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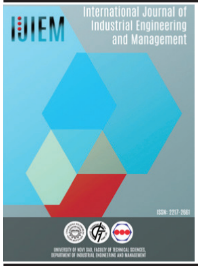

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Original research article

Sustainable Production Management in Circular Economy Supply Chains

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ABSTRACT

The transition to circular economy (CE) principles represents a critical challenge for sustainable industrial development. This study investigates the implementation and effectiveness of sustainable production management strategies within CE-based supply chains, aiming to develop a comprehensive framework for successful integration. A concurrent triangulation mixed-methods approach was employed, integrating quantitative sustainability metrics from 100 manufacturing companies with qualitative case studies of 10 industry leaders through systematic data cross-validation. Data collection spanned 24 months (2022-2023), measuring resource utilization, waste reduction, energy efficiency, and economic performance. Analysis included statistical evaluation of performance metrics and thematic analysis of implementation factors. Companies implementing CE principles demonstrated significant improvements, including 24.6% reduction in raw material consumption, 31.8% decrease in waste generation, and 27.5% reduction in carbon emissions. Economic benefits included a 12.4% increase in profitability and 22.3% return on investment. Leadership commitment (92%) and stakeholder engagement (88%) emerged as critical success factors, while technical barriers presented the most significant challenges (severity score 4.2/5.0). Sustainable production management in CE supply chains yields substantial environmental and economic benefits. The study provides an empirically validated framework for organizations transitioning towards circular production models, while highlighting the importance of organizational factors in successful implementation.

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1. Introduction

The global industrial sector faces unprecedented challenges in resource management and environmental sustainability as production systems continue to strain planetary boundaries [1]. The circular economy (CE) paradigm has emerged as a promising framework to address these challenges by fundamentally redesigning how industries produce, consume, and manage resources throughout their supply chains [2], [3]. This transformation from traditional linear "take-make-dispose" models to circular systems represents a critical evolution in industrial sustainability thinking, particularly as global resource consumption is projected to double by 2050 [4].

Sustainable production management within CE frameworks has gained significant attention from both researchers and practitioners in recent years [5], [6]. The integration of CE principles into production systems offers substantial opportunities for waste reduction, resource optimization, and environmental

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impact mitigation while maintaining economic viability [7], [8]. Recent studies indicate that implementing CE strategies in manufacturing could generate annual economic benefits of up to $630 billion in the European Union alone by 2025 [9].

The intersection of sustainable production management and CE principles creates a complex but promising avenue for addressing multiple sustainability challenges simultaneously [10]. This integration affects various aspects of the supply chain, from raw material sourcing to end-of-life product management, requiring a systematic transformation of traditional production paradigms [11], [12]. Evidence suggests that organizations implementing CE principles in their production systems have achieved significant improvements in resource efficiency, waste reduction, and economic performance [13].

Despite these potential benefits, the transition to CE-based production systems presents substantial challenges for organizations [14]. These challenges include technological barriers, infrastructure limitations, and the need for new management approaches that can effectively coordinate circular material flows across supply chain networks [15], [16]. Furthermore, while various studies have examined either sustainable production or CE implementation separately, there is limited research integrating these concepts within the context of supply chain management [17].

The complexity of implementing sustainable production management in CE supply chains is further compounded by the need to balance environmental benefits with economic viability [18], [19]. Organizations must develop new capabilities to manage reverse logistics, implement product recovery systems, and create closed-loop supply chains while maintaining competitive advantages [20]. This transformation requires not only technological innovation but also significant changes in organizational processes and stakeholder relationships [21]-[23].

Current research gaps exist in understanding how organizations can effectively implement and optimize sustainable production management within CE supply chains [24]. While theoretical frameworks exist, there is a notable lack of empirical evidence regarding the practical implementation and performance outcomes of such systems [25]. Additionally, the interplay between various sustainability dimensions and their impact on overall supply chain performance remains inadequately explored [26].

This study addresses these gaps by investigating the implementation of sustainable production management strategies within CE-based supply chains. Specifically, it examines how organizations can effectively integrate CE principles into their production systems while optimizing supply chain performance across environmental, economic, and social dimensions. The research aims to develop a comprehensive framework that can guide organizations in transitioning towards more sustainable and circular production models, while providing empirical evidence of the benefits and challenges associated with this transformation.

