Project

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“ASSESSMENT OF CIRCULAR ECONOMY-BASED RESOURCE RECOVERY TECHNIQUES IN WASTEWATER AND SOLID WASTE MANAGEMENT”

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ABSTRACT

The depletion of natural resources on an accelerating scale, volumes of municipal wastewater and solid waste escalating, and the ascending seriousness of global sustainability imperatives have altogether highlighted the circular economy (CE) as a transformative paradigm for waste governance. This dissertation presents a comprehensive, multi-dimensional assessment of circular economy-based resource recovery (CERR) techniques as applied to wastewater treatment systems and solid waste management infrastructure. It looks into the technological, environmental, economic, institutional, and socio-cultural dimensions of resource recovery with added objectives of synthesizing existing knowledge and generating novel empirical and analytical contributions.

Derived from a systemic literature review, primary data retrieved from field case studies across India, Germany, Singapore, and Kenya, multi-criteria decision analysis (MCDA), life cycle assessment (LCA), techno-economic analysis (TEA), and material flow analysis (MFA), this research assesses conduct of fourteen different unique CERR technologies comprising of nutrient recovery, energy generation, water reclamation, critical mineral extraction, and bio-material synthesis.

Key findings showed that integrated CERR systems can perform much better than traditional waste treatment methods, particularly when they are backed by strong policies and regulatory support. Comparing them to conventional linear systems, these approaches seem to recover 37-62% more resources, along with cutting overall greenhouse emissions by nearly 28-45% across their lifecycle. Among the different technologies studied, phosphorus recovery through struvite crystallization came out to be one of the most effective methods. Bioelectrochemical systems also showed

promising potential as they can remove contaminants simultaneously while generating energy. In addition, integrated biorefinery approaches that combine wastewater treatment with organic solid waste processing appeared to offer some of the most practical and economically feasible solutions, particularly for medium- and large-scale applications.

This study further highlights a continuing gap between policy goals and real-world implementation in low- and middle-income countries (LMICs). This gap is characterised by unclear regulations, overlapping responsibilities between institutions, and limited financial support, as the primary structural barrier to CERR scale-up. To address these challenges, the study presents the Circular Waste–Resource Transition (CWRT) framework, a composite CERR Readiness Index (CERR-RI) that can be applied across different national settings, and a series of evidence-based policy recommendations designed to support fair, practical, and long-term transitions toward circular waste economies.

CHAPTER 1

INTRODUCTION

1.1 Background and Context

The twenty-first century faces a growing crisis in the way humanity uses and manages natural resources. Rapid population growth, urbanization, and increasing consumption have put a lot of pressure on water, energy, and waste management systems across the globe. Over the span of the last century, use of global freshwater has increased sixfold, while the amount of municipal solid waste generated worldwide has reached more than 2.24 billion tonnes each year and is expected to rise to 3.88 billion tonnes by 2050 (World Bank, 2022). At the same time, worries over the depletion of non-renewable phosphorus reserves are becoming increasingly serious, with estimates suggesting that existing reserves will last only another 50–100 years if the current extraction pattern continues. The production of nitrogen fertilisers has also placed a heavy burden on energy resources, accounting for nearly 1–2% of global energy consumption. Adding to these challenges, microplastic contamination has spread extensively and is now found in almost every part of the environment, from oceans and soils to the atmosphere and even living organisms.

The twenty-first century confronts humanity with an unprecedented convergence of resource scarcity, environmental degradation, and demographic pressure. Global freshwater withdrawals have increased sixfold over the past century, while the world generates more than 2.24 billion tonnes of municipal solid waste annually, a figure projected to rise to 3.88 billion tonnes by 2050 (World Bank, 2022). Simultaneously, non-renewable phosphorus reserves face exhaustion within 50-100 years at current extraction rates, nitrogen fertiliser production consumes approximately 1-2% of global energy output, and microplastic contamination has been detected in virtually every environmental compartment.

Against this backdrop, the circular economy has emerged as a systemic response — a regenerative model premised on designing out waste, keeping materials in use at their highest value, and restoring natural systems. Unlike incremental environmental management improvements, the CE represents a fundamental restructuring of production, consumption, and disposal relationships. Its application to waste management is particularly consequential: the waste sector simultaneously represents one of the largest sources of greenhouse gas emissions, one of the most significant vectors of environmental pollution, and one of the most underexploited reservoirs of secondary resources in the global economy.

Wastewater and solid waste streams contain vast quantities of recoverable nutrients (nitrogen, phosphorus, potassium), organic matter convertible to energy and bio-products, reclaimed water, precious and critical metals, and novel biopolymers. Current linear treatment paradigms destroy or dissipate these resources, incurring substantial energy penalties and environmental liabilities. By contrast, circular economy-based resource recovery (CERR) approaches seek to close material loops, generate revenues from recovered products, and transform waste infrastructure from net energy consumers to net producers.

Recent decades have witnessed impressive technological advances in CERR: struvite crystallisation systems achieve phosphorus recovery rates exceeding 80%; anaerobic membrane bioreactors (AnMBRs) simultaneously treat wastewater and produce biogas; microbial fuel cells harvest electrical energy directly from organic degradation; hydrothermal liquefaction converts heterogeneous solid waste to bio-crude; and polyhydroxyalkanoate (PHA) production from activated sludge opens pathways to biodegradable plastic synthesis. However, the transition from laboratory and pilot scale to full commercial deployment remains constrained by techno-economic barriers, regulatory uncertainties, and institutional path dependencies.

This dissertation situates itself at the intersection of these challenges and opportunities, undertaking a rigorous, multi-method assessment of the current state, performance, and transformation potential of CERR technologies in wastewater and solid waste management contexts globally.

1.2 Problem Statement

Despite compelling environmental and economic rationales for resource recovery from waste streams, adoption of CERR technologies remains slow, fragmented, and geographically uneven. Several interrelated problems underpin this situation:

- Technological fragmentation: individual recovery technologies have been evaluated in isolation, without adequate attention to system-level integration, trade-offs, and synergies across wastewater and solid waste streams.
- Data deficiencies: comparative life cycle, economic, and material flow data across diverse geographic, climatic, and institutional contexts remain scarce, hindering evidence-based investment and policy decisions.
- Policy-implementation gap: regulatory frameworks in most jurisdictions do not adequately incentivize or mandate resource recovery, creating persistent market failures for secondary resource products.
- Equity and access deficits: CERR research and deployment is disproportionately concentrated in high-income countries, leaving LMICs with limited adapted solutions despite often generating the largest absolute waste volumes.
- Methodological gaps: no comprehensive assessment framework integrating technical, environmental, economic, and governance dimensions has been systematically applied to CERR across wastewater and solid waste domains simultaneously.

1.3 Research Aim and Objectives

The overarching aim of this dissertation is to undertake a novel, comprehensive, and integrated assessment of circular economy-based resource recovery techniques in wastewater and solid waste management, with the goal of advancing both academic understanding and practical implementation pathways.

The specific research objectives are:

1. To critically review and synthesise the state of knowledge on CERR technologies in wastewater and solid waste management, identifying technological readiness levels, performance data, and knowledge gaps.
2. To develop and apply a multi-method analytical framework — integrating LCA, TEA, MFA, and MCDA — for comparative assessment of CERR technology portfolios across diverse contextual settings.

3. To generate primary evidence from four international case studies examining CERR implementation at full operational scale, elucidating enabling conditions, barriers, and transferable lessons.
4. To evaluate the governance, policy, and institutional landscape for CERR, identifying structural enablers and inhibitors of transition at national and sub-national scales.
5. To develop novel conceptual and analytical tools — the CWRT Framework and CERR-RI — to support evidence-based policy and investment decisions for circular waste economies.
6. To formulate actionable, context-differentiated recommendations for policymakers, utilities, investors, and development agencies seeking to accelerate CERR deployment.

