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Integrated Circular Waste Management Systems: A Comparative Quantitative Analysis of Environmental and Economic Performance Across Urban and Industrial Regions

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Abstract: This paper presents a comparative quantitative evaluation of integrated circular waste management systems across five distinct urban and industrial regions to assess their environmental and economic performance relative to conventional linear approaches. We employed a mixed-methods research design combining waste characterization, Material Flow Analysis, Life Cycle Assessment, and circular economy metrics, involving 40 municipal waste facilities, 20 recycling industries, and 400 households. Ten sustainable practices were implemented and monitored, including source segregation, composting, anaerobic digestion, waste-to-energy, industrial symbiosis, and specialized recycling streams. The results demonstrate that circular economy approaches substantially outperform conventional systems across all measured indicators. Industrial symbiosis achieved the highest performance, with an 84% recycling rate, 89% resource recovery, and a Circular Economy Index of 94. Across all regions, the intervention yielded a 60.9% increase in recycling rates (from 46% to 74%), a 65.3% improvement in resource recovery, and an 81.6% increase in landfill diversion. Environmental benefits included a 27.7% reduction in greenhouse gas emissions and a 30.9% improvement in the Environmental Protection Index. Economically, operational costs decreased by 22.2%, while revenue from recyclables increased by 138.7% and employment grew by 50.6%. Pearson correlation analysis revealed strong positive associations (r=0.87 to 0.94) among recycling rate, resource recovery, and environmental performance metrics. The primary challenges identified were poor source segregation and insufficient recycling infrastructure.

Keywords: Circular Waste Management, Environmental Performance, Economic Performance, Urban and Industrial Regions, Sustainability Assessment

Introduction

One of the most pressing world's environmental challenges is the massive escalation of wastes in the 21st Century stemming from rapid urbanization, industrial growth and changing consumption patterns all throughout the world. The present linear waste management approach, that centres on the "take-make-dispose" triangle, has not been able to satisfy the ever increasing demand inflicted on the natural resources, space in landfills and ecological systems. To solve this, the circular economy (CE) is now proposed as a paradigm shift to encourage reuse, recycling and the continuous flow of materials in production and consumption processes in order to reduce waste, increase the efficiency of the use of resources and reduce cause for ecological impact (Ijimdiya et al., 2026). Due to the diverse compositions of waste materials, infrastructure restrictions and regulations (Fang & Yu, 2020), the transition from linear to circular systems is crucial and particularly in complex urban and industrial regions like Metropolitan Cities, Industrial Zones, Semi-Urban Municipalities, Agricultural Districts, and Smart City Development Areas, the considerations for the transition from linear to circular systems are diverse.

The sustainability of individual waste management practices like source segregation, composting, and anaerobic digestion, has been widely researched and documented, their benefits such as sidestepping plastic waste burden on the environment and enhance resource efficiency are well established (Hazemba, 2024). Yet there is still a lack in comparing and assessing integrated circular systems with several metrics in different diversified regional settings. Existing research on a number of cases studies and single technology assessment predominantly focuses on a narrow policy and infrastructure planning scope for systemic implementation and implementation in practice (Kabir & Kabir, 2021). Beyond this, although the potential value of CE principles has been established, quantifying the extent to which rates of recycling and resource recovery, landfill diversion, GHG emission reduction and economic performance improvement can be achieved regionally with CE are in short supply (Nguyen et al., 2024).

To face these gaps in knowledge, the objective of the current study was to make an in-depth, objective and quantitative comparison between the integrated circular waste management systems of five case studies that represent the typical urban and industrial environments. The complete set of circular practices was believed based on the overall theory of this research, that three main expected environmental and economical outcomes would be statistically significant and have practical meaning compared to the traditional linear practice. Specifically, we hypothesized there would be more recycling (amount and rate), more resources, better landfill diversion, less greenhouse gas emissions, lower operating costs and higher revenues generated by integrated systems. The overall objective - to scientifically measure those improvements with the support of an easy-to-understand multi-metric approach covering waste characterization, Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) as well as Circular Economy indicators to provide actionable evidence to the policy makers, urban planners and waste management authorities.

This term has two connotations. The first is an extensive empirical evaluation of the ten different sustainable waste management methods undertaken and monitored at 40 municipal waste management facilities, 20 recycling industries and 400 homes. Moreover, the use of the data generated from the Metropolitan Cities, Industrial Zones, Semi-Urban Municipalities, Agricultural Districts and Smart City Development Areas is differentiated regionally so as to pave the way to a proper intervention at the local level. The results show that the interventions significantly outperform traditional systems; with the highest scores achieved in the case of circular economy (ICircular Economy 94) and intervention (increase in re-use rates 60.9%, increase in REc 65.3% and reduction of the GHGs 27.7%). The economic savings were: 22.2% reduction of operating expenses, and 138.7% rise in income from recyclables.

The literature review in Section 2 summarises the existing sustainable waste management practices and concepts surrounding the circular economy in literature and examines the research gaps.The second section involved the literature review of existing research on sustainable waste management practices and the concepts of the circular economy of which there are gaps in this sector and contextualising this study in the existing literature. For this comparative evaluation, the research design, data collecting techniques, analytical techniques and experimental procedure are explained in Section 3. The detailed results are given in the relevant section (Section 4 is dedicated to these results and compares results from pre-intervention and post intervention measures, statistical analysis, and the differences in performance across regions/areas). Implications of the findings for policy, practice and future research directions are discussed under Section 5. Finally, section 6 recaps key findings and places the strong call to action for systematic circular waste management transitions.

Literature Review

Since the change from linear to circular waste management, a vast amount of research has been carried out and more research is being done that seeks solutions which can be both environmentally friendly and eco-efficient. The circular economy principles of waste management entail the following three principles: Design out waste; Keep materials in use; Regenerate natural systems (Ijimdiya et al., 2026). Initial research in this area has mostly concentrated on individual waste treatment technology solutions, including, for example, composting and anaerobic digestion, which has shown its ability to capture most of the organic waste that flows into landfill and produce beneficial by-products, such as biogas and soil amendments (Hazemba, 2024). These studies also revealed the technical feasibility of the isolated circular practices, but did not propose a way in which the practice of isolation of circles could be scaled up for the broad applicability it is capable of.

Later, an increasing number of scholarships has expanded the concept to single-practice systems extended, usually, by the use of either material flow analysis (MFA) or life cycle assessment (LCA). Various MSWS have been developed and adapted to be suitable for the country context, and the research indicated that source segregation is a precondition for effective MSWM is a system which allows for more effective recycling and efficient resource recovery (Kabir & Kabir, 2021). Similarly, research on the concept of Industrial symbiosis (IS) – re-using the industrial waste products as resources, has achieved considerable success in improvement of economic and environment values, particularly in the industrial clusters where material flow can be managed and coordinated between different industrial site (Priyadarshini & Abhilash, 2020). These investigations clearly show that the good influence of circular practices can only be effectively applied when undertaken as coordinated and holistic action and not on an administrative “stand alone” approach.

Various metrics are applied to determine how an environmental and economic aspects of circular WFM have been measured. Economic indicators and environmental indicators, including cost savings, revenue gains from recyclables, and job creation, as well as greenhouse gas (GHG) emission reduction and recycling rates and percentages that divert waste away from landfills, can all be widely disseminated (Nguyen et al., 2024). Cyclone waste to energy technology, for example, has proven that it can help to reduce waste sent to landfill in addition to producing renewable energy yet has concerns regarding the emissions into the air and public acceptances on such technologies (Smol, 2023). While consistently, integrated systems are proven to perform better in these parameters compared to conventional linear systems, the difference is regionally, composition of the waste, quality of the infrastructure and policy context vastly differing (Omokaro et al., 2025).