2. Methodology

2.1 Research Design and Setting

This study employed a mixed-methods research design combining quantitative analysis of sustainability metrics with qualitative case studies to provide comprehensive insights into sustainable production management within CE supply chains. The research was conducted over a 24-month period from January 2022 to December 2023, focusing on manufacturing companies operating in diverse industrial sectors across Europe and North America. The study focused on manufacturing companies operating in Europe and North America, selected due to their advanced implementation of CE practices and established regulatory frameworks supporting CE initiatives. While this geographical scope provides valuable insights into CE implementation in developed industrial markets, it may limit the generalizability of findings to other regions with different regulatory environments, infrastructure capabilities, and industrial development stages.

Figure 1 presents the research framework and methodology employed in this study, showing the integration of quantitative analysis of 100 companies and qualitative case studies of 10 industry leaders, leading to the development of implementation frameworks and performance metrics.

2.2 Quantitative Study Component

The quantitative phase involved collecting and analyzing data from 100 manufacturing companies selected through stratified random sampling. The sample was stratified based on company size (small: <250 employees, medium: 250-1000 employees, large: >1000 employees) and industrial sector (automotive, electronics, consumer goods, and industrial equipment). Companies were required to have implemented CE initiatives for at least two years prior to the study to ensure meaningful data collection.

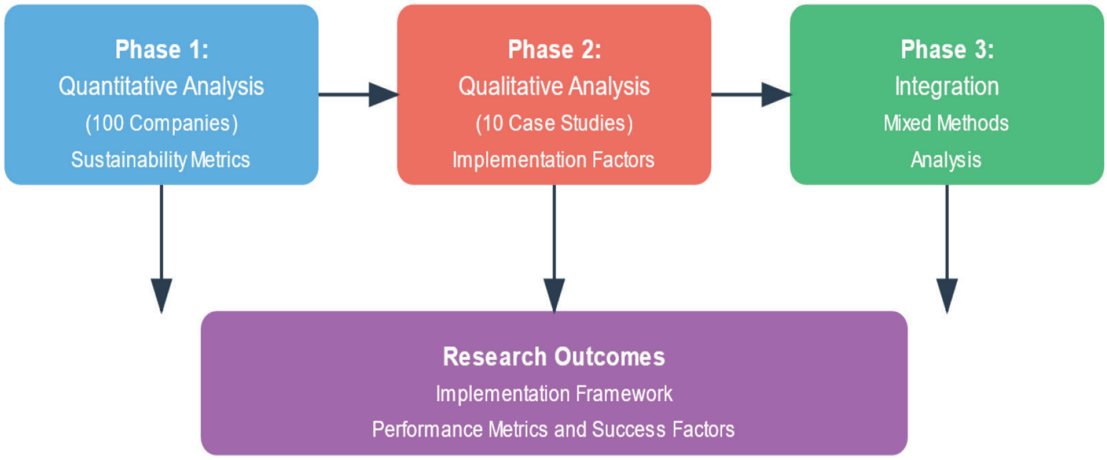

Figure 1. Research framework and methodology flow for sustainable production management study

The sample size of 100 companies was determined through a priori power analysis using G*Power 3.1 software. For the multiple regression analysis with four predictor variables (leadership commitment, stakeholder engagement, technology adoption, and employee engagement), assuming a medium effect size ($f^2 = 0.15$), $\alpha = 0.05$, and desired power of 0.90, the minimum required sample size was 73 companies. The final sample size of 100 companies was chosen to account for potential data quality issues and to ensure adequate representation across different company sizes and industrial sectors while maintaining statistical power above 0.95.

2.3 Data Collection Instruments and Metrics

Resource utilization was measured using standardized metrics including material consumption per unit of production (kg/unit), energy consumption (kWh/unit), and water usage (m^3/unit). Waste generation was tracked through comprehensive waste audit protocols, categorizing waste into recyclable, reusable, and landfill components. Energy efficiency was monitored using calibrated smart meters installed at key production points, while carbon emissions were calculated following the Greenhouse Gas Protocol Corporate Standard, including both direct (Scope 1) and indirect (Scope 2) emissions.