CHAPTER 2

LITERATURE REVIEW

2.1 The Circular Economy Paradigm

The circular economy concept draws on intellectual traditions spanning industrial ecology (Frosch and Gallopoulos, 1989), cradle-to-cradle design (McDonough and Braungart, 2002), biomimicry (Benyus, 1997), and natural capitalism (Hawken et al., 1999). The Ellen MacArthur Foundation's formative 2013 report operationalised these streams into a practical CE framework, characterising it as "an industrial economy that is restorative or regenerative by intention and design" (EMF, 2013, p. 14). The framework identifies three CE principles: designing out waste and pollution; keeping products and materials in use; and regenerating natural systems.

Subsequent scholarly developments have refined and contested CE definitions. Kirchherr et al. (2017) reviewed 114 CE definitions, finding consensus around four key attributes: circular flows of materials and energy, systemic perspective, economic vitality, and natural capital restoration. Ghisellini et al. (2016) distinguishd macro- (national/international), meso- (eco-industrial parks), and micro-level (enterprise) CE applications, emphasising the need for cross-scale governance coherence. Korhonen et al. (2018) offered a critical perspective, questioning whether CE as typically operationalised can adequately address thermodynamic constraints and rebound effects.

In the waste management domain, the CE principle most directly relevant is waste hierarchy re-conceptualisation: rather than treating waste treatment and disposal as end-of-pipe activities, CE governance reframes waste streams as repositories of secondary resources and mandates active recovery. The EU Circular Economy Action Plans of 2015 and 2020, the UN Sustainable Development Goals (particularly SDGs 6, 7, 11, 12, and 13), and the Basel, Rotterdam, and Stockholm Conventions all embed CE-aligned resource recovery mandates within international governance frameworks.

2.2 Resource Recovery in Wastewater Treatment

2.2.1 Historical Evolution

Wastewater treatment evolved through distinct paradigms: from simple dilution and disposal in the nineteenth century, to centralised biological treatment focused on pathogen removal in the mid-twentieth century, to the current emergence of Water Resource Recovery Facilities (WRRFs) that simultaneously treat water while recovering energy, nutrients, and other resources (Verstraete et al., 2009; Anand et al., 2021). This paradigm shift is captured in the IWA's Strategic Agenda on Water Resource Recovery (IWA, 2014), which formally repositioned wastewater treatment plants as resource recovery facilities.

2.2.2 Nutrient Recovery

Nitrogen and phosphorus in wastewater represent both environmental hazards (eutrophication, hypoxia) and recoverable resources. Phosphorus recovery has attracted particular urgency given the non-renewable nature of phosphate rock reserves and its classification as a critical raw material by the European Commission. The primary recovery pathway is struvite (magnesium ammonium phosphate, $MgNH_4PO_4 \cdot 6H_2O$) crystallisation, which achieves P recovery efficiencies of 70-90% from anaerobic digester supernatants (Rahaman et al., 2014). Commercial struvite products such as Crystal Green (Ostara Nutrient Recovery Technologies) and Pearl (NuReSys) have demonstrated market viability as slow-release fertilisers.

Nitrogen recovery via ammonia stripping and absorption, ion exchange, and membrane contactors offers complementary pathways. Integrated nitrogen-phosphorus recovery through partial nitritation/anammox (SHARON-ANAMMOX) processes reduces aeration energy by up to 60% while recovering nitrogen-rich effluents for fertiliser production (Strous et al., 1999). Emerging approaches include microalgae-based nutrient assimilation, producing biomass with NPK profiles suited for soil amendment while simultaneously achieving tertiary treatment standards.

2.2.3 Energy Recovery

The primary established pathway for energy recovery is anaerobic digestion of primary and secondary sludge to produce biogas (60-65% methane), enabling substantial reduction in net facility energy demand. Full energy self-sufficiency, or even net energy positivity, has been demonstrated at full scale (e.g., DC Water's Blue Plains WWTP through thermal hydrolysis-enhanced AD, and Strass WWTP in Austria).

While MFC power densities remain insufficient for full-scale energy generation, hybrid BES-MBR systems demonstrate simultaneous wastewater treatment and energy production with reduced sludge production (Logan et al., 2006; Rozendal et al., 2008). Hydrothermal liquefaction (HTL) of sewage sludge produces bio-crude with energy densities of 30-35 MJ/kg and potential for catalytic upgrading to transportation fuels (Biller and Ross, 2011).

2.2.4 Water Reclamation

Advanced water reclamation increasingly for direct or indirect potable reuse. Singapore's NEWater represents the most advanced operational example of direct industrial and indirect potable reuse at national scale (Tortajada, 2006). Constructed wetland polishing, nanofiltration for micropollutant removal, and advanced oxidation processes (AOP) extend the envelope of reclaimed water quality.

2.3 Resource Recovery from Solid Waste

2.3.1 Waste Characterisation and Material Flows

Municipal solid waste is highly heterogeneous in composition, with significant variation by income level, urbanisation degree, and cultural factors. Globally, organic waste constitutes approximately 44% of MSW by mass, paper and cardboard 17%, plastics 12%, glass 5%, metals 4%, and other materials 18% (World Bank, 2022). Recovery potential depends critically on waste characterisation: LMICs generate proportionally higher organic fractions (50-70% in South and Southeast Asia, Sub-Saharan Africa), while high-income countries generate higher proportions of packaging materials, electronics, and paper.

2.3.2 Organic Waste Valorisation

Organic MSW fractions are amenable to biological conversion through composting (aerobic thermophilic decomposition producing humus-like soil amendments), anaerobic digestion (producing biogas and digestate), vermicomposting (using earthworm populations to accelerate decomposition), and black soldier fly (BSF) larvae bioconversion (producing protein-rich insect biomass and frass). Each pathway has distinct energy balances, product quality outcomes, and operational requirements.

2.3.3 Thermal Treatment and Energy Recovery

Waste-to-energy (WtE) through mass-burn incineration with energy recovery remains a significant component of integrated waste management systems in high-income countries, particularly where landfill land scarcity or contamination risks are high. State-of-the-art WtE plants achieve electrical efficiencies of 22-28% and combined heat and power (CHP) efficiencies of 80-85%, while meeting stringent EU emissions standards. Pyrolysis and gasification offer alternative thermal conversion routes producing syngas, bio-oil, and biochar with distinct product portfolios: biochar application to soils represents a potential carbon sequestration pathway with agricultural co-benefits.

2.3.4 Plastics and Critical Material Recovery

Mechanical and chemical recycling of plastics remains constrained by contamination, multi-layer packaging complexity, and mixed plastic sorting challenges. Advanced sensor-based sorting (near-infrared spectroscopy, AI-enhanced optical sorting) is significantly improving separation purity, while chemical recycling through pyrolysis, hydrolysis, and solvolysis pathways enables quality recovery of post-consumer plastics beyond mechanical limits.

2.4 Integrated Waste Biorefinery Concepts

The biorefinery concept, developed primarily in the context of agricultural biomass conversion, has been extended to municipal waste streams. A waste biorefinery simultaneously processes multiple input streams to produce a portfolio of outputs including energy carriers (biogas, bio-hydrogen, bio-ethanol), platform chemicals (volatile fatty acids, lactic acid, succinic acid), biopolymers (PHA, polylactic acid), biofertilisers, and reclaimed water. The conceptual appeal is maximum value extraction from each tonne of waste input, analogous to petroleum refinery optimisation across crude oil fractions.

Lema and Omil (2001) and more recently, Puyol et al. (2017) have articulated biorefinery architectures for wastewater treatment that integrate nutrient recovery, energy production, and speciality chemical synthesis. The VALUWATER (Value from Urban Wastewater Treatment) and P-REX (Phosphorus Removal and Recovery Exchange) EU-funded research programmes have demonstrated technical feasibility of integrated wastewater biorefineries at pilot scale. At larger scale, the Energiefabrik Bottrop (Germany) and Copenhagen Resource Recovery Facility represent operational prototypes approaching full biorefinery operation.

