilization of household food waste as a renewable biomass for bioenergy production: Potential, challenges and social-environmental impacts. *Biomass and Bioenergy*, *200*, p.107995.
6. Bhatt, R. and Mohapatra, B., 2023. Waste management to achieve sustainable development goals: approach for Indian cities. Urbanism. Arhitectura. Constructii, 14(2), pp.111-120.
7. CCP, 2021. Corporation of the city of Panaji. https://ccpgoa.com (Accessed: 11/02/ 2026).
8. CEWEP, n.d.. Waste-to-Energy in Europe. Available at: https://www.cewep.eu/waste-to-energy/ (Accessed: 15/02/2026).
9. Chojnacka, K. and Moustakas, K., 2024. Anaerobic digestate management for carbon neutrality and fertilizer use: A review of current practices and future opportunities. Biomass and Bioenergy, 180, p.106991.
10. CPCB, n.d.. Best Practices in Municipal Solid Waste Management. New Delhi: Central Pollution Control Board, Government of India. Available at: https://www.cpcb.nic.in/municipal-solid-waste-rules/ (Accessed: 11/02/2026).

11. DDWS, n.d.. GOBARdhan: Galvanizing Organic Bio-Agro Resources Dhan – Operational Guidelines and Implementation Framework. New Delhi: Department of Drinking Water and Sanitation, Ministry of Jal Shakti, Government of India. Available at: https://www.myscheme.gov.in/schemes/gobardhan (Accessed: 11/02/2026).

12. EEA, 2016. Municipal Waste Management across European Countries. Available at: https://www.eea.europa.eu/en/topics/in-depth/waste-management (Accessed: 17/02/2026).

13. EEA, 2026. Waste and Recycling. Copenhagen: European Environment Agency. Available at: https://www.eea.europa.eu/en/topics/in-depth/waste-and-recycling (Accessed: 15/02/2026).

14. European Commission, n.d.. A New Circular Economy Action Plan: For a Cleaner and More Competitive Europe. Brussels: European Commission. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0098 (Accessed: 11/02/2026).

15. Federal Environment Agency (Umwelt Bundesamt, UBA), 2014. Waste Management in Germany. Dessau-Roßlau: Federal Environment Agency. Available at: https://www.umweltbundesamt.de/en/topics/waste-resources/waste-management (Accessed: 05/02/2026).

16. Gour, A.A. and Singh, S.K., 2023. Solid waste management in India: a state-of-the-art review. Environmental Engineering Research, 28(4).

17. Government of Goa, n.d.. Goa Waste Management Corporation. Available at: https://gwmc.goa.gov.in/ (Accessed: 01/02/2026).

18. Government of Goa, 2024. Revised Solid Waste Management Policy for the State of Goa, 2022–2037. Panaji: Department of Urban Development, Government of Goa. Available at: https://goaprintingpress.gov.in/downloads/2324/2324-48-SI-SUG-1.pdf (Accessed: 11/02/2026).

19. Government of Japan, 2019. In Pursuit of a Zero-Waste Society. Highlighting Japan, December 2019. Cabinet Office, Government of Japan. Available at: https://www.gov-online.go.jp/eng/publicity/book/hlj/html/201912/201912_01_en.html (Accessed: 11/02/2026).

20. Government of Kerala, 2021. The State of Decentralised Solid Waste Management in Kerala Report 2021. Available at: https://www.kila.ac.in/wp-content/uploads/2022/04/Report.pdf (Accessed: 11/02/2026).

21. Government of the Netherlands, 2023. National Circular Economy Programme 2023–2030. The Hague: Government of the Netherlands. Available at: https://www.government.nl/documents/2023/09/27/national-circular-economy-programme-2023-2030 (Accessed: 17/02/2026).

22. Goyal, K. and Kumar, A., 2021. Development of water reuse: a global review with the focus on India. Water Science and Technology, 84(10-11), pp.3172-3190.

23. Hamdan, A., Panda, S., Jain, M.S., Raj, V. and Mathew, S., 2025. Assessing municipal solid waste in Indian smart cities: A path towards Waste-to-Energy. Heliyon, 11(6).

24. Hariyani, D., Hariyani, P., Mishra, S. and Sharma, M.K., 2025. A literature review on waste management treatment and control techniques. Sustainable Futures, 9, p.100728.

25. IEA Bioenergy, 2023. Bioenergy: Accelerating to Net Zero. Available at: https://www.ieabioenergy.com/wp-content/uploads/2024/06/Annual-Report-2023.pdf (Accessed: 01/02/2026).