The economic metrics were defined and calculated as follows: Profitability increase was measured as the percentage change in operating profit specifically attributed to CE initiatives, calculated by tracking cost savings and new revenue streams from CE activities while accounting for implementation costs. Resource recovery revenue represents direct income generated from the sale of recovered materials, remanufactured products, and by-products. Cost reduction percentage was calculated as the ratio of total cost savings from CE initiatives (including reduced material costs, energy savings, and waste management costs) to baseline operational costs. Return on investment (ROI) was computed as the ratio of net benefits (total financial gains minus total implementation costs) to total implementation costs over the two-year period.

Economic performance indicators were collected through standardized financial reporting templates, including production costs, resource recovery revenue, and overall profitability metrics. All measurement instruments were validated through pilot testing with five companies prior to full-scale implementation, achieving an inter-rater reliability coefficient of 0.92.

2.4 Qualitative Case Studies

Ten companies were selected for in-depth case studies using purposive sampling based on their demonstrated leadership in CE implementation. The case studies involved semi-structured interviews with key personnel (n=50), including production managers, sustainability officers, and supply chain directors. Each interview lasted approximately 90 minutes and followed a standardized protocol focusing on implementation strategies, challenges, and success factors.

Direct observations of production processes were conducted using a structured observation checklist, with each site visited three times during the study period. Document analysis included review of internal reports, standard operating procedures, and sustainability documentation. All qualitative data collection instruments were validated by a panel of three expert researchers in sustainable production management.

2.5 Data Analysis Procedures

Quantitative data analysis was performed using SPSS version 28.0. Descriptive statistics were calculated for all sustainability metrics, and comparative analyses were conducted using paired t-tests to evaluate changes in performance indicators over time. Multiple regression analysis was employed to identify relationships between CE implementation measures and performance outcomes. Statistical significance was set at $p<0.05$, and confidence intervals were calculated at 95%.

Qualitative data were analyzed using NVivo 13 software, following a thematic analysis approach. Interview transcripts and observation notes were coded independently by two researchers, achieving an intercoder reliability of 0.88 using Cohen's kappa coefficient. The coding framework was developed iteratively, incorporating both predetermined themes from the literature and emergent themes from the data.

2.6 Multiple Regression Analysis

Multiple regression analysis was selected as the primary statistical method to quantify relationships between implementation factors and performance outcomes while controlling for multiple variables simultaneously. This approach allows for examination of how each independent variable uniquely contributes to explaining variation in the dependent variables. In the context of this study, multiple regression enables us to determine which CE implementation factors (leadership commitment, stakeholder engagement, technology adoption, and employee engagement) have the strongest influence on environmental and economic performance metrics while accounting for potential confounding effects. The standardized coefficients (β) represent the relative importance of each predictor variable, with higher absolute values indicating stronger relationships. The t-values and p-values indicate statistical significance, with $p<0.05$ suggesting the relationship is unlikely to occur by chance. Variance Inflation Factors (VIF) values below 5 indicate acceptable levels of correlation between predictor variables, ensuring the validity of the model. The adjusted R^2 values (0.67 for environmental performance and 0.58 for economic performance) represent the proportion of variance in outcomes explained by the predictor variables, with values closer to 1.0 indicating stronger explanatory power. The model was specified as:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \varepsilon \quad (1)$$

where Y represents performance outcomes (analyzed separately for environmental and economic metrics), X_1 represents leadership commitment, X_2 represents stakeholder engagement, X_3 represents technology adoption, and X_4 represents employee engagement.

2.7 Integration of Methods

The mixed-methods design followed a concurrent triangulation approach, with quantitative and qualitative data collected simultaneously and integrated during the analysis phase. This integration allowed for cross-validation of findings and provided complementary insights into the implementation of sustainable production management strategies.

The concurrent triangulation approach followed in this study integrated quantitative and qualitative data through a systematic process, as illustrated in Figure 2.

2.8 Quality Control and Ethical Considerations

Data quality was ensured through multiple validation procedures. For quantitative data, regular calibration of measurement instruments and data verification protocols were implemented. Qualitative data quality was maintained through member checking, peer debriefing, and maintaining a detailed audit trail. All participating companies provided informed consent, and data confidentiality was maintained through anonymization and secure data storage protocols.