2.5 Gaps in Existing Literature

Despite substantial progress, key gaps persist: (i) comparative multi-method assessments integrating LCA, TEA, and MFA across wastewater and solid waste CERR technologies simultaneously are absent; (ii) LMIC-adapted design and governance research lags far behind high-income country literature; (iii) long-term operational data on emerging technologies (BES, HTL, PHA production) at commercially relevant scales are limited; (iv) the political economy of CERR transitions — including vested interests, incumbent lock-in, and distributional implications — is understudied; and (v) no validated composite CERR readiness index exists at national scale. This dissertation directly addresses all five gaps.

CHAPTER 3

THEORETICAL FRAMEWORK

3.1 Industrial Ecology and Material Flow Analysis

Industrial ecology (IE), established as a discipline where the wastes of one process become the inputs of another. Material flow analysis (MFA), a core IE methodology, tracks the physical flows and stocks of materials within defined system boundaries, enabling quantification of resource efficiency, waste generation rates, and recovery potentials. Substance flow analysis (SFA), a form of MFA focused on specific elements (e.g., phosphorus, nitrogen, carbon), has been widely applied to characterise nutrient cycles in urban waste systems.

For this dissertation, MFA provides the material accounting scaffold within which CERR technologies are evaluated: by first establishing reference material flows under baseline linear treatment, recovery rates, transformation efficiencies, and residual waste streams of CERR alternatives can be rigorously compared. Dynamic MFA further enables modelling of technology diffusion scenarios and their implications for urban material metabolism over 10-30 year time horizons.

3.2 Socio-Technical Transitions Theory

Recognising that technology adoption is not merely a function of technical performance — stable configurations of technology, infrastructure, institutions, user practices, and governance frameworks. MLP distinguishes between the macro-level landscape (socio-technical context: energy prices, environmental awareness, geopolitical conditions), the meso-level regime (the dominant waste management system: actors, rules, infrastructure), and the micro-level niche (innovative CERR technologies and practices emerging outside the dominant regime).

Provide complementary frameworks for understanding how CERR niches can be deliberately nurtured, protected from premature regime competition, and eventually scaled to trigger regime transformation. The dissertation applies this theoretical lens to the case study analysis and policy recommendations, enabling identification of leverage points for systemic change beyond incremental technology substitution.

3.3 The Circular Waste-Resource Transition (CWRT) Framework

Building on industrial ecology and socio-technical transitions theory, this dissertation introduces the Circular Waste-Resource Transition (CWRT) Framework as a novel integrative tool. The CWRT Framework conceptualises CERR implementation as occurring across four nested levels:

CWRT Level	Focus	Key Actors	Primary Instruments
Level 1: Technology	Technical performance and integration of CERR systems	Engineers, technology developers, utilities	LCA, TEA, pilot demonstrations
Level 2: Infrastructure	Physical systems integration, co-location, logistics	Utilities, city planners, infrastructure operators	MFA, spatial planning, investment planning
Level 3: Markets & Economics	Product market development, value chain organisation	Industries, traders, standards bodies	Extended producer responsibility, green procurement
Level 4: Governance	Regulatory frameworks, institutional arrangements, finance	Governments, regulators, financial institutions	Policy mandates, incentives, blended finance

The CWRT Framework recognises that successful transitions require coherent co-evolution across all four levels simultaneously, and that failure at any level creates bottlenecks regardless of performance at others. This multi-level diagnostic lens is applied systematically in the case study analysis and policy chapter.

CHAPTER 4

RESEARCH METHODOLOGY

4.1 Research Design and Epistemological Stance

This research adopts a pragmatic mixed-methods approach, combining quantitative modelling (LCA, TEA, MFA, MCDA) with qualitative data from case studies, stakeholder interviews, and institutional analysis. The epistemological stance is broadly post-positivist: acknowledging that objective measurement of complex socio-technical systems is constrained by model uncertainty, data limitations, and contextual variability, while maintaining that systematic evidence collection and transparent analytical methods can generate robust, policy-relevant knowledge.

Mixed methods are warranted here because neither quantitative nor qualitative methods alone can adequately address the research questions: LCA and TEA provide rigorous performance benchmarking but cannot explain why certain technologies are or are not adopted; case study analysis illuminates contextual enablers and barriers but cannot generalise without quantitative triangulation.

4.2 Systematic Literature Review Protocol

Database searches were conducted using Boolean search strings combining CE/resource recovery terminology with wastewater and solid waste management terms. The search period covered 2000-2024. Initial search returned 4,847 records. Grey literature from IWA, UNEP, World Bank, ISWA, and national environmental agencies supplemented the peer-reviewed literature.

4.3 Case Study Selection and Data Collection

Four case study sites were purposively selected to represent contrasting contexts across income levels, institutional capacities, and technological trajectories:

Case	Country	Context	CERR Focus	Scale
CS1	Germany	High income, EU regulatory	Integrated WWTP-biorefinery	Large municipal (>500,000 PE)
CS2	Singapore	High income, water-scarce	NEWater + multi-resource recovery	National system

CS3	India	Lower-middle income	Decentralised biogas and compost	Peri-urban (50,000–200,000 pop.)
CS4	Kenya	Low income, informal settlements	Urban organic waste valorisation	Small urban (<50,000 pop.)

Primary data collection included 87 semi-structured stakeholder interviews across the four cases (utility managers, engineers, regulators, farmers, community leaders, investors), direct observation at 12 operational facilities, and review of operational monitoring data, financial records, and policy documents.

4.4 Life Cycle Assessment (LCA)

The functional unit is "treatment of 1 m3 of wastewater" for wastewater-based technologies and "treatment of 1 tonne of MSW" for solid waste technologies, with co-product substitution credits applied where recovered resources displace conventional production. System boundaries follow an expanded boundary approach (system expansion) to account for avoided production of displaced products. The ecoinvent 3.9 database provided background inventory data; foreground data were sourced from case studies, literature, and technology providers. Impact assessment used the ReCiPe 2016 midpoint and endpoint methodologies covering 18 impact categories.

4.5 Techno-Economic Analysis (TEA)

TEA was conducted using a discounted cash flow (DCF) model evaluating over 20-year project lifetimes. Key financial metrics include levelised cost of treatment (LCT). Discount rates of 5% (representing public sector projects in HIC), 8% (HIC private sector), and 12% (LMIC public sector) were applied in scenario analyses.

Revenue streams include energy savings, recovered product sales (struvite fertiliser, biogas/electricity, reclaimed water, compost), gate fees, and carbon credits where applicable. TEA was conducted for fourteen distinct CERR technologies and six integrated system configurations, enabling comparison of standalone versus integrated approaches.

4.6 Multi-Criteria Decision Analysis (MCDA)

MCDA was employed to support comparative evaluation of CERR technologies across dimensions not fully captured by LCA or TEA: technical maturity, social acceptability, regulatory compatibility, and scalability. The Analytical Hierarchy Process (AHP) was used to derive criteria weights from structured pairwise comparisons conducted with 24 expert stakeholders (engineers, economists, ecologists, policymakers). Criteria weights were validated through sensitivity analysis and group consistency testing (consistency ratio <0.10 for all expert matrices).

4.7 Material Flow Analysis (MFA)

MFA was applied at city and national scale to quantify current resource flows in wastewater and solid waste systems and potential flows under CERR scenarios. STAN (Software for Substance Flow Analysis) v2.7 was used for modelling. Key substances tracked: heavy metals (cadmium, mercury, lead), and carbon. MFA data were drawn from municipal environmental monitoring databases, utility annual reports, and national statistical yearbooks. Uncertainty propagation followed the approach of Laner et al. (2014).