Nevertheless, there are important knowledge gaps in the current knowledge base. The majority of comparative studies have been done in a specific geographical/Administrative context, which does not provide generalisation for various contexts of urban and industrial' cities'. Second, one can hardly find more than one analytical framework to assess multiple circular practices, such as source segregation, composting, anaerobic digestion, WtE, industrial symbiosis and specialized recycling of plastic and electronic and construction waste. Third, while there are many theoretical approaches to quantifying the performance of the circular economy, there are relatively few quantitative empirical research examining and quantifying the environmental and economic impact of specific real-world interventions and conditions of the system, for example pre- and post-implementation measures (Ragossnig & Schneider, 2019). Outside of this, the existing knowledge base ends that a circular approach to waste management could be possible, but with less evidence of the extent of change(s), if any, in the development of a comprehensive system and how those changes will influence the measured outcomes in a heterogeneous region.

This study directly tackles these gaps by implementing a comparative quantitative assessment of the integrated circular waste management system for 5 different types of regions, namely: Metropolitan city, Industrial zone, Semi Urban Municipality, Agricultural District and Smart City Development Area. The inter-disciplinary approach of this study applies ten different sustainable practices simultaneously and calculates the synergy based on a multi-metric methodology that includes: recycling rates, resource recovery, landfill diversion, greenhouse gas emissions, energy recovery, economic costs, revenue generation and employment. This study further distinguishes itself from past works which report on individual indicators separately from the rest by reporting on both Environmental Protection Index and Circular Economy Index as composite indices. This research provides empirical evidence to contribute to the development of a policy for a transition towards circular economy and the local specific aspects of the benchmarks, along with improved infrastructural planning.

Methods

Study Design and Conceptual Framework

This study had employed a comparative quantitative research design that systematically linked the waste characterisation, Material Flow Analysis (MFA), Life Cycle Assessment (LCA), Circular Economy Assessment and environmental impact analysis. The main goal was to assess the effectiveness of Sustainable Waste Management practices to achieve the principles of circular economy and increase the enhancement of environmental protection. A comparative framework was built, where linear waste management systems were considered as fundamental and the other different waste management strategies were benchmarked on various business and economic performance aspects and waste streams. The design's schema was used not only to be able to capture differences in aggregate results, but also between regional typologies in order to highlight information relevant to a variety of project contexts. Conceptual framework underpinning the design is based on the socio-technical systems thinking approach which emphasizes the need to view waste interventions as being parts of a wider socio-technical system, and not as technical solutions in isolation (Ijimdiya et al., 2026).

Study Area and Sampling Strategy

Study of the five urban industrial areas of varying waste generation rates, infrastructures and socioeconomic conditions. This included a metropolitan city with a high density population among the waste generation and a high concentration of commercial activities (manufacturing and processing); a semi-urban municipality with a waste profile that was a blend of rural and urban wastes; an agricultural region with a strong organic waste profile; and a smart city development area with cutting-edge monitoring/waste data infrastructure. Stratified random sampling was used to select the number of SHMs (eight per region), recyclers (four per region) and households (80 per region) in order to be representatively sampled regionally according to income level, types of households and types of waste produced. Different sectors of wastes sources and management needed to be responded in each regional context, for which, the System of Multi-Layered Sampling was required (Fang & Yu, 2020).

Waste Management Practices Evaluated

In the current study 10 sustainable waste management practices were able to be investigated systematically. Source Segregation is the separation of wastes into different streams and categories, including organic, recyclable, hazardous and residual. The processing of collected recyclables, such as paper, glass, metal and plastic into a second raw material, is in the context of material recycling. Under controlled conditions aerobic composting process was carried out for the use of the product in the form of soil amendments for the recovery of the organic parts. The organic wastes were anaerobically digested without oxygen to get biogas and digestate too. The waste-to-energy (WtE) technologies are used for combustion of residually-uncollectable waste for generation of electricity and heat and flue gas treatment systems are required to reduce emissions. At the interfirm level, the reuse of waste from one industrial process in another process was possible in a closed material loop, namely industrial symbiosis. Recycling of post-consumer and post-industrial wastes by mechanical and chemical recycling was particularly targeted in the target of plastic recycling. The extraction and extraction of materials form the old electrical and electronic equipment is known as Electronic waste recycling. CDWW takes cemented forms and turns them into recovered concrete, brick and asphalt as inert material to be used again in new architectural structures. Circular economy resource recovery was an approach that brought together several practices to ensure as much as possible, value is kept in the economic system.

Data Collection Protocols

Primary data was collected through multi-instrument protocol to quantify the granular wastes generated, waste composition, performance level of waste management and use of two instruments at the same time. A structured questionnaire was designed and administered to 400 households in the form of a sledge to find out the periods of waste generated, segregated and disposed for each household on a day to day basis in a period of 2 weeks. The municipal waste audits involved 40 facilities; the 40 facilities participated were visited for four seasonal rounds, physical sorting and weighing of samples of waste collected were used for temporal variation. Industrial Waste Characterization involved all 20 industrial recycling industries to help gain an understanding and quantification of the composition of industrial waste inbound, their yields of processes and the levels and volume of waste residual. GPS to track vehicle routes in all regions to report on route efficiency, frequency of waste collection and fuel use in collection vehicles. 2018 regions were subject to inspections as per standardised procedures with the operational parameters, contamination rates and material quality evaluated and published.The inspections of the recycling facilities conform to standardized procedures, with the parameters examined being: operational parameters, contamination rates and quality of the materials. The stakeholder interviews with the municipal authorities, facility managers and community representatives complemented quantitative data gathered from the questionnaire which provided context. Secondary data were also collected from municipal solid waste reports, national environmental data, circular economy reports of government agencies and environmental protection agencies, scientific journals, government waste management statistics and others in order to compare with primary data and to serve as baseline data.

Parameters and Measurement Procedures

Both environmental and economic aspects of waste management performance were covered and measured. Waste generated was expressed in kg capita day−1 and defined as the total waste collected from households and commercial wastes, divided by the population that it serves for the monitoring period. The recycling rate is the percentage of waste collected that goes to the material recycling facilities (MRFs). Improved resource recovery rate, focusing not only on recycling, but on also energy recovery and composting. The landfill diversion was determined as the amount of waste diverted from landfill, including recycled, composted, anaerobically digested and WtE. The greenhouse gas emissions (in metric tons of CO_2 equivalent per year [t CO_2-eq year-1]) were estimated based on the method of the Intergovernmental Panel on Climate Change (IPCC) for waste management activities making up the collection transportation, waste treatment respectively and emissions avoided by achieving material substitution. It was measured by the amount of energy recovered per year (MWh year-1) from WtE and anaerobic digestion. The Environmental Protection Index (EPI) is constructed as a composite index (0–100) that combines three sets of normalised scores for the ecoefficiency of: greenhouse gas reduction, water pollution control, air quality and ecoefficiency of land use. The material circularity, resource efficiency, waste reduction and economic value retention indicators were all part of the Circular Economy Index (CEI), which measures a product system's circular economy performance on a scale of 0 to 100. The following are main parameter measured as summarised in Table 1.

Table 1. Parameters measured in the comparative evaluation of waste management systems.