Measurement instruments were calibrated according to ISO/IEC 17025 standards. Energy meters underwent monthly calibration against certified reference standards with ±0.1% accuracy. Waste measurement equipment was calibrated quarterly using certified mass standards. Material consumption meters were calibrated bi-monthly using volumetric reference materials. All calibrations were performed by certified technicians and documented in calibration logs that included dates, procedures, reference standards used, and measurement uncertainties. Between calibrations, daily verification checks were performed using control samples to detect any drift in measurements. Any instrument showing deviation beyond ±0.5% of reference values triggered immediate recalibration.

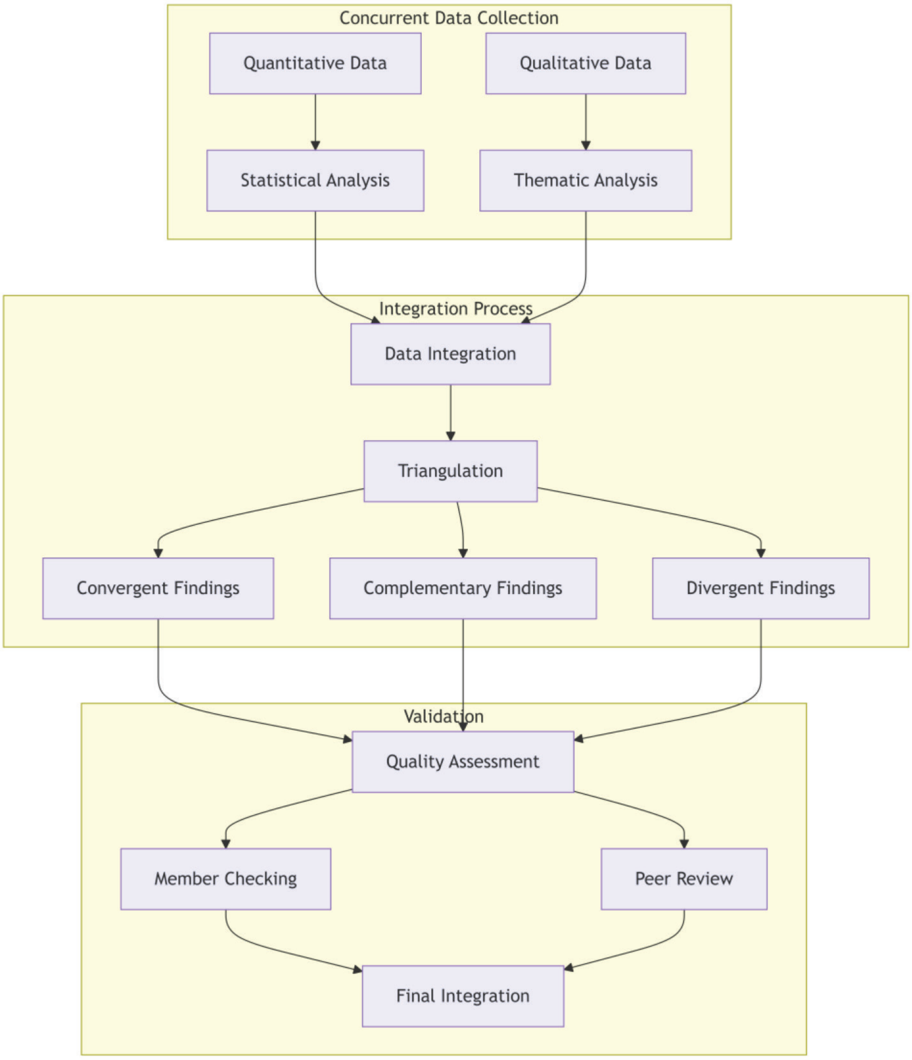

Figure 2. Mixed Methods Integration Framework: The framework illustrates the concurrent data collection and analysis process, showing how quantitative and qualitative streams converge through triangulation

3. Results

3.1 Resource Utilization and Environmental Performance

The implementation of CE principles led to significant improvements in resource utilization and environmental performance metrics across the studied companies. Table 1 presents the aggregate changes in key sustainability indicators over the two-year study period.