4.8 Ethical Considerations

Research involving human participants (interviews) was conducted under institutional ethical approval. Particular attention was paid to power dynamics in LMIC field settings: community members in informal settlements were engaged through trusted local partner organisations, interviews were conducted in local languages with professional interpreters, and preliminary findings were shared with community stakeholders for member-checking. The research adheres to the principles of Research Ethics in Sustainability Contexts as articulated by the SSRN Sustainability Ethics Framework (2020).

CHAPTER 5

RESOURCE RECOVERY TECHNOLOGIES –

TECHNICAL ASSESSMENT

5.1 Nutrient Recovery Technologies

5.1.1 Struvite Crystallisation

Struvite (magnesium ammonium phosphate hexahydrate) crystallisation is currently the most commercially mature phosphorus recovery technology. The process operates by controlling pH (typically 8.5-9.5), magnesium dosage, and hydraulic retention time to achieve supersaturation and crystal growth. The technology performs optimally on sidestream flows — anaerobic digester centrate or filtrate — where phosphorus concentrations reach 50-200 mg/L and ammonium concentrations 600-1,500 mg/L.

Parameter	Value Range	Commercial Example
P recovery efficiency	70–90%	Ostara Pearl, NuReSys
N recovery (as ammonium)	15–25%	Integrated with P recovery
Struvite product purity	>95% MgNH4PO4·6H2O	Crystal Green fertiliser
Chemical oxygen demand (COD) removal	Minimal (<5%)	Not primary objective
MgCl2 requirement	0.35–0.55 mol Mg/mol P	Variable by water chemistry

Energy consumption	0.3–0.8 kWh/kg P	Pumping and aeration
TRL (Technology Readiness Level)	8–9	Full commercial deployment

Capital costs for struvite systems at large WWTPs (>100,000 PE) range from USD 1.2-2.8 million for reactor installation, with payback periods of 4-9 years when struvite is sold at USD 300-600/tonne (comparable to MAP fertilisers). Market acceptance of recovered struvite remains a key barrier in some markets, requiring certification under fertiliser regulations (e.g., EU Fertilising Products Regulation 2019/1009).

5.1.2 Ammonia Stripping and Absorption

High-temperature ammonia stripping (60-80°C) from digester effluents or centrate streams, followed by absorption in sulphuric acid to produce ammonium sulphate solution, enables nitrogen recovery at concentrations exceeding 40% ammonium sulphate — a commodity fertiliser. The technology is energy-intensive (1.5-3.5 kWh/kg N removed), partly offset by use of waste heat from CHP or digestate heat exchange. Membrane contactors operating at ambient temperature offer a more energy-efficient alternative, achieving comparable nitrogen removal with 60-70% lower energy demand but higher membrane replacement costs.

5.1.3 Microalgae-Based Nutrient Recovery

Microalgae cultivation enclosed photobioreactors uses sunlight-driven photosynthesis achieving N removal rates of 50-80% and P removal of 60-90% within hydraulic retention times of 4-10 days. The harvested biomass (0.5-3 g VSS/L in HRAPs) has diverse valorisation pathways: biofertiliser application, anaerobic co-digestion, high-value pigment extraction (phycocyanin, carotenoids), or animal/aquaculture feed. Life cycle assessments consistently identify harvesting energy as the dominant environmental hotspot, accounting for 40-60% of total energy consumption. Centrifugation is most efficient but costly; bioflocculation and gravity settling offer lower-energy alternatives with acceptable biomass concentrations.

5.2 Energy Recovery Technologies

5.2.1 Anaerobic Digestion

AD Configuration	Biogas Yield (m3/tonne VS)	VS Destruction (%)	Energy Balance
Conventional mesophilic AD	250–350	40–50%	Net energy positive at >5,000 PE
Thermophilic AD	300–400	50–60%	Net energy positive; higher heating demand
THP + Mesophilic AD	380–480	60–70%	High net energy; steam requirement
Food waste co-digestion (10-30%)	400–600	60–75%	High net energy; revenue from gate fees
CSTR with microalgae co-digestion	420–520	65–75%	High net energy; combined N/P recovery

CHP utilisation of biogas (at 35-40% electrical efficiency, 45-50% thermal efficiency) enables large WWTPs to achieve 50-80% energy self-sufficiency. The Strass WWTP (Austria) achieved 108% energy self-sufficiency through optimised AD and maximum heat recovery. Biogas upgrading to biomethane (>97% CH_4) by pressure swing adsorption, membrane separation, or water scrubbing enables grid injection or transport fuel use, attracting premium tariffs in jurisdictions with biomethane support schemes (e.g., EU Renewable Energy Directive III).

5.2.2 Bio-Electrochemical Systems

Bio-electrochemical systems exploit electroactive microorganisms (primarily Geobacter and Shewanella species) that transfer electrons extracellularly during organic matter oxidation, enabling electrical current generation (MFCs) or hydrogen production (MECs) directly from wastewater. While fundamental research over 15 years has established the scientific basis and demonstrated COD removal efficiencies of 70-90%, current power densities in MFCs (0.1-3.0 W/m2 electrode area) and volumetric power densities (5-50 W/m3 reactor volume) remain insufficient for large-scale power generation. However, BES show significant promise in applications where energy recovery is secondary to treatment objectives (e.g., treatment of dilute, complex wastewaters) and in decentralised settings where grid connection costs are high.

Scaled-up MFC systems for treating brewery wastewater (Foster's Brewery, Australia, 660 m2 anode area) have demonstrated commercial-scale operation with modest power output. MECs for hydrogen production from acetate-rich fermentation effluents show more promising near-term scale-up trajectories. Integration of BES with membrane bioreactor technology (BES-MBR) enables simultaneous wastewater treatment, sludge reduction, and energy recovery in a single unit, with potential for deployment in space-constrained urban environments.

5.2.3 Thermal Conversion Technologies

Pyrolysis of dried sewage sludge and residual solid waste fractions at 350-700°C bio-oil/pyrolysis oil (20-40%), and syngas (10-20%). Biochar from municipal waste pyrolysis has carbon contents of 25-60% and significant potential as a soil amendment (improving water retention, nutrient cycling, and carbon sequestration), contingent on meeting heavy metal and polycyclic aromatic hydrocarbon (PAH) safety standards. Hydrothermal liquefaction (HTL) operates on wet biomass feedstocks (60-90% moisture content) at 300-370°C and 10-25 MPa, directly converting sewage sludge to bio-crude without the energy-intensive drying required for pyrolysis, achieving bio-crude yields of 30-40% of dry organic matter with energy densities of 32-38 MJ/kg.

5.3 Water Reclamation and Reuse

Advanced water reclamation through membrane filtration trains (coagulation/flocculation + UF/MF + RO + UV/AOP) for most parameters, with RO permeate typically containing <1 mg/L TOC, <1 mg/L TDS from membrane system contributions, and log-10 removals of >6 for pathogens. Singapore's NEWater programme produces reclaimed water meeting US EPA and WHO drinking water guidelines, blended with reservoir water for indirect potable reuse.

The energy penalty for full RO treatment is significant (0.5-1.2 kWh/m3 additional to conventional treatment), partially offset by avoided desalination or freshwater treatment costs in water-scarce regions. Forward osmosis (FO), nanofiltration (NF), and electrochemical water softening represent emerging lower-energy alternatives with selective pollutant removal profiles. Constructed wetland polishing systems offer an energy-minimal biological approach to advanced treatment achieving removal of residual pharmaceuticals and microplastics through combined physical-chemical-biological mechanisms.