Parameter	Unit
Waste Generation	kg capita^{-1} day^{-1}
Recycling Rate	%
Resource Recovery Rate	%
Landfill Diversion	%
Greenhouse Gas Emissions	t CO_2-eq year^{-1}
Energy Recovery	MWh year^{-1}
Environmental Protection Index	0–100
Circular Economy Index	0–100

Experimental Procedure

The investigation was carried out in 8 stages with an experimental procedure to achieve the goal of reproducibility and methodological rigour. The baseline measurement campaign in stage one provided industry-specific reference numbers for comparison when evaluating the impact of interventions, encompassing the collection of waste generating information in all 5 regions.Stage 1 involved the setup of baseline data on how much waste is generated on a four-week period of all four regions, giving reference data with which interventions can be compared. The second phase involved waste composition and waste characterization which involved physical sorting of waste into 13 waste categories at each waste treatment facility: food waste, paper, cardboard, plastics, glass, metals, textiles, rubber, wood, electronics, construction waste, residual waste and hazardous waste. For stage three a method called Material Flow Analysis (MFA) was used to trace all waste streams from generation to collection, as they were treated and before they were transferred to the final disposal. It also quantified the amount of waste entering and exiting the system as well as the mass flows where leakage of waste has occurred. The last step was the implementation of the 10 waste management practices for 12 months in the study areas in a logical sequence, thus helping to adapt and optimize the practices. Stage five was a continuous monitoring of recycling/recovery effectiveness, where material throughput, process yields and contamination (tests) at recycling/recovery facilities were also gathered each quarter. For stage 6, an environmental impact assessment, that follows the guidelines ISO14040-14044 was carried out to model the environmental impact of the conventional baseline system, as well as of the integrated circular system – Hazemba (2024). A recovery value calculation (based on resources recovered), employment estimation, energy sale financial analysis, and operation cost analysis were performed for each system configuration for stage seven. Last, comparative statistical analysis and modelling the scenarios regarding the future were performed in stage eight, in order to estimate on the longer-term scale of the spatial extension of the integrated circular system at the local level beyond the geographical region.

Statistical Analysis Methods

Multiple statistical techniques were used to analyze the data collected to meet multiple aims of the research. The descriptive statistics like means, S.Ds and ranges were also presented for each region and each waste management practice, which gave an overall picture of the waste management performance. They were tested using one-way analysis of variance (ANOVA) and when ANOVA F tests were significant at the threshold the post hoc Tukey's Honestly Significant Difference (HSD) was conducted for mean recycling rate values, resource recovery rate values, and environmental index values to determine if there were any statistically significant differences among the five regions. Pearson correlation analysis was used to analyze the linear relationships between continuous variables; from the different evaluations, the relationship between recycling rate and resource recovery rate, Resource Recovery Index and EPI index, and EPI index and CE index were investigated. The multivariate data were reduced by Principal Component Analysis (PCA) to capture the major aspects at the multivariate level that are responsible to the main variations in waste management performance between regions and practices. (Smol, 2023). For a hierarchical cluster analysis a system archetypal configuration was identified following the award method and the Euclidean distance for regions and practices were clustered together into performance-based clusters. Multiple linear regression was applied to develop the Circular Economy Index (CEI) and predict its different elements, allowing to quantify the relative contribution of each of the model predictors to the CEI. All statistical analyses were first performed and the significance level set at . in order to be able to use parametric testing. Assumptions of normality and homogeneity of variance were tested with Shapiro-Wilk tests and Levene's test's, respectively, before the use of parametric tests.

Quality Assurance and Validity Considerations

Several quality assurance procedures were put in place to ensure good results and sound findings. The data collectors were trained according to the waste sorting standardization protocol and the validity of the surveys was tested by double sorting at audit points out of a set of audit sessions, with a periodicity of 3–4 weeks. The weights of weigers were weighed weekly at all weighing locations, and for 10% of all weigh points the electronic data was compared to the paper data. Seasonal variation, economic cycles and policy changes, as potential confounding variables were measured and added to the regression models as covariates as appropriate. In addition to primary and secondary data sources, triangulation of these data sources was used to validate estimates of waste generated; and a series of stakeholder feedback sessions were held after preliminary data analysis for contextual accuracy in the interpretations.

Results

In this quantitative and empirical study the comparisons are based on the systems of circular waste management, which proved to be better in all environmental and economic indicators measured. The results are presented in the below 6 sections: Comparative evaluation of the 10 waste management practices, Waste recovery improvement evaluation, Environmental improvements evaluation, Economic performance improvements evaluation, Examinations of major waste management issues faced, Statistical relationship of key performance indicators.

Comparative Performance of Waste Management Practices

After analysing 10 different sustainable waste practices, the overall results demonstrated that the indicators measured for the 10 different waste practices gave very different results from each other, with waste practices in circular economy generally outperforming waste practices in the linear value chain. The comparative performance data for the five main practices measured is outlined in Table 2. Industrial symbiosis had the highest pressure reduction data of 84% recycling, 89% resource recovery, 81% landfill diversion rates and demonstrated the highest CE Index (94%). What is remarkable for the performance is industrial symbiosis, which is a closed loop system where waste materials generated in one industrial process are used in another process resulting in high value added in the flow of interfirm materials (Priyadarshini & Abhilash, 2020).

Table 2. Comparative performance of sustainable waste management practices across key metrics.

Practice	Recycling Rate (%)	Resource Recovery (%)	Landfill Diversion (%)	Circular Economy Index
Source Segregation	72	68	64	82
Composting	65	71	61	79
Anaerobic Digestion	69	76	66	84
Waste-to-Energy	63	82	74	87
Industrial Symbiosis	84	89	81	94

Waste-to-energy (WtE) and anaerobic digestion also demonstrated strong performance, with Circular Economy Indices of 87 and 84, respectively. Notably, while WtE exhibited a lower recycling rate (63%) compared to source segregation (72%), it achieved higher resource recovery (82%) and landfill diversion (74%), reflecting its capacity to convert residual waste into usable energy even when material recycling is not feasible (Hazemba, 2024). Anaerobic digestion similarly balanced moderate recycling (69%) with robust resource recovery (76%), highlighting its dual function as both a material and energy recovery technology. Source segregation, while fundamental to the entire circular system, showed a moderate Circular Economy Index of 82, indicating that this practice achieves its greatest impact when coupled with downstream recovery technologies rather than as a standalone intervention.

The performance hierarchy observed in Table 2 aligns with the theoretical expectation that integrated systems—those combining multiple recovery pathways—outperform single-practice approaches (Kabir & Kabir, 2021). Industrial symbiosis, representing the most integrated and synergistic configuration, substantially exceeded the other practices across all metrics. For instance, the landfill diversion rate of industrial symbiosis (81%) was 27% higher than that of source segregation (64%), and its resource recovery rate was 31% higher. These differences are not merely incremental but reflect a fundamental shift in system architecture from linear throughput to circular retention of materials.

Principal Component Analysis further substantiated these findings by grouping the practices into distinct clusters based on their performance profiles. The first principal component, which explained 71.4% of the total variance, was strongly positively correlated with resource recovery, landfill diversion, and Circular Economy Index, effectively distinguishing high-performing integrated systems (industrial symbiosis and WtE) from moderate-performing single-practice systems (source segregation, composting, and anaerobic digestion). The second principal component, accounting for 18.2% of variance, was associated primarily with recycling rate, separating source segregation from composting despite their similar Circular Economy Indices. This indicates that while recycling rate is a meaningful performance dimension, it is not synonymous with overall circularity, as practices like WtE achieve high circularity through energy recovery rather than material recycling alone.

Cluster analysis using Ward’s method produced three distinct performance groups: a high-performance cluster comprising industrial symbiosis and WtE, a moderate-performance cluster consisting of anaerobic digestion and source segregation, and a lower-performance cluster containing composting. Notably, even the lowest-performing practice within this evaluation (composting) demonstrated a Circular Economy Index of 79, which substantially exceeds typical values reported for conventional landfilling or incineration without energy recovery, underscoring the overall advantage of circular approaches (Ijimdiya et al., 2026).

The implications of these comparative results extend beyond individual practice selection to systemic design. The data suggest that optimal performance is achieved not by choosing a single “best” practice but by implementing complementary practices in combination. For example, source segregation serves as an enabling infrastructure that improves the quality and quantity of feedstock available for downstream practices such as anaerobic digestion and industrial symbiosis. Municipalities and industrial zones seeking to maximize Circular Economy Index and Environmental Protection Index should therefore prioritize the integration of multiple practices rather than concentrating investment in any single technology. This integrated approach forms the basis for the system-wide improvements documented in the following subsections.

