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Assessing Circular Economy Performance Across Industrial Sectors: Barriers, Sustainability Impacts, and Future Projections to 2035

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Abstract: This paper presents a mixed-methods investigation into the performance of circular economy (CE) practices across five resource-intensive sectors—manufacturing, construction, agriculture, electronics, and municipal solid waste management. We collected data from 50 industries, 15 municipal authorities, and 200 experts through structured questionnaires, expert interviews, field observations, and industrial waste audits. The analytical framework integrated resource input assessment, material flow analysis, waste characterization, and sustainability performance evaluation, with indicators such as the material circularity index (0–100 scale), recycling rate, carbon emission reduction, and economic savings. The electronics sector achieved the highest material recovery efficiency at 88% and a circularity index of 91, whereas agriculture exhibited only 60 for the index due to limited technological adoption. High initial investment (mean score 4.61 on a 1–5 scale) and inadequate recycling infrastructure (mean score 4.42) emerged as the foremost barriers. Implementation of CE strategies substantially reduced greenhouse gas emissions, with electronics cutting emissions by 56% from 8.5 to 3.7 Mt CO_2, and manufacturing by 45% from 12.6 to 6.9 Mt CO_2; annual economic savings reached 34.8 million USD in electronics and 28.4 million USD in manufacturing. Pearson correlation analysis further revealed strong positive relationships among recycling rate, circularity index, carbon reduction, and savings, with coefficients ranging from 0.79 to 0.91. Predictive modelling projected that sustained CE adoption could elevate the circularity index from 64 in 2025 to 90 by 2035, with the recycling rate rising from 66% to 91% over the same period

Keywords: Circular Economy, Industrial Sustainability, Resource Efficiency, Sustainability Assessment, Future Projections (2035)

Introduction

The world economy has traditionally functioned on a linear "take-make-dispose" model that has resulted in great economic expansion but come at a high environmental price. This linear approach is becoming increasingly problematic and is directly responsible for depleting resources, damaging the ecosystems and adding greenhouse gas to the emissions from industrial activities (Gupta & Palsule-Desai, 2011). The climate crisis, the loss of biodiversity, as well as the erratic financial state of resources, have led to a new search for new paradigms: A new paradigm of change in the system, which is gaining momentum and is being called the "Circular Economy" (CE), that is (Teixeira, 2025). The notions of CE attempt to decouple economic growth and use of resources, design out waste, keep resources in use and regenerate nature (Tyagi et al., 2026). The current body of empirical evidence concerning the performance of CE at a sector level is not comprehensive, particularly regarding measurable environmental and/or financial benefits.There is a lack of consistency with the support base about the performance of CE in the sector level, such as measurable environmental and economic outputs (Handoyo & Sueb, 2026).

In this sense, the present research was formulated to bridge a gap in research – give light to the effectiveness of the CE implementation in a cross sectoral sense. To quantitatively assess circular economy practices in five key sectors with significant resource content (manufacturing, construction, agriculture, electronics and municipal solid waste), through a network of integrated sustainability indicators, was the major aim of the study. We hypothesized that differences would be observed in the resources productivity, environmental performance, and economic savings of these sectors in relation to their implementation of circular economy strategies on a systematic and statistical basis, and that these differences would vary significantly from one sector to another, depending on the maturity of technology, and on structural obstacles.

This is a really important investigation because it provides great primary data that will be factored into the policy development, both on the industrial policy, and through evidence based policy. The study was designed to be a mixed method study involving questionnaires for 50 industries, 15 municipal authorities, and 200 experts – this included structured questionnaires, expert interviews, and waste audits. To achieve this, we have developed and applied our analytical framework which was based on material flow analysis, waste characterization, and sustainability performance evaluation based on indicators such as the material circularity index, waste recycling rate, reduction in carbon emission and direct economic savings. The learning embodied in the research is three-fold: to provide a comparative case of CE performance in the different industrial contexts; to provide metrics of the relative significance of adoption barriers and to project forward the trajectory of CE by 2035 that support long-term strategic planning of resource management systems.

In Section 2, CE literature is introduced and the main aspects of the CE principles, sustainable resource management and other policies and supply chain presented. Mixed methods research design, data collection and analysis is presented in Section 3. The quantitative results are expanded by sector in Section 4, including performance measures, barriers and results of the predictive modelling exercise. The results from this research have implications for theory (Section 5), practice and policy. The final section presents some main conclusions and recommendations for future work.

Literature Review

In the past decade or so, circular economy has matured from a well-defined concept into the fundamental concept of sustainable resource use and has become an academic hotspot. In the conceptual framework of CE developed by Kirchherr et al. (Kirchherr et al., 2017), the end-of-pipe perspective on CE can be summarised as an economic system characterised by a concept of 'end of life' wherein waste minimisation or 'directed end of life' may include minimization, re-use, recycle, and 'recover'. This concept has been used to date; however, later research has highlighted the need for an operational understanding and measurable measures to get beyond the rhetoric to the empirical assessment (Verdone et al., 2012).

There is a wide-range of literature that studies the implementation of CE at the sectoral level. In manufacturing, closed-loop production is proven to decrease the input of raw materials and waste generation, while some companies get a 20-30% productivity level for their resources via remanufacturing and component re-using (Lüdeke-Freund et al., 2019). Investigations have been carried out for the valuable recovery of precious metals and rare earth elements (REEs) in e-waste where the economy of these processes is influenced by the collection efficiency and processing technologies (Shittu et al., 2021). However, agricultural system studies focused on the structural barriers—the distribution of organic residues, fewer structures for bioenergy conversion or composting—that impede with the attainment of the circularity results (Khan & Mahajan, 2025).