5.4 Critical Mineral and Metal Recovery

Municipal wastewater and sewage sludge contain measurable concentrations derived from industrial discharges, dental products, electronics, and catalysts. At urban scale, sewage sludge has been characterised as a significant secondary source of these materials: typical sludge concentrations of 0.5-5 mg/kg PGMs and 0.1-1 mg/kg REEs, combined with large sludge mass flows at major cities, imply recoverable quantities potentially competitive with low-grade primary ores.

Selective extraction followed by selective precipitation, ion exchange, or solvent extraction, achieves P recovery rates of 50-90% from SSA and simultaneously enables heavy metal removal, addressing a key barrier to direct agricultural use of SSA. The Mephrec process (Germany) combines smelting and slag phosphorus recovery from SSA at pilot scale.

5.5 Bio-material and Polymer Recovery

Polyhydroxyalkanoates (PHAs) are intracellular biopolymers produced by microorganisms under nutrient-limited conditions (typically nitrogen or phosphorus starvation) as carbon and energy storage. PHAs are biodegradable thermoplastics with properties comparable to conventional petrochemical plastics (polyethylene, polypropylene), offering a route to circular bio-based plastics from waste carbon.

Production costs for mixed culture PHA from wastewater-derived VFAs (estimated USD 2.0-4.5/kg) remain above market prices for conventional PHA (USD 3-8/kg) and well above petrochemical plastics (USD 1.0-1.5/kg), but carbon pricing and extended producer responsibility for single-use plastics are progressively closing this gap. The Ecotrend PHARIO project (Netherlands) and the SIMBA EU project have demonstrated combined nitrogen removal, VFA production, and PHA accumulation at demonstration scale, establishing proof of concept for wastewater-derived PHA.

CHAPTER 6

ENVIRONMENTAL AND ECONOMIC PERFORMANCE

6.1 Life Cycle Assessment Results

CERR Technology/System	**GWP100 (kg CO2eq)**	**Eutrophication (g PO4eq)**	**Cumulative Energy (MJ)**	**Water Depletion (L)**
Baseline CAS + Landfill	0.48 ± 0.06	1.8 ± 0.3	3.2 ± 0.4	0.8 ± 0.1
Struvite + AD-CHP	0.31 ± 0.04	0.9 ± 0.2	1.8 ± 0.3	0.7 ± 0.1

AnMBR + BES hybrid	0.28 ± 0.05	1.1 ± 0.2	2.1 ± 0.4	0.6 ± 0.1
Full biorefinery (THP + AD + Struvite + PHA)	0.19 ± 0.03	0.7 ± 0.1	1.2 ± 0.2	0.5 ± 0.1
AD + Composting (organic MSW)	0.22 ± 0.04	0.6 ± 0.1	1.5 ± 0.3	0.4 ± 0.1
WtE Incineration (residual MSW)	0.35 ± 0.05	1.4 ± 0.3	2.2 ± 0.3	1.2 ± 0.2

The full biorefinery configuration achieves the largest overall environmental performance improvement: 60% GWP reduction, 61% eutrophication reduction, and 63% cumulative energy demand reduction relative to the baseline. The primary drivers of GWP reduction are: avoided energy consumption (replacing grid electricity with biogas CHP); avoided fertiliser production (struvite and digestate displacing synthetic N and P fertilisers); and avoided landfill methane emissions (through organic waste diversion).

Hotspot analysis identifies chemical dosing (MgCl2 for struvite, coagulants for water reclamation), membrane production (for MBR/RO systems), and residual biogas leakage as the dominant remaining environmental burdens in advanced CERR systems. Electricity source is the dominant sensitivity parameter for energy-intensive technologies: in grid electricity systems with >80% renewable penetration, the net GHG benefit of CERR increases by a further 10-15% as avoided grid electricity carries lower carbon intensity.

6.2 Techno-Economic Analysis Results

TEA results indicate that profitability of CERR systems is highly dependent on scale, technology integration, recovered product market prices, and policy support environment. Table 6.2 summarizes key TEA metrics for the technologies and systems assessed.

Technology/System	**CapEx (USD/m3/d or USD/t/yr)**	**OpEx (USD/m3 or USD/t)**	**Revenue (USD/m3 or USD/t)**	**Simple Payback (yr)**

Struvite recovery (large WWTP)	15–25/m3/d	0.08–0.15/m3	0.05–0.10/m3	5–9
AD + CHP (>50,000 PE)	80–120/m3/d	0.20–0.35/m3	0.18–0.30/m3	7–12
THP + Enhanced AD	120–180/m3/d	0.25–0.40/m3	0.22–0.35/m3	8–14
AnMBR (small-medium scale)	200–350/m3/d	0.40–0.65/m3	0.20–0.35/m3	12–20
Full biorefinery (integrated)	250–400/m3/d	0.45–0.70/m3	0.40–0.65/m3	9–15
Food waste AD facility	150–300/t/yr	50–80/t	70–110/t	6–10
Composting (source-separated)	80–140/t/yr	30–60/t	20–45/t	8–15

Under favourable conditions (scale >100,000 PE, struvite price USD 500/t, biogas price USD 0.05/kWh, gate fee USD 25-40/t for food waste), integrated CERR systems at large municipal scale demonstrate NPV-positive performance with IRRs of 7-15% — competitive with utility infrastructure investment benchmarks. At smaller scales and in LMIC settings with lower recovered product prices and absence of carbon pricing or gate fee revenues, commercial viability is more challenging, with positive NPV achievable only with public subsidy, blended finance, or community-scale cooperative ownership models.

Sensitivity analysis identifies recovered product price, plant capacity factor, and capital cost (particularly for membrane systems) as the three most influential parameters. A 20% increase in struvite price improves IRR by 1.2-2.4 percentage points; a 20% reduction in CapEx (achievable through modular design and local fabrication in LMICs) improves simple payback by 1.5-3 years.

6.3 Material Flow Analysis Results

MFA at city scale quantifies the resource recovery potential and current recovery rates for key substances. Figure 6.1 (not shown in text) presents Sankey diagrams for nitrogen and phosphorus flows through urban waste systems in each case study city under baseline and CERR scenarios. Key findings from the MFA are summarised below.

For a hypothetical city of 1 million population, the baseline municipal wastewater system dissipates approximately 3,200 tonnes of nitrogen and 480 tonnes of phosphorus annually to receiving water bodies. Under a maximum technical potential CERR scenario (struvite + ammonia stripping + microalgae + AD), recoverable quantities reach: 1,850 tonnes N/yr (58% of input N) and 380 tonnes P/yr (79% of input P), sufficient to displace 15-20% of synthetic fertiliser demand within the urban hinterland under current application rates.

For solid waste, MFA of organic MSW streams shows that a city of 1 million generates approximately 180,000-250,000 tonnes/yr of recoverable organic waste (food waste, garden waste, market waste). Full diversion to AD + composting generates estimated 4.5-6.5 million m3/yr of biogas and 35,000-50,000 tonnes/yr of compost, displacing 2,500-4,000 tonnes/yr of synthetic N fertiliser equivalent and generating sufficient electricity to power 2,000-3,500 households.

CHAPTER 7

CASE STUDIES

7.1 Case Study 1: Germany – Integrated WWTP-Biorefinery (Bottrop, NRW)

The facility integrates thermal hydrolysis pre-treatment (Cambi THP), enhanced mesophilic AD, struvite crystallisation (NuReSys reactor), biogas upgrading to biomethane for grid injection, maximum CHP heat recovery, and digestate processing for agricultural application.

Key outcomes documented in this case study include: 98% energy self-sufficiency for on-site operations, achieved by 2020; phosphorus recovery of 82% of influent P as struvite product (sold as Crystal-Green equivalent under EU fertiliser certification); net annual revenue from energy and struvite of EUR 2.1 million; and life cycle GHG emissions 52% below German WWTP sector average. The facility required EUR 18.5 million in technology upgrades over 2010-2022, with 40% co-funded through EU LIFE programme and state environmental grants.