26. Islam, M.S., Kannan, A., Chen, Q., Toh, J. and Loh, L., 2024. A political economy of water security: The case of Singapore. In The water, climate, and food nexus: Linkages, challenges and emerging solutions (pp. 421-434). Cham: Springer International Publishing.

27. Jalalipour, H., Morscheck, G., Schwetje, A. and Nelles, M., 2025. Sustainable solid waste management: The German case and lessons for South America. Waste Management & Research, 43(10), pp.1476-1490.

28. Jithendra, S. and Godihal, J.H., 2023. Evaluation of Solid Waste Management in Rural Areas of Udupi, Including an Adaptation Strategy. In International Conference on Interdisciplinary Approaches in Civil Engineering for Sustainable Development (pp. 289-299). Singapore: Springer Nature Singapore.

29. Kamble, R.R., 2025. Rural Sanitation Programmes in India: An Overview of Initiatives, Challenges and Achievements.

30. Kandpal, R. and Saizen, I., 2022. Self-help group participation towards sustainable solid waste management in peri-urban villages: evidence from Mumbai Metropolitan Region, India. Environment, Development and Sustainability, 24(3), pp.3791-3814.

31. KECO, n.d.. Operation of RFID-Based Food Waste Management System. Available at: https://www.keco.or.kr/en/lay1/S295T387C404/contents.do (Accessed: 05/02/2026).

32. Kotwani, S., Agrawal, S.S., Kohli, N.K., Singh, R. and Kumar, R., 2025, November. From Linear to Circular: Indore's Journey Towards Economic and Urban Sustainability through Waste Management. In 2025 IEEE 7th International Conference on Computing, Communication and Automation (ICCCA) (pp. 1-9). IEEE.

33. Kullmann, F., Markewitz, P., Kotzur, L. and Stolten, D., 2022. The value of recycling for low-carbon energy systems-A case study of Germany's energy transition. Energy, 256, p.124660.

34. Kumar, L. and Kumar, N., 2024. Toward zero-waste cities: A comparative study of waste management strategies in Indore City and Surat City, India. In International Conference on Trends in Architecture and Construction (pp. 511-526). Singapore: Springer Nature Singapore.

35. Lee, E., Shurson, G., Oh, S.H. and Jang, J.C., 2024. The management of food waste recycling for a sustainable future: A case study on South Korea. *Sustainability*, *16*(2), p.854.

36. Maher, T., Antar, C., Alshrari, A. and Ali, H., 2025. Advancing Environmental Sustainability and Consumption Security through Wastewater Reuse in Arid Regions. European Journal of Sustainable Development, 14(2), pp.797-797.

37. Middha, M.C. and Kumar, A.S., 2024, October. Transforming Wastewater into Resource: A Comprehensive Approach to Urban Wastewater Management. In International Conference on Trends and Recent Advances in Civil Engineering (pp. 353-367). Singapore: Springer Nature Singapore.

38. MoHUA, n.d.. Available at: https://sbmurban.org (Accessed: 05/02/2026).

39. Ministry of Jal Shakti, n.d.. Swachh Bharat Mission (Grameen). Available at: https://jalshakti-ddws.gov.in (Accessed: 11/02/2026).

40. MoPNG, 2023. Available at: https://mopng.gov.in (Accessed: 11/02/2026).

41. Muzioreva, H., Gumbo, T., Kavishe, N., Moyo, T. and Musonda, I., 2022. Decentralized wastewater system practices in developing countries: A systematic review. Utilities Policy, 79, p.101442.

42. Narayanan, N.C., Ganapathy, G., Joseph, R., Cathareen, N., Viswan, D. and MG, G., 2023. Introducing Circularity in Decentralized Solid Waste Management: Lessons for Scaling-Up Technology Options from Alappuzha.

43. NEA, 2023. Available at: https://www.nea.gov.sg/our-services/waste-management/waste-management-infrastructure/integrated-waste-management-facility (Accessed: 11/02/2026).

44. OECD, 2021. Available at: https://www.oecd.org/content/dam/oecd/en/topics/policy-issues/resource-efficiency-and-circular-economy/OECD-G20-Towards-a-more-Resource-Efficient-and-Circular-Economy.pdf (Accessed: 05/02/2026).

45. Onyemesili, O.O., Egbueri, J.C. and Ezugwu, C.K., 2022. Assessing the pollution status, ecological and health risks of surface waters in Nnewi urban, Nigeria: implications of poor waste disposal. Environmental forensics, 23(3-4), pp.346-360.