Several review papers have tried to zoom out and considers the general issues and potentials of entering circular economy. While a linear model was just as valid, a thorough review by Geissdoerfer et al. (Geissdoerfer et al., 2017) concluded that CE needs to be a natural progression from it and warned that unless policies are backed up systemically and stakeholders are aligned with it, they risk being superficial and failing to generate measurable success. It was noted in a more recent review of CE in developing countries (Shi et al. 2026) that in such countries, inadequate infrastructure, weak enforcement of environmental regulations, and the informal waste sector were perceived as being important as constraints to CE performance. One research topic that has gained attention is the development of using digital technologies in order to increase monitoring capabilities of materials and improve reverse logistic processes (Handoyo & Sueb, 2026) as well as improve the execution of product-as-a-service. The costs of investment of these digital solutions are, however, quite high and it is troubling to consider smaller firms to be able to invest this, and questions have to be raised for their accessibility and availability (Celik et al., 2026).

People have looked at the role of policy as a enabler and deterent to the adoption of CE. Although EU policies, such as the CEAP, have been driving the standards on waste management and Product Design to high extent, regulatory fragmentation is impacting harmonized implementation within the EU Member States, according to studies (Tyagi et al., 2026). As regards the management of municipal solid waste, research has highlighted the need for implementing extended producer responsibility legislation to enable a shift of the responsibility for recycling from municipalities to producers, and shown inconclusive results according to the design of the scheme (Kotyal, 2023). Two important limitations of the existing literature are, first, that hardly any existing studies provide a cross-sectoral evaluation based on empirical data and multiple criteria of environmental and economic behaviour; second, hardly any are studies which investigate, with real-life examples, environmental and economic aspects in a sectoral context.

The purpose of the current research is to bridge this gap in a systematic approach that quantifies the scores of the circular economy, emission savings, and the economics gains for five sectors on a common analytical framework and applies mixed methodologies.This study takes a step towards filling this void by systematically evaluating circular economy scores for the five sectors, as well as emission reductions and economic savings, with the same analytical framework, and applying mixed methods. In the other research these barriers have not been analyzed or emphasized as such and are only mentioned as research potentials, but rarely as primary input from experts in industry on what sizes of the potential financial and infrastructural "winners" and "losers" would be. Moreover, due to the nature of the cases and the fact that the integration of PM is still in its early stages, very little of the identified work were related to PM to estimate circularity pathways for scenarios.Additionally, previous studies have failed to incorporate predictive modelling for their integration or projected circularity pathways based on scenarios. This combination of cross-sectoral benchmarking, quantifying barriers, and forecasting time makes the major leap we have taken in our research over what was known.

Methodology

The techniques used in this study were designed to obtain a total and repeatable rating of the performance of the CE under different industrial conditions. A 'mixed' (both qualitative and quantitative) research design was adopted, with qualitative analysis of both policy and barriers and quantitative performance measurement, so that there could be triangulation of results from various data and various analysis. The overall framework voluntarily adopted by the company was composed of six steps: 1st assessment of the resource inputs, 2nd material flow analysis, 3rd waste classification, 4th implementation of circular strategy, 5th sustainability performance assessment and 6th future scenario analysis. Specific data collection items and analysis procedures were developed for each stage, which are discussed in the ensuing subsections.

Study Design and Sector Selection

We have conducted a cross sectional and multi-sector monitoring and evaluation study in five selected sectors that consume a considerable amount of resources: manufacturing, construction, agriculture, electronics and MSW management. The sectors chosen were carefully selected, with particular emphasis placed on their high resource consumption and/or pollution output, and their diversity in terms of characteristics of material flows and levels of technological development. A total of 50 individual industrial facilities, 15 municipal waste management authorities and 200 expert stakeholders conducted the study. The expert panel consisted of 25 members from policy-making institutions, 35 members representing environmental regulatory institutions and 80 members from industry and academia, equally represented by a multiperspective input both on operational and governance aspects of the adoption of circular economy.

Data Collection Instruments and Procedures

The following four complementary instruments were used to collect primary data. The questionnaire used for capturing quantitative information regarding material inputs, energy usages, volume of wastes generated, recycling rates and economic losses of the waste management operations at the facilities was the structured questionnaire. Items describing barriers were based on a five-point Likert scoring, which ranged from 1 (strongly disagree) to 5 (strongly agree). Second, they conducted some ‘expert interviews' with the 200 stakeholders that lasted between 45 and 75 minutes to elicit qualitative feedback on identified institutional barriers, policy needs and opportunities to scale up CE. Third, Observation at 35 sites around the production-and-waste processing locations was done for confirmation of reported practices and conditions, and verification of their infrastructure. Fourth, an industrial waste audit was conducted at 25 industrial establishments (physical sorting, quantification and analysis of material flows during a 7-day period was carried out, with accurate results of material recovery efficiency).

Five key secondary data sources were used: Government Sustainability Reports, national and regional level; Environmental Protection Agency databases (including sectoral emission inventories); Circular Economy reports including the Ellen MacArthur Foundation which were peer-reviewed scientific literature published; and publicly available Company Sustainability Reports for the industries included. Secondary sources have been employed to provide background information for the papy and seek confirmation of the information gathered.

Evaluation Indicators

Eight indicators were identified and quantified in eight categories related to circular economy and summarized as shown in Table 1 to provide circular economy performance.

Table 1. Evaluation indicators for circular economy performance assessment.

Indicator	Unit
Resource Productivity	%
Recycling Rate	%
Waste Diversion Rate	%
Carbon Emission Reduction	%
Energy Recovery Efficiency	%
Material Circularity Index	Score (0–100)
Water Reuse Efficiency	%
Economic Savings	Million USD/year

The Method chosen to determine material circularity index is based on the following dimensions: Percentage deeping of input materials recycled, end of service life recovery, extension of service life, etc., and can range from 0 (fully linear) to 100 (fully circular) and are used to calculate the overall circularity index of the materials used. These estimates of carbon emissions reductions were carried out in terms of megatonnes (Mt CO_2) and in terms of percentage carbon emissions reductions (before and after implementation of the carbon emissions strategy). Economical savings relating to the lowered expenses of the procurement of raw material, as well as the lower expenses regarding waste disposal and energy savings were calculated in millions of USD/year.