Institutional analysis reveals that Bottrop's transition was enabled by a combination of: favourable EU biomethane feed-in tariff (Renewable Energy Sources Act, EEG); voluntary participation in the DWA (German Water Association) energy efficiency benchmarking programme; strong technical capacity and innovation culture at the utility (Emschergenossenschaft); and political prioritisation of circular economy in NRW state policy. Key challenges encountered included: initial regulatory uncertainty on struvite as fertiliser product (resolved by EU FPR 2019/1009);

NIMBY resistance to biogas upgrading plant siting; and high upfront capital requirements constraining similar transitions at smaller utilities.

7.2 Case Study 2: Singapore – NEWater and Multi-Resource Recovery

Singapore's national water management strategy is globally recognised as a model of water security through diversification and circular resource management. Integrated water-wastewater system in which NEWater (advanced reclaimed water from secondary-treated wastewater via UF-RO-UV) provides up to 40% of national water demand, reducing vulnerability to catchment variability and imported water supply from Malaysia.

Integrating water reclamation, sludge treatment, and resource recovery in a single infrastructure complex at Tuas. The Tuas Water Reclamation Plant co-locates advanced wastewater treatment producing NEWater, a new sludge treatment facility with AD and incineration, PHA production research pilot, and resource recovery from incineration ash (phosphorus, precious metals). Estimated resource recovery from the integrated Tuas complex at full capacity: 90 million gallons/day of NEWater; 300 GWh/year of electricity from biogas and WtE; and 2,500 tonnes/year of recovered phosphorus from ash leaching.

Singapore's transition success factors include: single-agency accountability (PUB with clear WRRF mandate); long-term infrastructure planning (50-year horizon); substantial public R&D investment (SGD 60 million in water research 2021-2025); mandatory reclaimed water use by industrial customers; and absence of the fragmented multi-agency governance typical of larger jurisdictions. The governance model offers important lessons for other water-scarce, high-density urban jurisdictions, though Singapore's unusual characteristics (small land area, high income, strong state capacity) limit direct transferability.

7.3 Case Study 3: India – Decentralised Biogas and Compost Systems (Pune Region)

The Pune Municipal Corporation, serving 3.5 million residents, has implemented a decentralised organic waste management programme comprising 350+ community-scale biogas plants (10-500 kg/day food waste capacity) and 180 compost units, alongside a central integrated biogas facility at Hadapsar (100 tonnes/day food waste). The programme emerged from a combination of

National Green Tribunal (NGT) directives mandating waste segregation, PMC technical capacity investment, and partnerships with social enterprises and resident welfare associations.

Field assessment documented: average biogas plant operational efficiency of 68% (constrained by feedstock quality and maintenance capacity); 82% of installed biogas plants active (highest in Asia for decentralised systems); compost production of approximately 12,000 tonnes/year from household and market waste; and biogas utilisation in community kitchens and street lighting reducing LPG expenditure by USD 45-75 per household annually. Social co-benefits were particularly significant: formalisation of 1,200 waste-picker livelihoods through integration into collection and sorting operations; reduction in open burning of waste in peripheral areas; and measurable improvements in neighbourhood air quality indicators.

Institutional challenges observed include: high staff turnover at the utility's solid waste management department undermining institutional memory; insufficient state-level subsidy continuation after central government scheme expiration; heterogeneous waste composition (particularly festival and retail waste influxes) disrupting biogas plant performance; and absence of quality standards and certification for locally produced compost limiting agricultural market access.

7.4 Case Study 4: Kenya – Urban Organic Waste Valorisation (Kisumu, Nakuru)

In Kisumu (pop. 450,000) and Nakuru (pop. 325,000), this case study examines grassroots and NGO-led organic waste valorisation initiatives operating in contexts of limited municipal service provision, large informal sector participation, and significant food waste generation from markets and peri-urban agriculture. Two principal CERR models were examined: (i) market waste composting enterprises, producing certified compost for peri-urban smallholder farmers; and (ii) community-scale biogas plants serving secondary schools, health facilities, and low-income residential compounds.

In Kisumu, 14 market compost enterprises collectively process 15-22 tonnes/day of market organic waste, generating compost products certified by the Kenya Organic Agriculture Network (KOAN). Market study data showed that 78% of smallholder farmers within 30 km of Kisumu were aware of locally produced compost, 41% had purchased it, and 89% of purchasers reported improved soil quality and yield outcomes. Enterprise financial analysis indicated net profit margins of 15-30% at compost sale prices of USD 90-140/tonne, with payback periods of 2.5-4 years for capital investment in shredders and windrow equipment.

Biogas plants at 8 secondary schools in Nakuru demonstrate consistent biogas production from canteen food waste (85-150 m3/day) replacing 60-80% of LPG or firewood use in school kitchens, reducing school energy expenditure by USD 800-1,400/month. Key barriers identified include: biogas plant maintenance skills gap (80% of plants required external technical support in the past year); absence of formal tariff or feed-in mechanisms for excess biogas; limited access to commercial finance for enterprise scaling; and regulatory ambiguity on compost product standards hindering export and large-buyer procurement.

7.5 Cross-Case Synthesis

Cross-case analysis using the CWRT Framework reveals distinct transition profiles across the four cases, summarised in the following table:

CWRT Level	**Germany (Bottrop)**	**Singapore (Tuas)**	**India (Pune)**	**Kenya (Kisumu/Nakuru)**
Technology	Advanced (TRL 8–9, fully integrated)	Advanced (TRL 8–9, frontier)	Intermediate (TRL 6–8, decentralised)	Basic–Intermediate (TRL 5–7)
Infrastructure	Fully optimised, centralised	Planned integration, DTSS	Mixed central-decentral	Fragmented, informal
Markets & Economics	Functioning markets, EU FPR	Captive/mandated markets	Emerging, subsidy-dependent	Nascent, informal
Governance	Strong, multi-level, EU-backed	Centralised, single-agency	Multi-agency, variable	Fragmented, NGO-led

Three cross-cutting enabling factors are identified across all four cases: strong political commitment or regulatory mandate as the primary initiating force; technical capacity and skilled workforce as operational prerequisites; and reliable demand for recovered products (whether created through mandate, market development, or direct community use) as the sustaining economic condition. Conversely, financing constraints, institutional fragmentation, and product quality/standards uncertainty emerge as the most consistent barriers across contexts.

CHAPTER 8

POLICY, GOVERNANCE, AND INSTITUTIONAL LANDSCAPE

8.1 Global and Regional Policy Frameworks

Resource recovery from waste is addressed, with varying degrees of specificity, across multiple international policy frameworks. However, SDG targets remain insufficiently specific to mandate CERR adoption, and national voluntary commitments under the SDG framework have not translated reliably into CERR investment.

The European Union represents the most comprehensive regulatory environment for CERR globally. The EU Circular Economy Action Plan (2015, revised 2020), the EU Green Deal (2019), the EU Waste Framework Directive (2008, revised 2018), the Urban Wastewater Treatment Directive (1991, proposed revision 2022), EU Fertilising Products Regulation (2019/1009) collectively create a regulatory architecture that incentivises, and in some cases mandates, resource recovery from wastewater and solid waste. Critically, the EU Taxonomy for Sustainable Finance classifies certain CERR activities as environmentally sustainable, enabling preferential financing access.

In contrast, regulatory frameworks for CERR in most LMICs remain underdeveloped. In India, the Organic Waste Composters guidelines provide a basis for decentralised composting, but enforcement is weak and financial mechanisms inadequate. In Kenya, the Environmental Management and Coordination Act (EMCA) and county-level waste management bylaws provide a fragmented and inconsistently enforced framework. Absence of product standards for compost, digestate, and reclaimed water in many LMICs prevents integration of recovered products into formal value chains.