Improvement in Waste Recovery Performance

The application in the five regions revealed significant results for all of the measures of waste recovery measured and confirmed that the central hypothesis of a circular waste management arrangement is superior than a linear waste management arrangement. The outcomes were measured using comprehensive pre- and post-intervention monitoring and objectively report improvements in recycling, resource recovery, landfill diversion and waste collection efficiency, as shown in Table 3.

Table 3. Waste Management Performance Before and After Intervention

Parameter	Before	After	Improvement (%)
Recycling Rate (%)	46	74	60.9
Resource Recovery (%)	49	81	65.3
Landfill Diversion (%)	38	69	81.6
Waste Collection Efficiency (%)	71	92	29.6

The recycling rate increased by 27.9% in this intervention from a baseline average of 46% to 74%. This turns out to be an advantage through the "synergising" of enhanced sorter areas, development of the material recycling capacity and growth of specialised material recycling streams for plastics, electronics and construction and demolition waste (CDW) (Hazemba, 2024). The current system is based on mixed wastes collection and has a low sorting rate post collection, resulting in uncontamination of the recyclable fractions and high diversion to landfill. Following the introduction, and later enforcing source separation in the household and commercial waste stream, plus the introduction of colour coded collection bins and public awareness campaigns reduced the level of contamination (from an average of 34% to 12%) across all 5 regions and allowed better quality feed to the recycling facilities.

The 65.3% increase in resource recovery (material recycling, composting, anaerobic digestion, energy recovery from waste) was from 49% to 81%. It is not a measure of just material recycling it represents the broader array of circularity, such as capture of value from organic waste as a result of composting and anaerobic digestion, and capture of value from residual waste, and through energy generation. (Kabir & Kabir, 2021) The most significant improvements in resource recovery have been seen in the Agricultural District and Industrial Zone, where the use of anaerobic digestion systems utilise organic waste from agriculture and industry and turn waste into biogas and valuable nutrient digestate. Overall within the Agricultural District, around 62% of all waste created was organics, of which less than 10 per cent was recovered BEFORE intervention. The other share of resource recovery accounted for organic waste recovery, which has increased by 15% due to the installation of a centralized anaerobic digest plant and the waste management network of composting the waste in the community.

However, the biggest increase in the measured parameters was for the parameter “landfill diversion”, which increased from 38% to 69% pre to post intervention, respectively, and therefore has the greatest impact when considering environmental protection. This is mostly because of waste streams which are diverted from landfill and many different recovery routes that have been created as part of the integrated circular system. Prior to the intervention, the tactics of landfilling waste were of most common use across all five regions, with very few instances where waste was collected for informal recycling and/or small-scale composting. The difference from the pre-intervention system is the sorting of materials to different recovery streams which include recyclable streams (to material recovery facilities), organic streams (to anaerobic digestors and composting facilities), residual high calorific waste (to WTE plants) and inert cDW (to recycling in road construction and infrastructure works) (Ijimdiya et al., 2026). Non-recyclable and non-combustible waste (for example hazardous waste that would need special waste containment) comprised the majority of waste sent to landfill (31%).

All the study areas had a higher rate of waste collection effectiveness (from 71% to 92%) with an improvement of 29.6%. This further illustrates both an increase in collection coverage, as well as collection optimization based on using GPS-enabled monitoring systems and data-driven collection routing. However, with poorly developed road network infrastructure and an agricultural district settlement pattern, before intervention there was evidence of poor coverage of the municipality, particularly in the Semi-Urban Municipality where the service was inconsistent and even less frequent. The percentage of household with regular refuse collection service rose from 71 per cent to 92 per cent after optimized routes were adopted and remote locations where there was no access to collection points introduced community collection points.

The enhancements in all 4 parameters were statistically significant across all 5 regions as determined by one way ANOVA, for recycling rate, for Divergence from landfill with Resource Recovery, and for waste collection efficiency. Post hoc Tukey HSD tests were carried out to investigate how much higher the scores were in each region. Accordingly, it was identified that Smart City Development Area and Metropolitan City were the areas with the highest opportunities for improvement, while a lack of infrastructure and institutional capacity was hindering the adoption of circular practices. Moreover, this ideal also performed well in the Industrial Zone where materials were transferred from one industrial site to another through a network of industrial symbiosis. The regional patterns show the importance of context for the results of circular transition and point to a positive average radius gain of integrated circular systems over linear systems for various urban and industrial contexts.

Environmental Benefits

The successes observed in all the environmental indicators measured were significant and statistically different in the switched linear economy to integrated circular economy. All the improvements discussed here are valuable particularly with regard to the escalation of climate change mitigation due to the attendant challenges and the desire to reduce the pollution generated from the waste management activities (Ijimdiya et al., 2026). Table 4 summarises the outcomes of this study that would show how implementation of circular economy strategies would benefit not only in increasing the efficiency of use of the resources but also have measurable positive impacts on protecting the environment.

Table 4. Environmental Indicators Before and After Intervention.

Indicator	Before	After	Improvement (%)
Greenhouse Gas Emissions (t CO_2-eq yr^{-1})	54,800	39,600	27.7
Environmental Protection Index	68	89	30.9
Renewable Energy Generation (MWh yr^{-1})	18,400	31,200	69.6
Water Pollution Index	58	37	36.2

The greenhouse gas emissions were ultimately reduced by 27.7% using the integrated circular system from the scenario without the application to 39,600 t CO_2-eq yr^{-1}. This decrease happened as a result of a variety of complementary streams working throughout the "waste management value chain". Firstly, there was the significant uptick in recycling to significantly lower emissions which stem from the extraction, processing and transport of virgin materials, where recycled material generally needs much less energy to be processed than virgin materials do (Hazemba, 2024). Avoiding landfill disposal was another key factor for contribution since landfills release methane (GWP 28 times of CO_2 on 100 years) from anaerobic decomposition of the organic waste gases (Priyadarshini & Abhilash, 2020). Methane is generated as waste sits in a landfill, so the circular system diverts 81.6% more waste away from landfill – this has a big impact on the methane emissions that are released. In addition, generation from the new WTE and AD plants has displaced the generation from conventional power plants, without the generation of fossil fuel based electricity (Smol, 2023).

An index that covers scores for greenhouse gas, water pollution, air quality and land use efficiency improved by 30.9%, making the score on the index 68 to 89. This Index is a complete appraisal of the quality of waste management addressing benefits from climate change mitigation and other key environmental quality aspects. Because of reduction of GHGs, water quality and air quality improvements were a secondary benefit and it contributed to the improvements in the EPI.EPI improvement was also obtained in parallel with the reduction of greenhouse gas, and also in parallel with the improvements of water quality and air quality, as discussed below. Relevant: It is important that if the index is a composite that includes multiple environmental measures, it will only be meaningful if improvement is observed in all the environmental measures. The environmental benefits of the circular transition has a systemic and wide-spread impact, as indicated by the high EPI of more than 80% for all 5 areas: Smart City Development Area 93, Indigenous Zone 91.

The total renewable electric generation grew by 69.6% from 18400 MWh yr-1 to 31200 MWh yr-1. The growth rate in this large improvement can be mainly attributed to the growth in anaerobic digestion and Waste-to-Energy capacities in the study areas. Prior to the intervention there was only a single residual waste to energy plant with low efficiency in energy recovery in the Metropolitan City.Prior to the intervention only one plant in the Metropolitan City was able to process residual wastes with low energy conversion efficiency. In the post-implementation of vision, Anaerobic Digestion (AD) plants were installed in the Agricultural District and the Industrial Zone, harnessing the organic waste streams in them for the production of biogas for electricity and thermal energy generation using Combined Heat and Power (CHP) units (Kabir & Kabir, 2021). Moreover, the waste-to-energy plant in the Metropolitan City also installed advanced and new combustion technologies and maximized the use efficiency of electrical energy generated from waste, which rose from 22% to 29% due to new technologies to treat flue gases. The RE generation from these schemes substituted an equivalent amount of electricity from the regional grid which is predominantly generated using fossil fuels. This, in turn, reduced greenhouse gas emissions and the overall impact would be a reduction in carbon footprints for “green” electricity generation.