Circular Economy Assessment Framework

This assessment was done in six phases, one after another. In position 1 – investigation of resource input, the procurement records of the facilities were used to quantify the weight and composition of the inexhaustible resource inputs per production unit, and mass balance equations were used to quantify the weight and composition of the exhaustible resources per production unit. To complete this material flow analysis, the second stage was in mapping the transformation and the movement of this material, which was conceived and visualised in Sankey diagrams, losses and recirculation of the material in the form of a loop. Waste characterization (Stage 3) determined Waste Streams to be, Recyclable, Compostable, Hazardous and Residual from audit information. For stage 4, the implementation of circular strategy demonstrated the type of the CE interventions carried out in each facility, for example design for disassembly, remanufacturing, industrial symbiosis, closed loop water system. The 8 indicators that have been defined in table 1, were calculated for each sector and facility in stage 5: sustainability performance evaluation. Future Scenarios Analysis, in stage 6, showed indicators at a future time point (year 2035), assuming that there will be a sustained CE adoption scenario.

Statistical Analysis

The data processing was carried out using a statistical set of methods which, in turn, were applied or performed in software "R" (4.2.1). The mean, standard deviation and range of all the indicators were calculated and are displayed, revealing the central tendency and variability of the sectors. The means for indicators were statistically determined across the 5 sectors with one-way ANOVA by using the Tukey HSD tests to test for differences between means of the 5 sectors. For bivariate relationships between continuous variables, bivariate relationships were analyzed by Pearson correlation coefficient and the values (weak), (moderate), (strong) were used. According to recommendation, the data set of the 8 indicators was reduced using a principal component analysis (PCA) which identified the factors to explain the variation in indicators' performances. Using ward's method with Euclidean distances, clustered the facilities into homogenous performance group to classify them. A series of models was developed with different set of predictor variables: recycling rate, carbon emission reduction and economic savings; the fitment of the different models was determined in calculating the "adjusted level" and by the application of the "diagnostic of the residuals". All of the inferential tests were considered significant if and only if the value of the test was 0 or less.

Results

The circular economy (CE) practices are evaluated and analyzed quantitatively based on quantitative data obtained from auditing and survey during the part and qualitative data obtained from interview with experts in each industrial sector in this section. The analysis starts with the benchmarking of resource recovery and material circularity, identifying the main barriers to the adoption of the CE, quantifying the environmental and economic outcomes of the CE, and examining both the interrelationships of and among the key indicators, and predictive projections for CE adoption by 2035.

Resource Recovery Performance Across Industrial Sectors

The resource recovery effectiveness of each sector has been assessed systematically using assessment criteria such as the recycling rate, resource productivity, material circularity index etc., to create a baseline understanding of the effectiveness of the various sectors. A second distinction can be observed from the comprehensive results in the sectors: the results for electronics manufacturing are better ranked and receive the highest mark, agriculture, the least good, with general manufacturing having intermediate results.

Table 2. Circular Economy Performance by Sector

Sector	Recycling Rate (%)	Resource Productivity (%)	Carbon Reduction (%)	Circularity Index
Manufacturing	81	78	45	83
Construction	73	69	39	72
Agriculture	62	61	28	60
Electronics	88	85	56	91
Municipal Waste	76	72	42	79

The electronics industry had the highest material recovery efficiency, recycling rate of 88% and resource productivity of 85%, of all the industries evaluated. The circularity index is a good integration of the circular principles, out of all the design operations; sustainable performance achieved is represented with the score of 91 in the range 0-100 (Shittu et al., 2021). In the manufacturing sector, recycling rates were also similar (81%) as well as the index of circularity (83); and circular value creation and recycling is common in the manufacturing sector (Lüdeke-Freund et al, 2019).

However, there was moderate progress during this period in the municipal solid waste management sector, with a recycling rate of 76% and a circularity index of 79 thanks to the introduction of EPR systems and improvement of sorting capacities (Kotyal, 2023). This industry's performance was in the middle range between higher performing electronics and manufacturing and lower performing agriculture and construction industries. The building industry has a recycling rate of 73% and the circularity index of 72, which suggests some possibilities for using concepts like selective deconstruction and membrane re-use.

In particular, agriculture was the lowest ranked agricultural category in terms of resource recycling (62% recycling) and circularity index (60%). The low technological adoption rate and the multifaceted nature of agricultural waste streams (crop residues and animal manures) with their associated logistical and economic challenges for collecting and processing is the major reason behind this relatively low performance (Khan & Mahajan, 2025). Interviews with farmers, processors and extensionists confirmed these, with many reporting that there is a lack of organic waste treatment (composting or anaerobic digestion) close to the farmers' premises to enable organic substance cycles to be closed.

There were statistically significant differences between the five sectors on the circularity index, results of one-way ANOVA test. Additionally, when using post-hoc Tukey's tests to determine differences between the sectors and products, the circularity index for the 'electron electronics' sector was found to be significantly higher than all other sectors (for all comparisons), consumers, service and goods'. Farmers, on the other hand, did not encounter significant barriers (>) for agriculture and construction areas, suggesting that there could be some common circularity barriers in both sectors.

Looking at the overall results of this benchmarking exercise, our assumption is that the benefits of systematic CE strategies indeed apply to specific sectors, and that the more developed technology/processes and the more centralised the waste stream (e.g. electronics, manufacturing…), the more this benefits. This is contrasted by the fact that in other sectors where the residues cannot easily be concentrated and distribution of processing facilities is limited like agriculture, significant underperformance is evident and policy interventions and technology transfer efforts need to be directed in this sector to facilitate its circular transition. In the next subsections, these sectoral differences will be explored further in an analysis to provide insight into the nature of the barriers, environmental impacts and economic drivers of CE adoption.

Major Challenges Hindering Circular Economy Adoption

The study took a systematic approach to analysing the barriers that industry stakeholders identify and for the sectors where the circularity index was the lowest, such as agriculture and construction, barriers observed were compared with the situation in other sectors. All three challenges that emerged from the field's debate among the 200 experts have highlighted the financial barriers and infrastructure for waste collection and recycling as the most prevalent challenges in all sectors. Each of these challenges were then ranked quantitatively by using the mean Likert scale score (1–5) (Table 3).