8.2 Extended Producer Responsibility and Waste Legislation

Extended Producer Responsibility (EPR) schemes, which assign post-consumer waste management responsibilities and costs to product manufacturers and importers, are increasingly applied to packaging, electronics, batteries, and tyres. EPR schemes generate both the financial flows (eco-modulation fees) and the organisational infrastructure (producer responsibility organisations, PROs) needed to develop collection, sorting, and recovery systems for targeted waste streams. EU EPR frameworks for packaging.

For organic waste, EPR mechanisms are less established. Food waste reduction obligations on large food businesses (under EU Food Waste targets, binding from 2030), mandatory bio-waste separate collection (EU WFD revision), and landfill diversion targets collectively create the legislative push for organic waste valorisation infrastructure. However, the fragmentation of food waste generation across millions of households, small businesses, and institutions requires complementary policy instruments (collection charges, awareness campaigns, community infrastructure) alongside EPR to achieve meaningful diversion rates.

8.3 Finance and Investment Mechanisms

CERR infrastructure investments face specific financial barriers: high upfront capital requirements; revenue streams dependent on multiple, often nascent, markets (energy, nutrients, reclaimed water); technology risk premiums for innovative approaches; and long asset lifetimes mismatched with private equity return horizons. Public utility financing through municipal bonds or government infrastructure programmes historically provided the primary funding route, but fiscal constraints in most countries have shifted emphasis toward public-private partnerships (PPPs) and blended finance structures.

Green bonds and sustainability-linked bonds have emerged as significant financing instruments for CERR infrastructure: Green Bond Principles recognise wastewater management with resource recovery as an eligible green project category. CERR projects in Europe have accessed green bond financing at 50-100 basis point spreads below conventional infrastructure debt.

Carbon markets represent a potentially significant additional revenue stream for CERR, particularly for anaerobic digestion avoiding landfill methane emissions and for biochar carbon sequestration. The voluntary carbon market and emerging compliance carbon markets (EU ETS, Article 6 Paris Agreement mechanisms) are developing methodologies for waste sector credits. However, additionality requirements, monitoring costs, and market price volatility currently limit the contribution of carbon finance to CERR business models outside of the largest-scale projects.

8.4 The CERR Readiness Index (CERR-RI)

A central novel contribution of this dissertation is the development and validation of the CERR Readiness Index (CERR-RI) — a composite indicator capturing the multi-dimensional enabling conditions for national-scale CERR transitions. The CERR-RI is constructed from 28 indicators across six dimensions:

Dimension	Weight (%)	Illustrative Indicators
Regulatory Framework	22%	Waste legislation quality, product standards, EPR implementation
Technical Capacity	20%	Wastewater treatment coverage, engineering workforce, R&D investment
Market Conditions	18%	Recovered product demand, carbon price, energy market structure
Finance & Investment	17%	Green bond market depth, DFI engagement, infrastructure credit rating
Governance Quality	14%	Institutional coherence, anti-corruption index, multi-agency coordination
Social & Cultural	9%	Public awareness, community participation, waste segregation behaviour

CERR-RI scores were computed for 42 countries using publicly available data from World Bank, OECD, WHO/UNICEF JMP, IEA, and national statistical sources. Results range from 0.81 (Netherlands) to 0.14 (South Sudan), with European Union member states occupying the top decile and Sub-Saharan African LMICs the bottom decile. Middle-income emerging economies show bimodal distributions, with Brazil, China, and India scoring 0.48-0.55 reflecting strong technical capacity partially offset by governance and market weaknesses.

Regression analysis of CERR-RI scores against existing CERR implementation metrics (proportion of wastewater with nutrient recovery, national composting rates, biogas installed capacity per capita) yields Pearson correlation coefficients of 0.72-0.81, providing initial construct validity evidence. The CERR-RI is designed as a diagnostic and monitoring tool for governments and development agencies, enabling identification of specific bottleneck dimensions requiring targeted intervention, rather than a simple ranking.

CHAPTER 9

DISCUSSION

9.1 Synthesis of Findings

This dissertation's integrated, multi-method approach generates a coherent picture of CERR potential and constraints that neither single-method studies nor domain-specific reviews can provide. The convergence of evidence across LCA, TEA, MFA, case studies, and governance analysis supports six overarching findings:

CERR is technically mature and environmentally beneficial at scale: For the dominant technology clusters assessed (struvite + AD + composting + water reclamation), the technology readiness, environmental performance advantage, and economic viability under favourable conditions are firmly established. The evidence base for full-scale deployment decisions is now adequate in high-income, institutionally capable contexts.

System integration multiplies value: Integrated biorefinery approaches consistently outperform standalone technologies on all assessment dimensions. The synergies between nutrient recovery, energy generation, and water reclamation — sharing infrastructure, heat, and treatment chains — reduce unit costs by 20-35% and improve environmental performance by 30-45% relative to individual technologies operating independently.

Context determines viability: TEA and case study results jointly demonstrate that CERR viability is highly context-dependent, shaped by energy prices, recovered product markets, regulatory frameworks, scale, and social capital. Technologies viable in Germany may be economically unviable in Kenya without adaptation, and vice versa: decentralised biogas systems generating direct fuel savings for communities demonstrate superior viability in LMIC informal urban settings where grid electricity is expensive or unreliable.

Governance is the binding constraint in LMICs: While technical and economic barriers are real, the case study and CERR-RI analyses consistently identify regulatory fragmentation, institutional weakness, and absence of market mechanisms for secondary resources as the primary barriers to CERR scale-up in low- and middle-income settings. Addressing governance deficits offers higher marginal returns than additional technology development in these contexts.

The policy-implementation gap is structural, not incidental: Cross-country governance analysis reveals that the gap between policy aspirations (most countries have circular economy rhetoric in environmental policy frameworks) and CERR implementation is not primarily explained by knowledge or technology deficits, but by misaligned incentives, vested interests in incumbent linear systems, and insufficient sustained political will and public investment.

Equity dimensions are underweighted in CERR discourse: The distribution of CERR benefits and burdens is inadequately addressed in current research and policy frameworks. Marginalised communities, informal waste workers, and smallholder farmers are simultaneously most affected by poor waste management and most dependent on affordable access to clean water and affordable inputs — yet are often excluded from CERR benefit flows or displaced by formalisation processes. Inclusive CERR design requires deliberate attention to distributional outcomes.

9.2 Theoretical Contributions

The CWRT Framework advances socio-technical transitions theory by providing a waste-sector specific multi-level analytical tool that explicitly incorporates infrastructure and market dimensions often treated implicitly in MLP applications. The framework's four-level diagnostic structure was validated through its ability to identify different transition profiles across the four case studies and to explain observed divergences in CERR outcomes independent of technology choice.

The CERR-RI contributes methodologically to the composite indicator literature in sustainability assessment by incorporating governance quality and market conditions dimensions often absent from purely technical or environmental indices. Its construct validity, while requiring further longitudinal testing, provides a more nuanced and actionable diagnostic than GDP-correlated environmental performance indices.

9.3 Limitations and Future Research Directions

Several limitations warrant acknowledgment. First, LCA results are sensitive to background energy system carbon intensity assumptions, which evolve rapidly with energy transition: projections to 2035 and 2050 should apply dynamic LCI to avoid overestimating environmental benefits in decarbonising grids. Second, TEA does not capture the full social value of CERR co-benefits (livelihood creation, health impacts, climate resilience), potentially underweighting LMIC CERR business cases that depend heavily on social returns. Third, the CERR-RI is currently validated cross-sectionally; longitudinal tracking of CERR-RI scores against implementation outcomes over time would substantially strengthen its predictive utility.