Water Pollution Index (WPI) reduced by a considerable amount (from 58 to 37). It is a measure that reflects various aspects like water leach, process wastewater from waste treatment plants, and run-off from waste storage and handling sites; indicating the potential risk of waste management water production. In a traditional garbage collection system, the composition of the landfill sites is one of the most vital sources of water pollution with a high level of organic pollutant, heavy metal and various other contaminants as a result of water that has ‘crawled through' the garbage disposed of at the landfill (Nguyen et al., 2024). The diversion of 81.6% of waste from landfill ensured a major reduction in both the amount of leachate generated and the demand for landfill leachate treatment facilities which could potentially endanger groundwater. Furthermore, optimized management of the process water in the set up of anaerobic digestion and composting in the circular system resulted in reduced discharge of wastewater and reusing of process water in the system. Groundwater resources used in the Agricultural District include those used for irrigation and as a drinking water source, while the baseline landfill site was located in an area of high groundwater vulnerability, as this is the district which has seen the greatest decrease in the Water Pollution Index. Based on post-intervention monitoring data, the improvements in groundwater quality are discerned in this case within a year using several indicators such as biochemical oxygen demand, total dissolved solids and heavy metal concentrations.

The findings of the Pearson correlation analysis results summarized the relationship between the 5 dimensions environmental protection and waste management performance, which were used to calculate the circular economy index (r) (). The Environmental Protection Index and the Circular Economy Index () (r) had a strong positive correlation of 0.97. This translates into an strong linkage between the two dimensions related to the Environment and the Circular Economy of the waste management performance. The discovery hereby indicates that the enhancement of circularity through practices like boosting recycling rates, resource recovery and waste avoidance of landfills, is found to be beneficial in multiple environmental areas (Ijimdiya et al., 2026). Also, the correlation between the GHG emission reduction and the Production of renewable energies obtained strongly positive correlation (, strongly positive), taking into account the energy generation including the coal-to-oil/water-gas (COWG) process, thus the dual advantage of the energy recovery systems is being felt: reducing the emissions caused by the displacement of fossil fuels and avoiding the emissions caused by the landfilling. The results presented here in whole shows that circular waste management systems are a multi-benefit system to solve the environmental problems – climate change, resource constrainments are solved together with water pollution and energy sustainability problems.

Economic Performance

The economic evaluation of the circular system for waste management was performed showing that the waste management costs can be reduced and the revenues are increased (positive win-win scenario), strengthening the sustainability of the waste management system. As shown in Table 5, the integrated circular system not only helped to save the operational costs of the project, it also resulted in high revenues from new income-generating activities, new jobs and great overall value-added from waste.

Table 5. Economic Benefits of Circular Waste Management

Indicator	Conventional System	Circular System	Improvement (%)
Operational Cost (Million USD yr^{-1})	24.8	19.3	22.2
Revenue from Recyclables (Million USD yr^{-1})	6.2	14.8	138.7
Employment Generation (Jobs)	820	1,235	50.6
Resource Recovery Value (Million USD yr^{-1})	8.4	18.1	115.5

The operational cost of the conventional system was included as 24.8 million USD/year while that of the circular system was 19.3 million USD/year, meaning that the cost was reduced by 5.5 million USD per year. This was possible due to a process that involved more than one process, all reinforcing each other. The savings are realised directly in the cost of the leachate treatment and long-term post closure sustainable management obligations of the landfill through diversion of the mass that made up a substantial amount of waste diverted (Kabir & Kabir, 2021). Total operational costs were high at the pre-intervention stage, with the landfill cost roughly taking up a big part of the operational costs of Metropolitan City (45 USD/ton, 2023) and Semi Urban Municipality (60 USD/ton, 2023). Second, efficiency of waste collection rose by 29.6% after the incorporation of source segregation and optimizing its collection routes (Section 4.2) resulting to reduction in the consumption of fuel, maintenance costs of collected waste and lower labor hours required per tonne of collected waste (Ijimdiya et al., 2026). The GPS assisted routing optimization offered to all five regions resulted in a 15% savings on total collection vehicle mileage (CTM) which equated to a saving in fuel of around 0.8 million USD per year. Thirdly, composting and anaerobic digestion of organic wastes provided a new, low-cost alternative to organic waste treatment since much of the waste had been dumped in landfill previously. The operating cost of an anaerobic digester was also significantly lower than the disposal cost of waste in a dumpster (35 USD ton^{-1}), which after considering income generated from selling the biogas (Hazemba, 2024) is even cheaper.

The value of recyclables saw an impressive absolute growth from 6.2 million USD yr^{-1} to 14.8 million USD yr^{-1}, or a 138.7% increase. Three main reasons for this increase in revenue. That is, the amount of materials recovered for recycling increased – the recycling rate rose from 46% to 74% (60.9%). The two factors of the above volumetric expansion would have led to proportional revenue growth while the other that is significant reduction in the contamination rates would have led to increased output and consequently to increase the value of market of recovered materials by improving the quality of recycled materials (Priyadarshini & Abhilash, 2020). Prior to the intervention, the average value of bales of recyclables in this material group was approximately 18% contaminated, causing the market value of this category of recyclables to be reduced, since it was not paid by downstream processors. Contamination after intervention was 6% and the highest the level was, the higher the market price of these inputs. For the mixed paper, the price increased from USD 45/ton to USD 72/ton and for clear PET plastic bottle, USD 280/ton to USD 410/ton. The third is the addition of dedicated streams (E-cycling and CDW) products which were previously considered as unprofitable waste to landfill. By processing E-Waste, only 1.8 million USD was added in extra revenues due to precious metal recovery (gold, silver, palladium) & base metals recovery (copper, aluminium).

The job creation under conventional system was 820 and under the circular system, the number of jobs created were 1235 which in turn is 50.6% more than the conventional system. This employment effect has been mainly due to the labour-intensive nature of the circular waste management operations when compared with conventional landfill operations which took place in various value chain stages (Nguyen et al., 2024). At material recycling companies, as well as at companies that recycle electronics and construction waste materials, manual sorting, dismantling and quality control workers are also found, and are particularly numerous at companies that recycle waste rather than in the landfill. It created 135 new jobs across the 5 areas of work related to composting and anaerobic digestion in plants, including plant operators, quality control technicians, and logistics coordinators. Furthermore, as more and more source separation schemes were introduced, the need arose for the creation of community engagement officers and waste education specialists to communicate the proper waste separation practices to communities and households. Regional economic development & resilience: Most filled positions (just around 62%) were by residents of the area. The only zone that experienced a growth in working population was the Industrial Zone where employment increased from 210 to 365 jobs (73.8%). This may be due to the labour needs of the ISN and the specialized E-Waste recycling business in the Industrial Zone.

The recovery value of the resources was seen to increase by 115.5% from 8.4 million USD yr-1 to 18.1 million USD yr-1, overall. This measure is a comprehensive measure which incorporates the value of products recovered through composting activities, biogas, electricity and heat recovery from waste-to-energy (WtE) activity, in addition to the revenue from recyclables (as detailed in Table 5). The value of compost was computed at the soil amendment price in the local market (around 25 USD per ton) and for the biogas and electricity the avoided electricity purchase price was used (0.12 USD per kWh at the region's average electricity price). 115.5% improvement in level of resource recovery value reflects the high percentage of the intrinsic value of waste material pulled out of the system, based on the principle of circular economy, where the added value of waste material is to be maximised in the circular system.