46. PMC, n.d.. Available at: https://pmc.gov.in (Accessed: 11/02/2026).

47. Rajendran, P., 2025. Nudging for Social Change: An Analysis of Nudge Theory in Communication strategies of the Public Health Initiative—Swachh Bharat Mission-Gramin, in Rural Tamil Nadu.

48. Raman, A.P.S., Aslam, M., Singh, P., Pandey, G., Jain, P. and Kumari, K., 2024. Solid and liquid waste management in urban and rural areas: current practices and future perspectives. In Integrated Waste Management: A Sustainable Approach from Waste to Wealth (pp. 141-157). Singapore: Springer Nature Singapore.

49. Rathod, S.V., Saras, P. and Gondaliya, S.M., 2024. Environmental pollution: Threats and challenges for management. In Eco-restoration of polluted environment (pp. 1-34). CRC Press.

50. RDPR, 2020. Solid and Liquid Waste Management (SLWM). Available at: https://rdpr.karnataka.gov.in/36/solid-liquid-waste-management/en (Accessed: 11/02/2026).

51. Sawant, R., Joshi, D.A. and Menon, R., 2023. Case study on river pollution of Pune City and waste management.

52. SBM-G, 2019. Available at: https://swachhbharatmission.ddws.gov.in (Accessed: 11/02/2026).

53. SBM-U, 2020. Available at: https://sbmurban.org (Accessed: 05/02/2026).

54. Shenyoputro, K. and Jones, T.E., 2023. Reflections on a two-decade journey toward zero waste: A case study of Kamikatsu town, Japan. Frontiers in Environmental Science, 11, p.1171379.

55. Sindhøj, E. and Cordeiro, C., 2025. Circular economy for nutrients in theBaltic Sea Region. Baltic Rim Economies, (2), pp.6-7.

56. STOWA, 2022. Available at: https://www.stowa.nl/english (Accessed: 11/02/2026).

57. Suchitwa Mission, n.d.. Available at: https://suchitwamission.org (Accessed: 11/02/2026).

58. SWaCH, n.d.. Available at: https://swachcoop.com (Accessed: 05/02/2026).

59. Waste management in Sweden, n.d.. Available at: https://www.naturvardsverket.se/en/topics/waste/ (Accessed: 11 June 2026).

60. Szafarczyk, A. and Agbasi, O.E., 2025. Emerging trends in gis and remote sensing technologies for environmental monitoring: innovations, applications, and future directions. Geoinformatica Polonica, 24.

61. Themelis, N.J., 2023. Energy and materials recovery from post-recycling wastes: WTE. Waste Disposal & Sustainable Energy, 5(3), pp.249-257.

62. Tiwari, D., Sreenivasan, S. and Vodapalli, M., 2024. Role of SHGs in MSW Management–A Case Study from Udupi. Urban India, 44, pp.96-110.

63. Tortajada, C. and Joshi, Y.K., 2013. Water demand management in Singapore: involving the public. Water resources management, 27(8), pp.2729-2746.

64. UNCRD, 2021. Available at: https://uncrd.un.org/sites/default/files/8th-3r_ps-1-p4.pdf (Accessed: 18/02/2026).

65. UNEP, n.d.. Available at: https://www.unep.org/resources (Accessed: 11/02/2026).

66. van Leeuwen, K., de Vries, E., Koop, S. and Roest, K., 2018. The energy & raw materials factory: role and potential contribution to the circular economy of the Netherlands. Environmental management, 61(5), pp.786-795.

67. Varma, V.G., Jha, S., Raju, L.H.K., Kishore, R.L. and Ranjith, V., 2022. A review on decentralized wastewater treatment systems in India. Chemosphere, 300, p.134462.

68. Varshney, K., Shet, P. and Hoosenally, M., 2025. Cleaning Bharat (India): a scoping review of perceptions regarding how swachh bharat can continue to improve hygiene across the nation. Hygiene, 5(2), p.17.

69. Witek-Krowiak, A., Gorazda, K., Szopa, D., Trzaska, K., Moustakas, K. and Chojnacka, K., 2022. Phosphorus recovery from wastewater and bio-based waste: an overview. Bioengineered, 13(5), pp.13474-13506.

70. Zero Waste Town Kamikatsu, 2024. Available at: https://zwtk.jp/en/ (Accessed: 19/02/2026).

71. Zueva, S., Ferella, F., Corradini, V. and Vegliò, F., 2024. Review of organic waste-to-energy (OWtE) technologies as a part of a sustainable circular economy. Energies, 17(15), p.3797.

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