Table 3. Major Challenges Hindering Circular Economy Adoption

Challenge	Mean Score (1–5)	Rank
High Initial Investment	4.61	1
Lack of Recycling Infrastructure	4.42	2
Weak Government Policies	4.11	3
Limited Consumer Awareness	3.96	4
Technological Limitations	3.81	5
Supply Chain Complexity	3.54	6

The cost of integration of a new sorting machine to the system, introduction of reverse logistics, and retrofitting production lines for remanufacture to existing systems is still a big challenge, referred to as High Initial Investment (mean score 4.61, SD = 0.48) (Celik et al., 2026). This was particularly important for the representatives from small and medium sized enterprises (SMEs) in the construction and agriculture industry as they mentioned that they did not have opportunities for capital access for transformative investments. The second most essential barrier was the perception of "Lack of Recycling Infrastructure" with a mean score of 4.42 (SD = 0.55). The result is similar to the conclusions of earlier studies on the complexity of the waste streams and limited material recovery rates (MRR) available in decentralized systems like agriculture (Khan & Mahajan, 2025).

The poor performance of the government policies came in as the third with a mean score of 4.11 (SD = 0.62). From the experts interviewed, some of their top concerns included inconsistencies in regulation, the lack of enforcement of existing environmental regulations, and the lack of economic incentives, such as tax credits and subsidies for circular investments, to mention a few (Tyagi et al., 2026). There was some recognition by a number of policy makers among the experts that sometimes there are nationally-applicable circular economy policies available but they would not be effectively implemented at the local level, in the form of instruments and enforcement. Limited consumers' awareness (mean score 3.96, SD 0.68) was the fourth highest ranked barrier. This reduces the demand in the circular economy since the end-users are not directly involved in SDW, or are not willing to purchase the recycled products, which makes the economic viability of reverse logistics and recycling processes less (Geissdoerfer et al., 2017).

Technology barriers (mean 3.81, SD 0.71) and supply chain complexity (mean 3.54, SD 0.78) also came in fifth and sixth most important but subordinate problems. In recycling cases, such as those for the waste of electrical parts whose composite materials can be recycled only to low-grade purity and wasteless in complex construction materials, technological problems were critical. One difficulty in the supply chain would be that it is very complex; it would take more actors to coordinate for efficient take-back schemes and material brokerage would also be a problem, so that companies refrain from implementing complete circular supply chain (Handoyo & Sueb, 2026).

To compare barrier scores within sectors, one way ANOVA was used and the information regarding barriers "Lack of Recycling Infrastructure" showed significant differences between sectors and type of sector (; ; agriculture, construction sectors were significantly more important than the electronics and manufacturing sectors respectively, post-hoc tests). Similarly, the agriculture industry's small-scale users, in comparison to the large-scale users in the manufacturing industry and electronics industry, rated "High Initial Investment" higher (). These sector specific patterns correspond to some of the documented patterns of performance in Table 2: the sectors where prospects for increased recycling and circularity are potential, exhibit broader infrastructure adoption and capital availability at sector level, while the sectors with poorer prospects for increased recycling and circularity, show lower sectoral infrastructure and lack of capital. The main barriers identified are essential for developing specific policy measures and investment alternatives for moving towards the transition from linear to circular resource cycles.

Carbon Emission Reduction Achieved

The outcomes of the implementation of CE practices in the 5 sectors indicated that greenhouse gas emissions could be significantly lowered in all of the 5 sectors as per their performance ranking for the 5 sectors, as stated above. The following table (Table 4) summarizes the emission reduction observed.

Table 4. Carbon Emission Reduction by Sector

Sector	Before CE (Mt CO_2)	After CE (Mt CO_2)	Reduction (%)
Manufacturing	12.6	6.9	45
Construction	10.1	6.2	39
Agriculture	7.2	5.2	28

Sector	Before CE (Mt CO_2)	After CE (Mt CO_2)	Reduction (%)
Electronics	8.5	3.7	56
Municipal Waste	9.4	5.5	42

The Emissions of the biggest decrease were in the electronics sector where emissions reduced by 56% from 8.5 Mt CO_2 to 3.7 Mt CO_2 as a CE result has been implemented. A similar decrease was seen in the value of this significant reduction; in retrenewing and remanufacturing procedures, which saw energy use efficiency improved by 50% to 1.4 Mt CO_2 (up from 2.8 Mt CO_2). Similarly manufactured saw a significant reduction from 12.6 Mt CO_2 to 6.9 Mt CO_2 (-50%). In the manufacturing sector, the use of closed-loop material flows without the intensive use of primary raw materials for carbon-bearing extraction and processing was the major factor for emission savings, and alternative fuel use in cement kilns and industrial boilers with energy recovery from materials in the waste streams was also one of the key fields in which energy was used ecologically (Lüdeke-Freund et al., 2019).

The municipal solid waste management sector experienced a 42% decrease in emissions, from 9.4 Mt CO_2 to 5.5 Mt CO_2. This was due to three reasons, namely: i) methane gas collection at waste disposal sites for energy generation, ii) optimized transportation routes and reduced transportation distances in waste collection due to the smart waste management system (Kotyal, 2023), and iii) diversion of organic waste from landfills to composting and anaerobic digestion plants. This is noteworthy because 5.5% of the carbon dioxide emitted is not spent on waste recycling - the waste residual must be disposed of through landfilling or incineration.

The other largest emissions falls were led by the construction industry, which saw a reduction of 39.0% (from 10.1 to 6.2Mt CO_2). The reduction is achieved due to application of recycled aggregates and reclaimed steel used in the production of concrete; The production of cement and primary steel have the greatest carbon footprint. Additionally, selectively deconstruction for structural parts that were possible to be reused also lowered virgin material production. Additional challenges in the recycling of the COW, as well as more difficult actions for additional reductions, relate to the recycling of especially composite construction wastes such as insulation products and treated woods (Handoyo & Sueb, 2026).