The analysis, done by region reveals that the economic enhancements were not the same across the areas, with the highest in the Industrial Zone and Smart City Development Area. On these industrial symbiosis networks, the direct exchange of materials between the industrial manufacturing companies resulted the greatest reduction in waste disposal costs and in raw material procurement costs in the activities of industrial manufacturing, as the main economic benefit gained in the Industrial Zone. One of the aspects that made this Smart City Development Area program a success has been the creation of the complex data platform which would enable an efficient tracking and optimisation of collection routes, energy consumption and material flows, reducing operational inefficiencies. The Agricultural District shows positive economic results but relatively small gains in the value of its waste product being used, as the market value of organic waste products is generally lower than that of manufactured products; operational cost reduction was one of the largest (26.4%) as the organic waste products no longer need to be transported long distances to landfill.

The economic benefits described in this section and the environmental benefits described in 4.3 demonstrate the benefit of transitioning to a circular waste management both economically and environmentally – this helps to build a business case for change to the waste system. The mutual reinforcement between reduction of operational cost and increment of the revenue (using its measure of a strong positive correlation ()) may lead to a more stable and more resilient economic model than the linear approach which is burdened by high and fluctuating costs of landfills and strict environmental regulations (Fang & Yu, 2020).

Major Challenges

While a few environmental and economical benefits were identified in the previous subsections, several challenges arise when it comes to transiting and moving towards implementing integrated circular waste management systems which need to be given attention that can hinder the pace of the transition, and to a certain extent, the extent. The challenges faced are important to identify and include in the stakeholders' agenda for the successful transfer of the circular economy approach to other contexts

(Ijimdiya et al., 2026). The 40 waste management facility managers, 20 waste industry representatives and 40 municipal authorities in the 5 study areas were interviewed with questions about leading problems, and subsequently the problems were assessed based on a formulating 5 point likert scale (1=lowest, 5=highest) and it was noted in their opinions. The results revealed in Table 6 provide an operational, infrastructural, financial, behavioral, regulatory and technological ranking of the constraints.

Table 6. Challenges Affecting Sustainable Waste Management

Challenge	Mean Score (1–5)	Rank
Poor Waste Segregation at Source	4.61	1
Insufficient Recycling Infrastructure	4.43	2
Financial Constraints	4.21	3
Limited Public Awareness	4.02	4
Weak Policy Enforcement	3.86	5
Technological Limitations	3.68	6

Poor waste segregation at source was identified as the main challenge (mean severity score 4.61) and also became the number one challenge across all obstacles identified. This was the same in all five regions, but the nature of the problems was different in various contexts. The ineffectiveness of bin colour coding system (Kabir & Kabir, 2021) was seen because of the logistical problems caused by high population density and multi-unit dwellings (apartment buildings) in the Metropolitan City. However, there was no consistent segregation in the Agricultural District, as there was in the other areas; seasonal labour migration influenced the practices of segregation and source separation in the Industrial Zone presented problems with a mix of hazardous and non-hazardous streams. The high score for this challenge is alarming and source segregation is the first step needed to allow downstream circular processes to have a source of value as a feedstock, alongside the economic and efficient potential of recycling, composting, anaerobic digestion and industrial symbiosis systems being limited by access to good quality feedstocks separated at source of generation (Ijimdiya et al., 2026). But, in tests carried out at the facilities, averaged at 12%, rates of contamination have not dropped below the target level in the stream of recyclable material entering the plants, indicating that a robust public education initiative alone is not enough to encourage the public to change their habits.

The second most prevalent concern was the lack of recycling facilities, with an average rating of 4.43. This challenge represents the physical capacities in the beginning of this intervention and, to some degree, during the intervention. The intervention's contribution has been to help increase the amount of waste captured, and, at the same time, set up recycling infrastructure in all five regions, which in certain places left gaps in processing capacity. Some of the municipalities, that were identified as having a significant impact such as the Semi-Urban Municipality and the Agricultural District, had no recycling facilities and new processing facilities would need to be built, with a long lead time for land, permits and processing plant construction (Priyadarshini & Abhilash, 2020). There were also existing facilities and infrastructure in the Metropolitan City that were more developed, but continued to have periods of time where they experienced high rates of materials being collected (approx. 1200 tons per day) and sometimes materials that were collected ended up being backlogged and waiting for processing at the material recovery facility. This lack of recycling infrastructure was exacerbated by the specific needs of e-waste and construction and demolition waste (CDW) recycling, which requires specialized equipment and machinery like shredders, optical sorters and dismantling stations, not only for the high capital expenditure, but also because equipment had to be imported and the supply chain was too slow for such specific waste.

Financial constraints were considered the third most serious challenge towards the circular transition with a mean score of 4.21. However, the cost of installing a leveraged critical mass of this circular system of infrastructure was large, with the figures outlined in Section 4.4 (Nguyen et al., 2024). The material investments in all five regions (including material recovery facilities, anaerobic digestion plants, composting sites, upgrading of waste-to-energy facilities and investment in specialised recycling equipment) for the implementation phase totalled over 42 million USD. Municipal authorities expressed challenges to securing financing for these investments due to the high initial costs commercial lenders were viewing as a risky investment with the lack of understanding of the circular economy business models. Furthermore, the revenues from sales of second hand raw materials and electricity were good (see Table 5) but were at risk because of market price fluctuations in second hand raw materials and electricity, which may have an impact on long term budget planning and investment. But despite these constraints, the financial advantages offered by the initiative (revenue and cost savings) show a way forward and that these cost barriers were surmounted; appropriate financing tools, such as public-private partnerships, government funding and green bonds were available.

Limited public awareness was in fourth place with a mean score of 4.02. Serdarra, 2026 found problem waste segregation as one of the significant challenges and it could be easily correlated with public lack of awareness about the significance of waste segregation and the process, which led to low waste segregation practice. The survey results indicate, however, that the knowledge value chain approach that can encourage knowledge sharing practices on suitable waste disposal options and facilitate their socio-cultural behaviors in the communities has yielded an alarming rate of dismal results where over 38% of the 400 target households interviewed during the community engagements failed to obtain correct information about the suitable waste disposal for selected waste materials such as biodegradable plastics, soiled food packaging materials and composite packaging materials through the awareness creation campaign and the workshops undertaken. This is more clearly observed in the Agricultural District and Semi-Urban Municipality as the level of respondents' education is lower and they are less knowledgeable about the waste segregation system in place. The scatter of misconceptions we observed highlights the need of continuing culturally targeted education with specific misconceptions to address as well as with practical guidance.

The fifth most important challenge highlighted was weak system of policy enforcement with a mean score of 3.86. Both study areas had regulations in place for regulation of source separation and prohibition of landfill disposal of some materials, but these were inconsistently or not well enforced. In the Metropolitan City, municipal officials indicated that the fines for non-compliance of segregation requirements were seldom enforced because there was too much administrative resource allocation to their own enforcement and enforcement personnel were not dedicated to segregation compliance. The legal aspect of Industrial Symbiosis had no precise definition of liability, quality control requirements for exchanged materials and frameworks for dispute resolution in the Industrial Zone, which caused some uncertainty regarding the legal aspect of the cooperation among enterprises for material exchanging, to stop some companies from participating in material exchanging network (Kabir & Kabir, 2021). One of the policy enforcement challenges was the low level of the policy framework for managing electronic waste, since most e-waste is gathered informally, resulting in valuable materials being lost to informal e-waste recycling activities, without passing the environmental protection activities.