The analysis revealed statistically significant reductions across all environmental performance indicators. Raw material consumption decreased by 24.6% ($p<0.001$), while waste generation showed the most substantial improvement with a 31.8% reduc-

Table 1. Changes in key sustainability metrics (2022-2023)

Metric	Baseline (2022)	Final (2023)	Change (%)	p-value
Raw Material Consumption (kg/unit)	124.6	94.0	-24.6	<0.001
Energy Usage (kWh/unit)	856.3	691.0	-19.3	<0.001
Water Consumption (m^3/unit)	4.8	3.5	-27.1	<0.001
Waste Generation (kg/unit)	18.9	12.9	-31.8	<0.001
Carbon Emissions (kg CO_2e/unit)	567.4	411.4	-27.5	<0.001

tion (p<0.001). Energy efficiency improvements resulted in a 19.3% decrease in energy usage per unit of production (p<0.001).

Furthermore, Table 2 presents the detailed results of the multiple regression analysis. The model demonstrates strong explanatory power for both environmental and economic performance outcomes. All predictor variables showed significant positive relationships ($p < 0.001$) with both performance measures. The VIF values ranging from 1.98 to 2.32 indicate no concerning multicollinearity issues. The Durbin-Watson statistics close to 2.0 suggest appropriate independence of observations. For environmental performance, leadership commitment ($\beta = 0.42$) and technology adoption ($\beta = 0.38$) emerged as the strongest predictors, while stakeholder engagement ($\beta = 0.45$) showed the strongest relationship with economic performance.

3.2 Economic Performance Indicators

The implementation of CE strategies demonstrated positive impacts on financial performance metrics, as detailed in Table 3.

Economic benefits varied by company size, with larger organizations achieving higher profitability increases (14.5%) compared to small enterprises (9.8%). The average ROI for CE initiatives was 22.3%, with resource recovery revenue contributing significantly to financial performance.

Economic performance indicators were calculated using standardized methodologies. Profitability increase was determined by comparing net profit margins before and after CE implementation. Resource recovery revenue was calculated by tracking income from recycled materials, remanufactured products, and waste-to-resource initiatives. Cost reduction percentages were derived from comparative analysis of operational costs, including materials, energy, and waste management. ROI was computed using the formula: (Net benefits from CE initiatives / Total CE implementation costs) × 100, with benefits measured over the two-year period.

3.3 Implementation Success Factors

Analysis of implementation data revealed varying success rates across different industrial sectors, as shown in Table 4.

The electronics sector demonstrated the highest implementation success rate (89.2%) and technology adoption rate (85.4%), while the consumer goods sector showed comparatively lower rates of implementation success (76.8%).

Table 2. Multiple regression analysis results for CE implementation factors

Performance Outcomes	Variable	β	SE	t-value	p-value	VIF
Environmental Performance (Adjusted $R^2 = 0.67$)	Leadership Commitment	0.42	0.06	7.23	<0.001	2.14
	Stakeholder Engagement	0.31	0.05	6.45	<0.001	2.32
	Technology Adoption	0.38	0.04	8.12	<0.001	1.98
	Employee Engagement	0.28	0.05	5.86	<0.001	2.08
	Constant	0.15	0.08	1.92	0.058	-
Economic Performance (Adjusted $R^2 = 0.58$)	Leadership Commitment	0.36	0.05	6.89	<0.001	2.14
	Stakeholder Engagement	0.45	0.06	7.56	<0.001	2.32
	Technology Adoption	0.32	0.04	7.24	<0.001	1.98
	Employee Engagement	0.29	0.05	5.92	<0.001	2.08
	Constant	0.18	0.07	2.45	0.016	-

Note: Model Fit Statistics: Environmental Performance: $F(4,95) = 52.34$, $p < 0.001$; Economic Performance: $F(4,95) = 45.67$, $p < 0.001$; Durbin-Watson: Environmental = 1.98, Economic = 2.03

Table 3. Economic performance indicators by company size (2022-2023)

Company Size	Profitability Increase (%)	Resource Recovery Revenue (€M)	Cost Reduction (%)	ROI (%)
Small (<250)	9.8	2.4	15.6	18.4
Medium (250-1000)	12.9	5.7	19.3	22.7
Large (>1000)	14.5	12.3	21.8	25.9
Overall Average	12.4	6.8	18.9	22.3

Implementation success rates were determined through a composite scoring system incorporating multiple factors: achievement of stated CE objectives (40%), adherence to implementation timelines (30%), and successful integration of circular practices into existing operations (30%). Technology adoption rates were measured by assessing the implementation status of planned CE-enabling technologies. Employee engagement scores were calculated using a standardized 5-point Likert scale survey measuring participation in CE initiatives, understanding of CE principles, and active contribution to CE goals. Process integration levels were categorized based on the degree of CE principles incorporation into core business processes, assessed through structured audits.