The agriculture sector will see a smallest reduction in emissions, which are 7.2 Mt CO_2 to 5.2 Mt CO_2. Table 2 shows a small circularity index for the sector, as well as a low recycling rate, which coincides with this. This small decrease is largely due to the fact that, anaerobic digestion of animal manure and crop residues is not being widely implemented to use the biogas in the place of fossil fuel energy and to reduce open emissions of methane from storage. Agro-processing for bio-energy generation is hindering in several operations of the sample and was also identified as a key constraint in the stakeholder survey (Khan & Mahajan, 2025) due to inadequate infrastructure to utilize agricultural products for bio-energy generation.

These are the actual absolute drop in emissions, and if you sum all of them, they would add up to a lot. Then, the total Baseline emission was 47.8 Mt CO_2 while after implementing the CE it came down to 27.5 Mt CO_2 equivalent to an overall reduction of 42.5%. The result reveals that, along with other decarbonization pathways that focus on energy efficiency and using renewable energy, the circular economy transition pathway is also important. The emission reduction focuses on those sectors in accordance with circularity and recycling rates, which shows that emission savings is a joined effect of the overall ability to achieve circularity. Differences between means of reduction percentages by sector were tested using One-way ANVOA which confirmed statistical differences; electronically sector had significantly higher reductions compared to Agriculture (); Construction ().

Economic Benefits

Results indicated a high level of cost saving advantages of implementing circular economy strategies, in all five industrial sectors, compared to implementing a linear economy, further reinforcing the economic gain for implementing the circular economy over the linear one. The direct economic impacts of wind in terms of net annual savings in million USD per sector are shown in Table 5.

Table 5. Estimated Economic Savings by Sector

Sector	Annual Savings (Million USD)
Manufacturing	28.4
Construction	18.6
Agriculture	12.1
Electronics	34.8
Municipal Waste	20.5

The highest yearly savings for electronics industry was as high as 34.8 million USD and related to this sector as indicated in Table 5. This significant financial gain is mostly from the ability to recover materials of high market value like gold, silver, palladium and rare-earth-elements which rose to a value much higher than the collection and dismantling as well as processing (Dang and colleagues, 2026) cost. Secondly, the electronics industry extended the lifespan of componentry with the help of refurbishment and e-recycling materials, as well as cheaper disposal expenses by not having to invest in virgin materials.

The manufacturing sector was almost as close with annual savings of 28.4 million USD. This could be attributed to the following reasons: savings in raw material control costs are realized by using recycled feedstock; savings in energy costs are realized because the energy consumption required for remanufacturing is less than that required for the primary production; and no tipping fees are paid at landfill or incineration facilities (Tu et al., 2025). Managers of facilities in this sector recounted that significant amounts of waste from one production process was used as an input in another within their facilities, resulting in a reduction of the need to purchase materials from outside that would be disposed of at external facilities.

In the construction industry per annum a saving of 18.6 million USD was effective. The meaningful savings that have been accomplished have been the use of reclaimed and recycled materials instead of virgin materials, which now are typically less expensive, and selling salvaged materials, such as doors, windows, structural steel beams recovered from the selective deconstruction process (Swarnakar & Khalfan, 2024). Despite such progress, however, additional costs were identified for on-site sorting and certification of reclaimed materials, and therefore some cost savings were identified that were considered acceptable.

The saved in the municipal solid waste management sector was 20.5 million USD per year. These savings were a result of the revenues that were collected from the sale of recovered materials (such as paper, plastics, glass, etc.) and the reduction in the cost associated with landfills while operating the landfills and through use of landfill gas-to-energy systems (Chareonvong et al., 2025). Among these, a significant amount was reinvested in the optimization of the collection network, according to municipal representatives that took part in the study.

The agriculture sector did not have the highest savings, which were valued at only 12.1 million USD, for one year. This is a lower value than the one previously stated, mainly because of low returns from the existing transformation pathways of agricultural waste into compost and simple bioenergy harvested, as well as the relatively high costs associated with collecting small amounts of dispersed liabilities (crop residues and animal manure; Chiaraluce et al., 2021). The need for additional capital to erect facilities for biogas and digestate (as a fertilizer) also needs a large capital investment, and this factor received high score (highest barrier) for "High Initial Investment" in Table 3.

The economic savings achieved in each sector was observed to be in a strong positive correlation with the circularity index. The electronics sector had the highest circularity index (91), and the highest annual savings (34.8 million USD), while agriculture had the lowest circularity index (60) and consequently the smallest annual savings (12.1 million USD). This link between the value or return from CE use and the degree of material circularity achieved in this pattern suggests that the added value of CE is closely related to the degree of material circularity achieved (Verdone et al., 2012). Recovered Footsteps' recovery technologies and Advanced Solutions have proven themselves to be an excellent way for the sectors to close material loops and to value them more, thus benefiting the economy in practice.

When looking at total cumulative savings, each of the 5 sectors has an annual savings of 114.4 million USD. This is a significant motivation to invest into further developing circular economy infrastructure and technology, but it needs to be taken with a grain of salt as the initial investment barriers estimated by stakeholders came up as 4.61 on the barrier scale on average. The positive net savings observed in each sector, however, highlight the environmental benefits of adopting CE but also the economic rationale that comes with the program the more important of which is the economic benefits of transitioning from an over-resourceful linear resource management system to an efficient and sustainable circular resource management system.

Correlation Analysis

Additionally, a Pearson correlation analysis was conducted on the most important circular economy performance indicators for all 50 included industrial facilities and 15 municipal entities in the data-set to explore further the interdependencies of the most important key circular economy performance indicators. Four main continuous variables were selected: recycling rate (in %), carbon emission reduction (in %), Material circularity index (0–100) and economic savings ($million/year). The analysis of the relationships was performed in a linear form between these variables. Using the formula developed results in a correlation matrix as shown in Table 6.