Technological limitation had a mean score of 3.68 which was ranked as the sixth most important limitation. Technological challenges were not a major barrier, but the technological barriers created inefficiencies and technological limitations for scaling up some circular practices. Some critical technology challenges may impact the success of these technologies, such as: lack of low-cost and efficient moisture removal solutions from the anaerobic digestion feedstock in humid regions, traditional optical sorters lack sorting accuracy to feed multi-layer packaging materials and there are not yet economically viable technologies for recycling composite materials such as glass-reinforced plastics (GRP) and textile blends.However, there are some environmental and technology related limitations that may affect the implementation of these technologies which includes low accuracy of sorting those which are two layered or more such as packaging material in traditional optical sorting, non-economic technologies of recycling composite material like glass-reinforced plastics (GRP) and textile blends etc. (Priyadarshini & Abhilash, 2020). In addition, advanced monitoring and optimization of waste flows with the use of digital infrastructure was not evenly distributed across the regions: the district covered by the Smart City Development was already equipped with infrastructure for digital monitoring and optimization of the waste flows, while the district of the Agricultural District had no digital infrastructure, even at the most basic level. While these are not necessarily a major constraint as operational or financial constraints, they point to the continued research and development potentials in the efficient and cost effective material recovery.

Moderate positive intercorrelations were found between severity scores of the individual challenges and analysis with Pearson correlation were used to determine these intercorrelations. However, there is a strong correlation between the level of education and awareness of the individuals and their behaviour in waste segregation in the source, and therefore, poor segregation in the source of waste is associated with a low level of awareness (). Financial constraints () were also related to insufficient recycling infrastructure, such infrastructure problems tend to be a result of or aggravated by lack of financial resources. The above correlations make the idea of the implementation of the circular waste management, as though additive, doesn't seem so, as it rather looks like a chain of constraints and it will happen that, if I make progress on a certain constraint, also the other one in the chain will be improved, while if I make progress on a certain constraint, the other one will be blocked. This interdependency implies important policy design implications: separately tackling various challenges will likely not sufficiently resolve the barriers to making a transition toward circular waste management – such as the operational, infrastructure, financial, behavioral, regulatory and technological challenges – because they are interconnected.

Correlation Analysis

Pearson correlation analysis was further performed on the Relationships among four major indicators of integrated circular waste management system including Recycling rate, Resource recovery, Environmental protection index, and Circular economy index, to explain the relationship amongst these indicators. Table 7 reveals that all the measured indicators are positively positively related and therefore support each other in some way which enlarges the light that the better the waste is recovered, the better the environmental and circular outcomes are.

Table 7. Pearson Correlation Matrix for Waste Management Performance Metrics

Variable	Recycling Rate	Resource Recovery	Environmental Index	Protection	Circular Index	Economy
Recycling Rate	1.00	0.92	0.87		0.94	
Resource Recovery	0.92	1.00	0.89		0.91	
Environmental Protection Index	0.87	0.89	1.00		0.90	

Variable	Recycling Rate	Resource Recovery	Environmental Index	Protection	Circular Index	Economy
Circular Economy Index	0.94	0.91	0.90		1.00	

The closest linear relationship found was between Recycling Rate and Circular Economy Index with a correlation coefficient of , . This is because the amount of material recycled is correlated with circular economy performance of the system as a whole. The results presented herein reinforce the theoretical basis for which material recyclability is very fundamental to the materials economy as it is helping to keep the material value in the economy and reduce the need for virgin material (Ijimdiya et al., 2026). The level of this correlation suggests that recycling rate is a reasonably good indicator of the performance of the CE, and therefore can be of great assistance in measuring and comparing the characteristics of the CE in these environments, in which consistent computation of an index that would represent full circularity may be difficult.

Similar positive correlations were achieved with Circular Economy Index (re: Circular Economy (,) for Resource Recovery (comprising material recycling, composting, anaerobic digestion and energy recovery). As recycling is a significant element of the resource recovery system being evaluated there would be high correlation between Resource Recovery and Recycling Rate as was observed. The perfect correlation (, not 1.00) demonstrates that the Resource Recovery also includes other aspects besides material recycling, such as energy recovery from waste-to-energy and anaerobic digestion facilities. This is a crucial aspect in the system design as another major contribution towards resource recovery across the region can be achieved through adopting complementary energy recovery technologies (Hazemba, 2024).

All positive correlation of EPI with all indexes were high with maximum correlation of EPI with Resource Recovery over Circular Economy Index being and . The correlation between EPI and the Recycling Rate (,) was not as good, but statistically significant and meaningful. These associations have verified the operational improvements in material recovery and circularity mentioned in Section 4.3 are closely and systematically correlated with the environmental benefits of these changes in terms of reduction of greenhouse gas emissions, production of renewable energy and abatement of water pollution. In this sense, EPI seems slightly more related to Resource Recovery () than to Recycling Rate (), indicating that RC can be seen as being slightly more efficient in terms of predicting environmental performance from a wider perspective encompassing the movement of energy as a component of RR as well as the treatment of the organic wastes. These findings also impact the selection of performance measures, which in this study include recycling rate, and could be a broader measure for systems interested in maximizing environmental co-benefit if they select to maximize resource recovery.

All the four metrics are highly correlated in practice, suggesting that M&E implications exist in the context of MsWs. There is a high level of correlation, and with some combinations of more easily-measurable indicators (e.g. the recycling rate and resource recovery) the CE index may reasonably be estimated with reasonable accuracy. This would decrease the amount of data which have to be collected, but would still capture the important system characteristics. The correlations are good but not highly. This does not mean that each of the individual measurements is useless, as each would reflect some aspect of the system performance that may be relevant for a number of policies or operational concerns.

Discussion

In addition to just accepting the expected performance gains of such a transition towards a circular economy of waste, conclusions from this empirical quantitative comparative analysis have practical and theoretical implications for gaining an understanding of how this process of successful implementation ought to look, of mechanisms, interdependency and socio-contextual aspects of this process. This discussion reviews current theories in relation to the observations and their implications to use in other contexts, limitations inherent in the methodology that limited generalizability in reaching conclusions and offers promising avenues for further research.

Theoretically, outcomes confirm and expand the ‘systemic view' theory used to robustly describe the Circular Economy (Ijimdiya et al., 2026). The high positive correlation between recycling rate, resource recovery, Environmental Protection Index, and Circular Economy Index (C.E) (from 0.87 to 0.94) are strong empirical evidence supporting that there is not opposition between circularity and environmental performance. Partial correlation analysis also found that there was a lower correlation between recycling rate and the Circular Economy Index (CEI), but, on the other hand, this analysis also showed a rather intricate relationship, as the literature does not seem to provide a clear explanation. The discovery is circularity is not merely a sum of parts practices, but the manifestation of the synergy created by the combined activation of several complementary circular recovery processes: material recovery, energy recovery and re-processing of the organic component; for this reason the different processes, if implemented within the architecture of a circular enterprise, should be synergistic. Therefore, the theoretical approaches to circular economy transitions must be more than linear.The systemic synergies in the theoretical approaches to CE transitions mean that they must transcend a linear approach.

The results of these findings are relevant for policy-makers, urban planners, and industrial managers in considering the system in which they make circular waste processing and management decisions. By establishing a performance hierarchy, the ten evaluated practices (where the industrial symbiosis achieved an index value of 94, the waste-to-energy 87 and the anaerobic digestion 84), a prioritisation framework based on a rigorous empirical basis for investment decisions is achieved (Hazemba, 2024). Our data confirm the highest agreed priority intervention for industrial zones and manufacturing clusters: industrial symbiosis, in which the exchanges of materias between firms substantially lowers waste disposals costs, decreases the raw material procurement cost and is the highest performing circularity practice overall. Waste-to-energy facilities, as a renewable energy generation technology, should be valued by those metropolitan governments that already have such facilities and are looking towards upgrading them with advanced combustion and flue gas treatment technologies as observed by a 69.6% increase in renewable energy generation after upgrading. The results of this study show that for the agricultural regions where the share of organic waste is a major percentage of the waste stream, the anaerobic digestion facilities are a particularly effective intervention with up to 83% of the organic waste becoming valuable biogas and digestate with a high concentration of nutrients, and a Circular Economy Index of 84. Most importantly, the data indicated that if you use the technology used "upstream" in combination, that is, in a complementary manner, the return of investment will be optimized, in comparison to the way you would use all your resources for one particular technology. A holistic, multi-step strategy starting from source segregation infrastructure – which our analysis shows is the core enabling practice – and then expanding to complementary processing facilities as appropriate based on the composition of local waste – should be adopted at the municipal level.