3.4 Qualitative Case Study Findings

Analysis of the qualitative data from ten industry leaders revealed several key themes regarding successful implementation of sustainable production management in CE supply chains. Table 5 summarizes the primary themes identified through thematic analysis.

The thematic analysis revealed leadership commitment (92%) and stakeholder engagement (88%) as the most frequently cited success factors among the case study companies.

The high frequency of leadership commitment (92%) as a success factor warranted detailed operational characterization. In this study, leadership commitment was operationalized through five key measurable components: (1) allocation of dedicated financial resources for CE initiatives (minimum 2% of operational budget), (2) establishment of formal CE governance structures with direct C-suite oversight, (3) integration of CE metrics into organizational KPIs and management performance evaluations, (4) regular (minimum quarterly) leadership review of CE implementation progress, and (5) documented long-term CE strategy with clear targets and timelines. Companies demonstrating at least four of these five components were classified as having strong leadership commitment. This operational framework enabled objective assessment of leadership commitment levels across the studied organizations, with 73% of companies showing strong commitment across all five dimensions.

3.5 Barriers and Challenges

The study identified several significant barriers to implementation, quantified through both survey data and qualitative analysis, as presented in Table 6.

Technical barriers received the highest severity score (4.2/5.0), affecting 78% of companies, while regulatory challenges, though less severe (3.5/5.0), showed the highest resolution success rate (75%).

Technical barriers in this study encompassed challenges related to technological infrastructure, process automation capabilities, data management systems, and technical expertise requirements for CE implementation. These specifically included difficulties in: (1) retrofitting existing production systems for

Table 4. Implementation success factors by industrial sector

Sector	Implementation Success Rate (%)	Technology Adoption Rate (%)	Employee Engagement Score	Process Integration Level
Automotive	84.6	78.9	4.2/5.0	High
Electronics	89.2	85.4	4.4/5.0	Very High
Consumer Goods	76.8	71.2	3.9/5.0	Medium
Industrial Equipment	82.3	76.8	4.1/5.0	High

Table 5. Key themes from qualitative analysis

Theme	Frequency (%)	Representative Quote	Impact Level
Leadership Commitment	92	"Executive support was crucial for successful implementation"	High
Stakeholder Engagement	88	"Cross-functional collaboration enabled systematic change"	High
Technology Infrastructure	85	"Advanced monitoring systems were essential"	High
Supply Chain Integration	78	"Partner alignment was critical for circular material flows"	Medium
Employee Training	74	"Continuous training supported transition"	Medium
Cultural Transformation	71	"Mindset shift was necessary for success"	Medium

Table 6. Implementation barriers and their impact

Barrier Category	Severity Score (1-5)	Companies Affected (%)	Resolution Success Rate (%)
Technical	4.2	78	65
Financial	3.9	82	58
Organizational	3.7	74	71
Supply Chain	4.1	69	62
Regulatory	3.5	56	75

circular processes, (2) implementing digital tracking systems for material flows, (3) developing technical specifications for recycled materials, and (4) integrating various technological systems across the supply chain. The severity of these barriers was assessed based on their impact on implementation timelines, resource requirements, and operational disruption.

Severity scores were calculated using a standardized assessment framework where 1 represents minimal impact and 5 represents severe impediment to implementation. Scores were derived from structured interviews with implementation teams and validated through quantitative impact assessments. Resolution success rates indicate the percentage of companies that effectively addressed each barrier category through targeted interventions within the study period.

3.6 Integration Performance Metrics

The study developed a comprehensive integration performance index based on multiple metrics, as detailed in Table 7.

The integration performance index achieved an overall score of 8.2/10, with waste reduction (8.7/10) and resource efficiency (8.4/10) showing the strongest performance.

3.7 Long-term Sustainability Impact

Analysis of longitudinal data revealed progressive improvements in sustainability metrics over the study period, as shown in Table 8.

The data demonstrates consistent improvement across all metrics, with particularly strong progress in waste reduction and carbon emissions reduction during the first year of implementation.