Table 6. Pearson Correlation Matrix of Circular Economy Performance Indicators

Variables	Recycling Rate	Carbon Reduction	Circularity Index	Economic Savings
Recycling Rate	1.00			
Carbon Reduction	0.84	1.00		
Circularity Index	0.91	0.86	1.00	
Economic Savings	0.79	0.82	0.88	1.00

The four performance indicators were associated with high correlation and in a statistically significant relationship (at level) as indicated in Table 6. The greatest correlation was with the recycling rate and the circularity index, which was . The figure depict a positive correlation between the material recovery rate associated with the recycling activity and the overall circularity indicator (composite index combining the different dimensions: input material composition, product life and end of life management) associated to the facilities, as explained in Verdone et al. 2012. The tight coupling verifies that recycling performance is a good proxy of overall circularity, for the data available in this current report.

There was also a fairly good association between the circularity index and the economic savings: It particularly demonstrates that the financial benefits (as provided in Table 5), as a result of integrating circular economy, are not simply added to the system but are a methodologically conducted approach, depending on the degree of material circularity. The higher the circularity index, the more strong cost savings were the annual difference made on the reduction of price of raw materials, waste disposal cost and the benefit of energy efficiency. This connection provides factual support for the theoretical argument that circular strategies can give environmental and economic added value (Geissdoerfer et al. 2017) and empirical corroborations to the economic feasibility of CE transitions from one sector to another.

Also the circularity index was correlated with carbon emission reduction that has a very high positive correlation. From here we can deduce that with the increase of circularity in the facilities, greenhouse gases will be reduced proportionally. This linkage is explained by the fact that more circularity means more of a shift in virgin material generation and energy use in primary processing, the major industrial carbon sources, compared to virgin material.This connection is attributed, because there is more of a shift from virgin material generation to energy use in primary processing with more circularity than with virgin material generation. Everything is confirmed by the correlation of about 100 that exists between the rate of recycling and the carbon saving; for each percentage point of recycling up to 100 emission savings are obtained.

A correlation coefficient was found between carbon reduction and economic savings as , and between recycling rate and economic savings, which were found to be . The values are in the low portion of the above correlations but still considered strong, and consistent of reinforcing the correlations, overall, amongst the four indicators. The lesser link between recycling rate and savings could be explained by other features which are closely linked with the economic benefit of recycling but cannot be fully summarized with recycling rate only, such as the cost of operating reverse logistics and the economic returns of the material market prices (Celik et al., 2026).

In support of primary analysis, a secondary analysis was conducted to delve into the latent factorial structure, using Principal Component Analysis (PCA) on 08 evaluation indicators. The positive factor loadings of recycling rate (0.88), carbon reduction (0.85), circularity index (0.92) and economic savings (0.83) confirm that the differences in the data on the recycling rate, carbon reduction, circularity index and economic savings likely reflect one single data dimension: circularity performance, representing 64.7% of all data variance. This reinforces the findings of the correlation matrix, showing that facilities with good scores on one indicator tend to get good scores on all indicators, suggesting that there is a systemic synergy between the environmental, resource and economic aspects of the circular economy intervention in the facilities.

The result of the cluster analysis used ward minimization method and Euclidean distances was 3 clusters. High mean values were found for all indicators for the first cluster with 18 facilities, most of which are in the electronics and manufacturing sectors: recycling rate 84.7%, circularity index 87.6, carbon reduction 49.2ton and economic savings 30.1 million USD. The second group (construction and municipal waste) had intermediate values: recycling rate 74.5%, carbon reduction of 40.3%, savings of 19.5 million USD and circularity index of 75.8. The third group of 18 facilities (mainly agricultural) had very low performance: recycling rate 61.2 %, circularity index 59.4, carbon reduction 27.1 % and savings 11.8 millions USD. All four indicators in the table were found to be statistically significantly different across the sectors based on whether the cluster membership variable was compared through a one-way ANOVA (for each); therefore, the hierarchy of the performances presented in this table suggest different and statistically distinct group of maturity of CE practices.

Based on the overall results of the correlation and multivariate analyses testing the hypothesis, the concepts of energy efficiency, material efficiency of circular economy practices are statistically correlated with good overall environmental and economic performance, are coherent and they integrate the practices. The high correlation coefficient values (0.80-0.91) indicate that these results found from recycling are not independent of each other but interconnected since they all demonstrate that one can achieve what the other outcomes are seeking – a circular economy. The outcomes justify the composite assessment approach and they also suggest that action on one indicator on one measure would, at least on its own, lead to an action on the other measure on the same indicator; this means that policies for sustainable resource management should not be based on a single indicator.

Future Circular Economy Adoption Scenario (2035 Projection)

Current performance indicators and the identified relationships between the drivers of the circular economy allowed the path of circular economy uptake to be forecasted using predictive modelling, under the assumption that no changes to policy and constant levels of investment. The composite sectoral average of material circularity index and recycling rate was applied using a multiple linear regression model that was calibrated with the cross sectional data with the baseline year 2025 till 2035. The model featured variables that captured the current recycling rate, emissions reduction, economic savings, as well as a time trend variable that encompasses accumulated recycling infrastructure investments and technology learning effects. The model succeeded in achieving good predictive fit (adjusted=0.89), with the majority of the variance of the results on the index of circularity being explained by a combination of the predictors selected. The performance metrics are those that are expected to be achieved as detailed in Table 7.

Table 7. Projected Circular Economy Performance under Sustained Adoption Scenario

Year	Circularity Index	Recycling Rate (%)
2025	64	66
2027	69	71
2029	74	75
2031	79	80
2033	84	85
2035	90	91

From 64 (2025) to 90 (2035), composite circularity index will gradually increase by 40.6% every 10 years, as noted in Table 7. This upward trend is a consolidation, with an average annual rate of around 3.5%, similar to the model's projection of the continued maturing of the infrastructure, the transition to new technical solutions and the scaling up of good practice applied in high-performance sectors, like electronics and manufacturing, to less performative sectors like agriculture and construction. The projected recycling rate will trend up as well, from 66% in 2025 to 91% in 2035, up 37.9% in 10 years.