This is based on research about the economy of practical transitions towards circularity. The reduction in operational costs of 22.2 % and the increase in contribution of recyclables of 138.7%, among others, show that a circular system is not only an environmentally preferred way, but also an economically beneficial in the medium term (Nguyen et al, 2024). It is however important to note that this high one-time capital expenditure requirement to create the complete circular infrastructure in all five study areas (>42 million USD) represents a significant hurdle for smaller municipalities, who may not have access to capital markets. To resolve this, it is proposed to put certain green financing arrangements in place, such as municipal green bonds, revolving loan funds etc. and public-private partnership schemes that also take the financial risks and economic benefits of investments in circular infrastructure. In addition, the social co-benefits of circular transitions are reflected in the employment opportunities generated (range 820–1235) and further underline the importance of a complementary policy rationale for circular transition for municipal decision makers in terms of the labour market.

However, some limitations in methodology underpin the limited generalizability and interpretability of our results. It is a representative, albeit not exhaustive, sample that does not cover all the waste management contexts of the world, but rather five regions have been selected to illustrate a variety of urban and industrial profiles. In other words, the moderate human population and moderate climate temperatures found in the Agricultural District would make it possible for admission rates to the compost pile and anaerobic digestion to be different from other parts of the tropics, due to the high ambient temperatures (which have a potential to increase rates of organic decomposition and therefore the optimal operation and configuration of composting and anaerobic digestion systems, respectively). Furthermore, even though the monitoring time has been 18 months so far, representing long enough time period in order to document the improvement effects observed for a short period of time, it is not long enough to monitor the effects of long term dynamics that may deteriorate the systems performance, perhaps due to degradation of equipments, changes in waste composition, or changes in market value of secondary raw materials. Based on linear extrapolation of the observed years' reduction in the observed GHGs, it is reasonable to make the assumption, but there is a need for further monitoring along the year to confirm potential quantified rebound effect and/or Green House Stabilization dynamics in the coming years.

Being cautious in the choice and measurement of the composite indicators (CEI, EPI) is important. These are good summary measures but have taken weighting decisions that may impact on the ordering of practices. The waste-to-energy and source segregation systems scores in Circular Economy Index can be directly linked to the weight given to the energy recovery. A sensitivity analysis that we conducted showed that changes in the weights (±10%) would not affect the overall order of the performances, but more dramatic changes in the weights in theory could have changed the ranking. For future studies, the robustness of composite circularity and environmental indices to different weighting approaches, as well as the possibility of creating context-specific indices for regional policy needs needs should be explored.

Another subjective aspect in the method of the stakeholder survey also lowers the accuracy of results. Limited public awareness (4.02/5) and segregation of waste at source (4.61/5) are severity score local perception of the facility managers, recycling industry and municipal authorities figures only. Such insider perspectives and experiences of institutional change helps to explain locations of operational impediments, but can be swayed by insider factors like the institutional roles and background of the respondents, and the process of institutional change. It is easy for local governments to underestimate financial issues because they weren't first on the scene with managing capital shortages as facility managers were. The perceptual data were triangulated with such objectively measured data as the degree of contamination from the sources as an indirect measure of the degree of their separation.

Solving these problems and filling in the gaps in substance revealed in our study to this snags are some interesting directions to take in future research. First, a longer-term follow-on time period of the research products (5+ years) would be highly desirable to determine how long such performance enhancements would last, as well as to identify pathways of degradation in performance, timelines for instability of the equipment or adaptability to altered waste streams as new waste streams evolve from the changes in consumption patterns and/or product design (Ijimdiya et al., 2026). The need for such studies that can fill the gap in the planning and decision making process required for investments involving long-term commitments of capital in infrastructure are real. Thirdly, future research should consider the generalizability of our results to geographical and socioeconomic settings not included in the sample, such as the low-income countries and tropical climatic zones where waste composition and institutional capacities may be different from areas studied, and market structures may be quite distinct from those in both the European and Mediterranean countries. A comparison of businesses placed across different nations, based on variables that relate to the context in which businesses run, can shed light on the context in which certain practices used in the circular economy have been found to be most effective.

Thirdly, the behavioural dimension of circular transitions is research led by technical/economic dimension.Thirdly, behavioural dimension of circular transition is under-researched relative to technical/economic. Lack of awareness of public (4.02/5) and confusion about waste segregation at source (4.61/5) were two of the highest frequencies obtained in terms of implementation problems, this is pointing towards the fact that the human factor is one of the main failures in the circular waste management system (CWMS) (Kabir & Kabir, 2021). The effectiveness of the various BCs types used, economic incentives/social norms messages/f feedback systems and/or gamification strategy, in different cultural and demographic settings, should also be explored to increase compliance rates. There is very limited literature that provides causal evidence, which would be best from randomized control trials showing alternative designs of intervention. Finally, there is an economic analysis in this study which, while solid, was not comprehensive enough to capture systemic or macro-economic effects of circular transitions, beyond effects of waste management operations. Future studies and analysis should use models of the economy, like computable general equilibrium models or IO analysis, to quantify the broader economy impacts of material losses including jobs created, impact on industries up-stream in supply chain, and impact on industry using second raw materials in waste stream.

Conclusion

The results presented in this comparative quantitative evaluation provide an robust empirical evidence to the superior performance of IcWMS when compared to linear methods' environmental, economic and circularity performances. We validated our central hypothesis, and recycling, resource recovery and landfill diversion rates went up by 60.9% and 65.3% and 81.6% respectively across the 10 practices in the five regions. The environment impact was also significant, with the Environmental Protection Index being raised by 30.9% and GHG emissions also reduced by 27.7%. The results provided additional clarity for theory building based on the observation of the correlation between circularity and expected environmental performance; however, the present results indicated that no correlation exists between these. The very positive correlation between circularity and environmental performance ranged between 0.07 and 0.94 on the environmental performance metrics measured. We also found an unequivocal performance ranking for individual practices: practice performance reaches its maximum with seven most effective possible practices: industrial symbiosis, WtE and anaerobic digestion. Using multi-practice system architectures is the best way to maximize the performance of the practice, avoid relying on a single one.

This study's greatest added value for policy makers and infrastructure planners to include in their toolbox when developing effective circular waste management was the provision of empirical based quantitative benchmarks. The consequences of this are significant, as municipalities can rely on not only the environmental benefits, but also a 22.2% reduction in operating costs, a 138.7% increase in environmental benefits generated from collection services and a 50.6% boost in job creation. The problems identified, especially the high percentage of waste collected from the door received together with the lack of collection infrastructure and funding (i.e. mean severity score of 4.61, 4.43 and 4.21 out of 5 respectively), however, signal the need to act in various directions (behaviour, infrastructure and economics). Future research could include longer term follow-up to examine if class improvement is maintained over time, and if the improvement that occurs in a class can be transferred to other classrooms or even other countries depending on how different the social and economic environment is. Future experimental tests of behaviour-change interventions should be performed for compliance with source segregation. The research not only clearly illustrates the identifiable advantages of systems of waste management that take a circular approach, but also presents the actual hurdles that exist for implementing those approaches, and yet at the same time gives a compelling and realistic picture of how the transition can be accelerated towards a sustainable and circular systems of waste management around the globe.

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