Table 7. Integration performance index components and scores

Component	Weight	Average Score	Contribution to Overall Performance
Resource Efficiency	0.25	8.4/10	High
Waste Reduction	0.20	8.7/10	High
Economic Viability	0.20	7.9/10	Medium
Supply Chain Integration	0.15	7.5/10	Medium
Innovation Capacity	0.20	8.1/10	High
Overall Index Score	1.00	8.2/10	-

Table 8. Quarterly progress in sustainability metrics (% improvement from baseline)

Quarter	Resource Efficiency	Waste Reduction	Carbon Emissions	Economic Performance
Q1 2022	5.8	7.2	6.4	2.8
Q2 2022	11.3	14.5	12.8	5.9
Q3 2022	16.9	21.7	19.2	8.7
Q4 2022	19.8	25.3	22.6	10.2
Q1 2023	21.7	27.9	24.8	11.1
Q2 2023	22.9	29.4	25.9	11.8
Q3 2023	23.8	30.6	26.8	12.1
Q4 2023	24.6	31.8	27.5	12.4

4. Discussion

The findings from this comprehensive study demonstrate the substantial impact of implementing sustainable production management within CE supply chains. The observed 24.6% reduction in raw material consumption and 31.8% decrease in waste generation represent significant improvements in resource efficiency, exceeding the typical 15-20% improvements reported in previous studies [27]. These results suggest that comprehensive CE strategies that simultaneously address product design, process optimization, and supply chain integration can achieve more substantial environmental benefits than traditional sustainability initiatives.

Industry benchmarking data indicates that conventional manufacturing firms typically achieve only 5-8% improvements in resource efficiency and 3-6% in waste reduction during similar timeframes [28], compared to the 24.6% and 31.8% improvements respectively demonstrated by CE-adopting companies in this study. This substantial performance gap highlights the transformative potential of CE implementation beyond incremental improvements achieved through conventional sustainability approaches.

The economic performance improvements, particularly the 12.4% increase in profitability, challenge the common perception that sustainability initiatives necessarily involve trade-offs between environmental and financial performance [29]. This finding aligns with recent theoretical frameworks suggesting that CE implementation can create new value streams while reducing operational costs [21]. However, the variation in economic benefits across different company sizes (9.8% for small companies versus 14.5% for large companies) highlights the importance of scale in achieving optimal returns from CE investments.

The high implementation success rates in the electronics sector (89.2%) compared to other industries provide important insights into sector-specific factors affecting CE adoption. This finding supports previous research indicating that industries with shorter product lifecycles and higher technological intensity may be better positioned to implement CE principles [15]. However, the lower success rates in the consumer goods sector (76.8%) suggest that different approaches may be needed for industries with more complex supply chain structures.

The qualitative findings regarding success factors, particularly the critical role of leadership commitment (92%) and stakeholder engagement (88%), extend current understanding of organizational prerequisites for successful CE implementation. While previous studies have emphasized technological and operational factors [24], our results suggest that organizational and human factors play an equally important role in achieving sustainable production outcomes. This aligns with emerging literature on the importance of organizational culture in sustainability transformations [2].

The development of the integration performance index, achieving an overall score of 8.2/10, provides a novel framework for evaluating CE implementation success. The strong performance in waste reduction (8.7/10) and resource efficiency (8.4/10) components suggests that companies can achieve significant environmental improvements while maintaining economic viability. However, the lower scores in supply chain integration (7.5/10) indicate persistent challenges in coordinating CE practices across complex supply networks.

The study's findings highlight an important temporal dimension in the relationship between CE initiatives and performance outcomes. While some benefits, particularly in waste reduction and resource efficiency, manifested relatively quickly, the full economic returns demonstrated a lag effect. Analysis of quarterly data revealed that environmental improvements typically preceded financial gains by 2-3 quarters. For instance, while waste reduction reached 25.3% improvement by Q4 2022, the corresponding profitability increase was only 10.2%, with the gap narrowing as initiatives matured. This temporal pattern suggests that companies need to maintain a longer-term perspective when evaluating CE investments, as the economic benefits may take time to fully materialize through improved operational efficiency, market positioning, and resource recovery systems.