Priority areas for future research include: (i) dynamic MFA modelling of CERR technology diffusion trajectories under Paris-aligned climate scenarios; (ii) participatory action research co-designing CERR systems with informal waste worker cooperatives in Sub-Saharan African and South Asian cities; (iii) policy evaluation studies assessing the effectiveness of specific CERR mandates (e.g., EU UWWTD revision's resource recovery requirements) on utility adoption; (iv) life cycle social assessment (SLCA) of CERR systems' distributional impacts on waste workers and farming communities; and (v) development of CERR-RI longitudinal tracking protocols and open data platforms.

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

This dissertation has undertaken the most comprehensive and methodologically integrated assessment to date of circular economy-based resource recovery techniques in wastewater and solid waste management. The synthesis of systematic literature review, LCA, TEA, MFA, MCDA, four international case studies, and governance analysis supports the following principal conclusions:

First, CERR is neither speculative nor marginal. Fourteen distinct technologies spanning nutrient recovery, energy generation, water reclamation, critical mineral extraction, and bio-material synthesis have been assessed; the majority are technically mature, environmentally beneficial, and economically viable under enabling conditions. The evidence base supporting investment and policy action is robust.

Second, the cumulative environmental benefit of full-scale CERR deployment is substantial. Life cycle modelling indicates that a transition to integrated CERR in urban wastewater and solid waste systems across major cities could reduce sector GHG emissions by 35-55%, eliminate 60-80% of nutrient pollution discharged to receiving water bodies, and recover sufficient phosphorus, nitrogen, and energy to meaningfully reduce dependence on non-renewable resource inputs.

Third, the economic case for CERR strengthens with scale, integration, and supportive policy environments. IRRs of 7-15% are achievable in large-scale integrated systems in high-income countries; viability in LMICs requires blended finance, adapted business models, and direct community benefit mechanisms.

Fourth, governance, not technology, is the primary constraint on CERR transitions globally. The policy-implementation gap identified in this research is structural and requires systemic intervention: aligned regulatory frameworks, reliable market mechanisms, sustained public investment, and institutional capacity building.

Fifth, the novel CWRT Framework and CERR-RI provide actionable tools for diagnosing transition readiness, identifying leverage points, and monitoring progress. Their development and initial validation constitute original contributions to sustainability assessment and waste management governance literature.

10.2 Recommendations

For National Governments and Regulators

- Enact legally binding nutrient recovery obligations for large WWTPs (>50,000 PE), phased over 5-10 years, building on the model of proposed EU UWWTD revision.

- Develop and harmonise product standards for recovered phosphorus (struvite, sewage sludge ash extracts), digestate, compost, and reclaimed water to enable integration into formal agricultural and industrial value chains.
- Implement carbon pricing mechanisms that encompass the waste sector, unlocking carbon revenue streams for CERR investments.
- Integrate CERR performance indicators into utility regulation, service quality benchmarking, and public procurement requirements for waste management services.
- In LMICs: prioritise governance strengthening and institutional capacity building at municipal level over technology specification, and ensure that CERR policy development processes meaningfully include informal waste sector stakeholders.

For Wastewater and Solid Waste Utilities

- Conduct facility-specific resource audits (using the MFA methodology described in this dissertation) to quantify recoverable resource flows and prioritise investment pathways.
- Pursue phased integration of CERR technologies: begin with AD/CHP and struvite recovery as foundation technologies, then layer advanced biorefinery functions as operational experience and market development accumulate.
- Develop public-private partnerships with agricultural, energy, and chemical sectors to secure long-term off-take agreements for recovered products, de-risking investment decisions.
- Invest in workforce development: CERR systems require multi-disciplinary skills (biological treatment, electrochemistry, market development) not typically present in conventional waste utility organisations.

For Development Finance Institutions and Investors

- Develop CERR-specific blended finance facilities combining concessional capital with commercial co-investment, targeting mid-scale ($5-50M) CERR projects in LMIC urban areas currently underserved by existing finance.
- Apply the CERR-RI as a due diligence and portfolio monitoring tool, targeting investments to countries/cities with medium CERR-RI scores (0.35-0.60) where marginal impact of finance is highest.

- Require social inclusion plans as a condition of CERR project financing, ensuring that informal waste workers are incorporated into, rather than displaced by, formal CERR systems.
- Support development of voluntary carbon market methodologies for waste sector CERR activities (particularly anaerobic digestion and biochar) to unlock additional revenue streams for project viability.

For the Research Community

- Prioritise LMIC-adapted CERR research: invest in longitudinal studies, participatory design research, and open-access data platforms that directly support CERR implementation in underserved urban contexts.
- Develop and adopt standardised LCA system boundaries and functional units for CERR technologies to enable meta-analysis and evidence synthesis across studies.
- Advance life cycle social assessment (SLCA) methodology for the waste sector to adequately capture distributional and livelihood implications of CERR transitions.
- Pursue interdisciplinary research programmes integrating engineering, economics, governance studies, and social science to address the inherently multi-dimensional nature of CERR implementation challenges.

In closing, the transition from linear waste disposal to circular resource recovery represents one of the most consequential and achievable environmental transformations available to cities and nations in the coming decades. The technologies exist, the environmental case is overwhelming, and the economic fundamentals are increasingly compelling. What remains required is the political will, institutional coherence, financial innovation, and equity-conscious implementation to convert potential into practice. This dissertation has sought to provide the evidence, frameworks, and recommendations to support that transformation.

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Appendices

Appendix A: MCDA Scoring Matrix – CERR Technologies

Technology	Technical Maturity	Environmental Benefit	Economic Viability	Social Acceptance	Regulatory Compatibility	TOPSIS Score	Rank
Struvite Crystallisation	9	8	7	7	8	0.74	1
AD + CHP (Sewage Sludge)	9	8	8	7	8	0.73	2
Food Waste AD	8	8	8	6	7	0.71	3
Composting (Source-sep.)	9	7	6	8	8	0.69	4

Water Reclamation (MF-RO)	8	7	7	6	7	0.65	5
THP + Enhanced AD	8	9	7	7	8	0.72	2*
Ammonia Stripping	7	7	6	6	7	0.60	6
Microalgae Cultivation	5	8	4	6	6	0.52	10
Bio-Electrochemical Systems	4	7	3	6	5	0.43	13
Hydrothermal Liquefaction	4	8	4	5	5	0.45	12
PHA Production	4	7	4	6	5	0.44	12*
BSF Larvae Bioconversion	5	7	5	5	5	0.50	11
Urban Mining (e-waste)	7	8	7	6	7	0.64	5*
Pyrolysis/Biochar	5	7	5	6	5	0.51	11*

Appendix B: CERR Readiness Index – Selected Country Scores

Country	Regulatory	Technical	Market	Finance	Governance	Social	CERR-RI Score
Netherlands	0.92	0.88	0.85	0.87	0.84	0.78	0.81
Germany	0.90	0.91	0.83	0.85	0.82	0.76	0.80
Singapore	0.88	0.89	0.78	0.88	0.90	0.70	0.79
Sweden	0.91	0.87	0.82	0.83	0.85	0.79	0.80
Japan	0.85	0.90	0.75	0.82	0.80	0.68	0.76
United Kingdom	0.82	0.85	0.80	0.84	0.79	0.72	0.75
USA	0.70	0.88	0.80	0.85	0.72	0.65	0.72
China	0.72	0.78	0.65	0.70	0.55	0.50	0.61
Brazil	0.62	0.68	0.60	0.62	0.52	0.48	0.57
India	0.55	0.65	0.55	0.58	0.48	0.42	0.52
South Africa	0.58	0.62	0.52	0.60	0.50	0.40	0.52
Kenya	0.40	0.42	0.38	0.42	0.38	0.36	0.38
Nigeria	0.32	0.38	0.32	0.38	0.30	0.32	0.33

Ethiopia	0.28	0.30	0.25	0.30	0.28	0.28	0.27

Project

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