On average, the sample of facilities has a circularity index of 90 by 2035, which is only exhibited by the highest performing electronics facilities in the baseline assessment. This forecast assumes that the financial and infrastructural barriers listed in Table 3 will be alleviated, in turn, through specific policy measures and private investments. Another key parameter that has been assumed to decrease overtime in the model is the hurdle factor for the adoption of an advanced recycling technology and reverse logistics, related to the Capital Costs (mean score 4.61 at baseline). Similarly, with the increase in public and private investment on recycling collection & processing plants, likelihood of occurrence of the barrier "Lack of Recycling Infrastructure" decreases with each increment (mean score = 4.42) and Khan and Mahajan (2025) observed that this is particularly associated with the agricultural and construction wastes, which is yet to be tapped effectively.

The regression model coefficient of the correlation between the circularity index and the recycling rate remains high even in the forecast period, which agreed with the correlation between the two in the empirical analysis; it can be seen that a small change in the recycling rate causes the greatest change in the circularity index. As the recycling rate benefits at the same time as the share of recycled materials benefits, i.e. from 66% to 91% of near complete material recovery, the circularity index is, naturally, driven upwards. What is thrown in is an economic accelerating feedback from economic savings, from 114.4 million USD of cumulative annual savings (total across all sectors) to an estimated 210.3 million USD by 2035, slowly but surely moving over the capital barrier identified in our barrier analysis.

Past literature shows that predictive modelling of future adoption of CE has been achieved, but for long-term national or macro-economic level material flows and emissions predictions rather than for the facility- and sector-level.In the past literature, long-term material flow and emissions predictions for the sector/facility-level were not found, but rather at a national or macro-economic level in terms of predictive modelling of the future adoption of CE. The year of 2035 estimated in this study is comparable to the recycling target of a 70-80% recycling rate in the municipal waste stream and industrial stream by the year of 2035 in several industrialised regions, which are set in the 'circular economy action plans' (Tyagi et al., 2026). This recycling expected rate is however relatively high at 91% in 2035 compared to many national projected rates, based on the current trajectory of technical and policy development.

Forecasts have implications beyond carbon emission reductions and economic costs and benefits as well. If the emissions reduction is proportional, the percent recycling from an average of 42 to an estimated value of 60.2 from the regression relationship between the two variables from the recycling rate, which were found in the correlation matrix, then there is a proportional increase in the amount of emissions reduction. To emphasise climate co-benefits from further uptake of circular economy in the upcoming decade, a significant extra mitigation is added. The related economic savings are projected to grow to 210.3 million USD per year – substantial financial incentives for investments to continue. These projections can be a policy tool to justify investing to reduce financial exposure to early installation of new infrastructure since the benefits of such investments will be much higher in the coming years than will the initial financial risks.

However, the situation that is proposed in Table 7 should be used with the proper level of suspicion. Projections are dependent on forecasts of support for policies and technological innovations and market conditions for recycled material. This path could be altered depending on extraneous factors, such as a recession, a major shift in the regulatory framework and new competitors that emerge with a different waste management method. There is no explicit representation of sector-specific variations in the adoption rate for the model, which can result in a weakness: agriculture and construction could be behind the scenes when compared to electronics/manufacturing in the composite average. These forecasts may be improved upon in the future by the generation of sector-specific models, and the inclusion of variable aspects like fluctuation in material prices and changing consumer behaviors. Nonetheless, the forecast results from the long-term scenario provide a compelling quantifiable snapshot of how much contribution systemic circular economy adoption can make towards 2035 and showcase the value of the cascade of initiatives being taken to move towards favouring circular resource flows by 2035.

Discussion

The results of this investigation have far reaching implications for theory, going beyond the current corpus of understanding about the dynamics of the circular economy. The high correlations between these four adopted performance aspects (recycling rate, circularity index, carbon reduction, economic saving) confirm that in order to highlight the benefits of the circular economy, they have to be approached synergically, that is, as a combination of aspects in which only a part of them is independent. Whereas reductionist dimension of circular economy brings only some separate indicators and measures which may be diagnosed independently from the rest of the circular economy, such empirical evidence confirms a theoretical assumption that the circular economy would not be a collection of isolated practices. Indeed, the analysis of the first principal component, which accounts for 64.7% of the variance for the 10 facilities, brings this reading to support, as it would reflect an extreme synergy between the different performance stages when it comes to implementing the concept of a circularity capacity within a facility. To translate this to practice: policy and Industry stakeholders should take a system-level approach to interventions based on these findings to optimise the entire circular system, rather than leveraging a single indicator. The second most important barrier (mean score 4.42) is investments on other infrastructure like recycling infrastructure, which will bring immediate carbon reducing benefits as well as economic savings, thus contributing to the overall ROI. Construction workers (72) and Agriculture workers (60) whose symmetry scores are the lowest may decide to work on aspects of the physical or material side of the equation, establishing recycling or re-processing centers that are able to collect, separate and treat diffuse waste.

It is evident that the level of hierarchy exists at an economic level, which could be beneficial when formulating policy inputs for each sector. Both the electronics and manufacturing sectors have relatively mature indices of 91 and 83 respectively, and the introspection for the potential of transition towards more circularity looks like more advanced practices such as design for recycling and extended producer responsibility (EPR) schemes could bring the shift (Shittu et al., 2021). On the other hand the agriculture industry's circularity index stands at 60, and the highest scores have been attained in the perception of the initial investments required and the need for infrastructure, indicating that basic measures are on-going. Policymakers could look at the possibility of offering subsidies for anaerobic digestion and composting infrastructure to agricultural areas, and helping companies to tackle the capital hurdle as the largest of all the levers to speed the circular transition, the predictive modelling shows. Moreover, an optimistic forecast of circularity from 64 in 2025, to 90 by 2035, further highlights the need for continued and secure policy assistance. Governments might increase or decrease circular economy policy interventions over every few years, which may affect the technological learning and/or infrastructure maturation reported in our scenario analysis at a later point and may reduce the expected positive environmental and economic effects.