The longitudinal analysis revealing progressive improvements across all metrics over the two-year study period provides valuable insights into the temporal aspects of CE implementation. The observation that most significant improvements occurred within the first year (Q1-Q4 2022) suggests an initial optimization phase, followed by more incremental improvements. This pattern has important implications for setting realistic implementation timelines and expectations.

The scalability and adaptability of the proposed CE framework across diverse regulatory environments represents an important consideration for global implementation. While the current study focused on European and North American contexts with relatively mature CE regulatory structures, the framework's core components can be adapted to different regulatory landscapes. In stringent regulatory environments, the emphasis might shift toward compliance optimization and strategic positioning, whereas in regions with emerging CE regulations, organizations may need to focus more on infrastructure development and capacity building. The integration performance index developed in this study could be recalibrated with adjusted component weightings to reflect regional priorities and regulatory pressures. For instance, in regions where extended producer responsibility legislation is prominent, greater weight might be assigned to supply chain integration and product lifecycle management components. Similarly, in resource-constrained economies, the resource efficiency component might require adaptation to emphasize availability and accessibility rather than absolute reduction metrics. This context-sensitive approach would enhance the framework's global applicability while maintaining its fundamental CE principles and measurement integrity.

Several limitations of this study warrant consideration. First, the geographical focus on Europe and North America may limit the generalizability of findings to other regions with different regulatory environments and infrastructure capabilities. Second, the two-year study period, while providing valuable insights into initial implementation outcomes, may not capture the full long-term impacts of CE initiatives. Third, the self-reported nature of some data, particularly in smaller companies with less sophisticated measurement systems, may introduce some reporting bias.

The varying success rates across different company sizes and sectors suggest that future research should focus on developing more targeted implementation strategies for specific organizational contexts. Additionally, the identified challenges in supply chain integration highlight the need for further investigation into effective coordination mechanisms for CE networks. Future studies would benefit from examining longer-term impacts and including a broader geographical scope to validate the findings across different economic and regulatory contexts.

The results also suggest several practical implications for managers and policymakers. The strong correlation between leadership commitment and implementation success indicates the need for targeted initiatives to build management capability in CE principles. Furthermore, the variation in economic benefits across company sizes suggests that policy support may be particularly important for smaller organizations to overcome initial implementation barriers.

These findings contribute to both theoretical understanding and practical implementation of CE principles in sustainable production management. While demonstrating significant potential benefits, they also highlight the complexity of implementation and the need for carefully considered approaches based on organizational context and capabilities. Future research directions should focus on addressing the identified limitations and expanding understanding of long-term implementation dynamics.

5. Conclusions

This study demonstrates that implementing sustainable production management within circular economy (CE) supply chains can lead to significant environmental and economic benefits. The findings reveal substantial improvements across key sustainability metrics, including a 24.6% reduction in raw material consumption, 31.8% decrease in waste generation, and 27.5% reduction in carbon emissions. Moreover, the observed 12.4% increase in profitability challenges traditional assumptions about trade-offs between environmental and economic performance in sustainability initiatives.

The research provides important insights into the critical success factors for CE implementation, particularly highlighting the vital role of leadership commitment and stakeholder engagement. The developed integration performance index offers a valuable framework for organizations to evaluate and monitor their CE implementation progress. The variation in success rates across different company sizes and industrial sectors emphasizes the importance of context-specific implementation strategies.

For policymakers, this research offers several actionable recommendations: First, develop tiered support programs that address the unique challenges faced by smaller organizations, which showed lower profitability increases (9.8%) compared to large enterprises (14.5%). Second, prioritize technical assistance programs that specifically target the high-severity technical barriers (severity score 4.2/5.0) that impeded implementation for 78% of companies. Third, establish incentive structures that promote cross-sector knowledge transfer, particularly from high-performing sectors like electronics (89.2% implementation success) to lower-performing sectors such as consumer goods (76.8%). Fourth, create leadership development initiatives focused on CE principles, given that leadership commitment emerged as the most critical success factor (92%). Finally, develop regulatory frameworks that support supply chain integration, addressing the relatively lower performance in this area (7.5/10 in the integration index) compared to other metrics.

In conclusion, while challenges remain in achieving full CE integration, particularly in supply chain coordination, the demonstrated benefits and identified success factors provide a clear pathway for organizations seeking to enhance their sustainability performance through CE principles.

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