The interpretation of the results of this study is limited for several reasons. It is diverse enough to cover a good cross-section of the 5 sectors, but doesn't always reflect all of the sectors and sub-types of industrial types, nor geographic regions, particularly in developing economies, where the infrastructure for a circular economy is even less developed. Care was taken in the development of the exclusion criteria to limit them to the facilities that had some existing waste management documentation to avoid selection bias towards the higher-performing facilities and potentially overestimate the average circularity performance. Furthermore, as the data used to estimate economic savings depends on self disclosure by the companies contained in their sustainability reports and in expert interviews, this could lead to overestimation of economic savings. In the example of the financial or the technical barrier, it can be evaluated fairly quantitatively, on the basis of the questions in the survey, and is likely to provide a good guide to the barriers currently faced by the respondents rather than ones that might actually manifest themselves at the facility level – and could even be quite different from facility to facility, because of variations in energy mix, process efficiency, etc. Lastly, the linking of adoption rates from past trends to the future projections in the predictive model relies on linear and continuous improvements, which may not be representative of potential discontinuous change like technological advances, economic downturns or eras of policy shifts that can speed up or slow down adoption.

In future research there are many areas to be explored that would be beneficial to be extended in this study. Longitudinal studies are needed for a series of years to test in an empirical way the assumed circularity pathway and to have knowledge about the time dynamics of the barriers. It would be useful to have some cross-national comparative studies, which would highlight how policies and economics differ across countries, and whether barriers such as those detailed above (such as weak government policies at 4.11) differ between those with better or worse governance of environmental regulation. Meanwhile, further study on the effective use of digital technologies to accelerate more circular uptake could also include how digital platforms can address some of the challenges in supply chain which was identified in this study as a moderate barrier (3.81). Elements of decentralised solution such as mobile processing units or community-scale biogas units, particularly in the agriculture sector are poorly researched and could be explored and evaluated.

Conclusion

In this study, we wanted to quantitatively assess the performance of the CE practices in 5 key resource-consuming sectors and identify the key hurdles and opportunities for CE practices for the next few years. The results indicate that both the environmental and the economic benefits of the system level circular economy strategies are positive, but not all are equally shared across the sectors. Agriculture was last worst in circularity and carbon reductions due to the challenges of finance and infrastructure.Manufacturing, electronics businesses ranked better than others based on their circularity indexes and carbon reductions due to economic and financial issues and the need for infrastructure. Contributions to the existing knowledge are provided by the multiple sector data, which shows that the recycling rate, the circularity index, carbon reduction and economic savings follow a close relationship, between 0.79 and 0.91 correlation coefficient. This is the contrary to the broken thinking of one indicator for a circular economy at a time and is more in line with a more circular approach whereby doing one benefit in one direction yields benefits in another direction as well.

The forecast composite circularity index is 64 in 2025 and reaches 90 in 2035 with consequent recycling rates of 91% in both years if such actions continue to be taken and investments are maintained. The projections also describe in the long term the strategic relevance of a transition to a circular resource economy, but also indicate how the investment and infrastructure gap is a major constraint in the uptake of the transition, particularly in the field of agriculture and construction. Future research should continue the longitudinal monitoring of facilities to test on an empirical level, these expected trajectories and build the empirically-based sector-specific models and models recognising sector-specific differences in the level of uptake..

References

Celik, S., Chen, Z., Yildizbasi, A., et al. (2026). Generative artificial intelligence for adopting circular economy in supply chains: Opportunities, challenges, and future pathways. *International Journal of Gestion of Artificial Intelligence and Big Data*.

Chareonvong, C., Chansungnern, S., Auiwong, K., et al. (2025). Implementation and education of circular economy in community solid waste management: A systematic literature review. *Journal of Education and Learning*.

Chiaraluce, G., Bentivoglio, D., & Finco, A. (2021). Circular economy for a sustainable agri-food supply chain: A review for current trends and future pathways. *Sustainability*.

Dang, L., Duong, Q., Zhou, L., & Meng, M. (2026). Resilience in closed-loop supply chain: A systematic literature review. *Industrial Management & Data Systems*.

Geissdoerfer, M., Savaget, P., Bocken, N., & Hultink, E. (2017). The circular economy - a new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768.

Gupta, S., & Palsule-Desai, O. (2011). Sustainable supply chain management: Review and research opportunities. *IIMB Management Review*.

Handoyo, S., & Sueb, M. (2026). Integrating digital technologies into the circular economy: A systematic literature review of trends, challenges, and opportunities. *Circular Economy and Sustainability*.

Khan, M., & Mahajan, R. (2025). Barriers and drivers to CE in agribusiness: A systematic review. *Circular Economy and Sustainability*.

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources Conservation and Recycling*, *127*, 221–232.

Kotyal, K. (2023). Sustainable waste management in the circular economy: Challenges and opportunities. *Environmental Reports*.

Lüdeke-Freund, F., Gold, S., et al. (2019). A review and typology of circular economy business model patterns. *Journal of Industrial Ecology*.

Shi, Y., Werku, B., Chebo, A., et al. (2026). Thematic mapping of circular economy of waste management in developing countries: Challenges and future perspectives. *Waste Management & Research*.

Shittu, O., Williams, I., & Shaw, P. (2021). Global e-waste management: Can WEEE make a difference? A review of e-waste trends, legislation, contemporary issues and future challenges. *Waste Management*.

Swarnakar, V., & Khalfan, M. (2024). Circular economy in construction and demolition waste management: An in-depth review and future perspectives in the construction sector. *Smart and Sustainable Built Environment*.

Teixeira, N. (2025). Circular economy perspectives: Challenges, innovations, and sustainable futures. *Discover Sustainability*.

Tu, Y., Si, X., Wu, Y., Shen, X., & Chen, J. (2025). Remanufacturing process under uncertainty: Review, challenges, and future directions. *Processes*.

Tyagi, S., Goel, A., & Chauhan, A. (2026). A comprehensive review of circular economy: Concepts, strategies, and future perspectives. *Circular Economy and Sustainability*.

Verdone, M. A., Engberg-Pedersen, P., & Martínez, C. (2012). *IUCN's ENVIRONMENTAL ECONOMICS OCCASIONAL PAPER SERIES ON GDP AS AN INSUFFICIENT TOOL FOR MEASURING PROGRESS TOWARDS a GREEN ECONOMY*.