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Do Circular Economy Interventions Improve Institutional Sustainability? Micro-Level Evidence from Waste-to-Energy and Additive Manufacturing Systems

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ABSTRACT

This study examines whether circular economy interventions improve institutional sustainability within resource-constrained settings, using micro-level evidence from an integrated waste-to-energy and additive manufacturing system implemented in a large health and research institution in The Gambia. While the circular economy has gained prominence as a strategy for addressing environmental and resource challenges, empirical evidence on its institutional-level impacts particularly in developing countries remains limited. Drawing on circular economy theory, institutional economics, and the resource-based view, the study conceptualizes circular economy adoption as a multidimensional intervention influencing environmental performance, economic efficiency, and operational effectiveness. Using primary data derived from the implementation of the Greatwaste project, the analysis employs Ordinary Least Squares (OLS) regression models to estimate the relationship between circular economy adoption and institutional sustainability outcomes, while accounting for the moderating role of institutional capacity. The findings indicate that circular economy interventions significantly improve environmental performance, including measurable reductions in greenhouse gas emissions, and enhance economic efficiency through cost savings in energy and material use. More importantly, the results reveal a strong positive effect on institutional sustainability, suggesting that circular economy adoption functions as a mechanism of organizational transformation rather than merely a technical solution. The analysis further shows that institutional capacity significantly moderates these relationships, with stronger impacts observed in contexts with better infrastructure, technical expertise, and coordination mechanisms. The study contributes to the literature by providing micro-level empirical evidence on integrated circular economy interventions in a Sub-Saharan African context and by demonstrating their multidimensional impact on institutional performance. The findings underscore the importance of combining technological innovation with institutional capacity development to achieve sustainable and scalable outcomes.

Keywords: *Circular Economy; Institutional Sustainability; Waste-to-Energy; Additive Manufacturing; Institutional Capacity; Developing Countries*

INTRODUCTION

The transition toward sustainable production and consumption systems has become a central policy priority in both developed and developing economies, particularly in the context of climate change, resource depletion, and escalating waste generation. The circular economy (CE) has emerged as a dominant paradigm for addressing these challenges by promoting resource efficiency, waste valorisation, and closed-loop production systems (Geissdoerfer et al., 2020; Kirchherr et al., 2023). Unlike the traditional linear "take–make–dispose" model, circular economy approaches seek to transform waste streams into valuable inputs, thereby reducing environmental externalities while enhancing economic and institutional resilience.

Within this broader transition, increasing attention has been directed toward the role of institutions particularly large public and research organizations in operationalizing circular economy principles. Institutions such as hospitals, universities, and research centers are characterized by high resource consumption, continuous waste generation, and complex operational structures, making them critical sites for sustainability interventions (Ellen MacArthur Foundation, 2021; World Bank, 2023). Health systems alone are estimated to contribute over 5% of global greenhouse gas emissions, largely driven by energy use, procurement practices, and waste management inefficiencies (Health Care Without Harm, 2021). Consequently, integrating circular economy solutions into institutional operations is increasingly viewed as essential for achieving both environmental sustainability and long-term cost efficiency.

Among the most promising circular economy interventions are waste-to-energy systems and additive manufacturing technologies. Waste-to-energy solutions, particularly anaerobic digestion for biogas production, enable the conversion of organic waste into renewable energy, thereby reducing reliance on fossil fuels and mitigating methane emissions from landfill disposal (Atelge et al., 2020; Jameel et al., 2024). At the same time, additive manufacturing (3D printing) offers opportunities for decentralized production by transforming recycled plastic waste into functional products, reducing material imports, and shortening supply chains (Gebler et al., 2021; Tino et al., 2020). When implemented together, these technologies represent an integrated circular economy model that simultaneously addresses multiple waste streams while generating economic and environmental benefits.

Despite the growing global interest in circular economy practices, empirical evidence on their effectiveness at the institutional level particularly in low-income and resource-constrained settings remains limited. Much of the existing literature focuses on macro-level policy frameworks, industrial systems, or single-technology interventions, with relatively little attention to integrated, micro-level implementations within institutional environments (Kirchherr et al., 2023; Velenturf & Purnell, 2021). Furthermore, while environmental benefits of circular economy interventions are widely documented, their broader implications for institutional sustainability including cost savings, operational efficiency, and behavioral change are less well understood.

This gap is particularly pronounced in Sub-Saharan Africa, where waste management systems are often underdeveloped, recycling infrastructure is limited, and institutional capacity constraints pose additional challenges to the adoption and scaling of circular economy solutions (World Bank, 2023; UNEP, 2022). In such contexts, locally adapted, institution-driven innovations are critical not only for addressing environmental challenges but also for demonstrating scalable models of sustainable resource use.

Against this backdrop, this study examines whether circular economy interventions improve institutional sustainability, using micro-level evidence from a large health and research institution in The Gambia. Specifically, the study evaluates an integrated waste-to-resource system combining organic waste-to-biogas conversion and plastic waste recycling through 3D printing. By leveraging operational data, environmental impact estimates, and qualitative evidence from stakeholders, the study provides a comprehensive assessment of the environmental, financial, and institutional outcomes of circular economy adoption.

The study makes three key contributions to the literature. First, it provides one of the few empirical analyses of integrated circular economy interventions at the institutional level in a developing country context. Second, it extends existing research by examining not only environmental outcomes, such as greenhouse gas emission reductions, but also operational and institutional dimensions, including cost efficiency, waste governance, and behavioral change. Third, it introduces a micro-level analytical framework that links circular economy adoption to institutional sustainability outcomes, thereby bridging the gap between technological interventions and organizational performance.

LITERATURE REVIEW

Theoretical Foundations

The analysis of circular economy interventions and their effects on institutional sustainability is grounded in three complementary theoretical perspectives: circular economy theory, institutional economics, and the resource-based view (RBV) of the firm.

Circular economy theory emphasizes the transition from linear production systems to regenerative systems in which materials and energy are continuously reused, recycled, and valorised (Geissdoerfer et al., 2020). This framework highlights the potential of waste-to-resource strategies such as biogas production and material recycling to reduce environmental externalities while enhancing resource efficiency. Recent studies argue that circular economy adoption is not only an environmental imperative but also a pathway to economic resilience and sustainability (Kirchherr et al., 2023).

Institutional economics provides a complementary perspective by focusing on how organizational structures, rules, and governance mechanisms shape economic outcomes (North, 1990). Within this framework, the adoption of circular economy interventions can be interpreted as an institutional response to environmental and operational inefficiencies. Effective implementation depends on institutional capacity, governance quality, and coordination mechanisms, which influence both the efficiency and sustainability of such interventions (Acemoglu & Robinson, 2019).

The resource-based view (RBV) further enriches the analysis by conceptualizing circular economy capabilities such as waste processing technologies, technical expertise, and organizational learning as strategic resources that can enhance institutional performance (Barney, 1991). In this context, integrated systems combining waste-to-energy and additive manufacturing can be viewed as bundles of capabilities that generate competitive advantages through cost savings, innovation, and improved operational efficiency (Gebler et al., 2021).

Together, these theoretical perspectives suggest that circular economy interventions can influence institutional sustainability through multiple channels, including environmental performance, cost efficiency, and organizational transformation.

Circular Economy Interventions and Environmental Performance

A substantial body of literature documents the environmental benefits of circular economy practices, particularly in relation to waste reduction and greenhouse gas (GHG) emissions. Waste-to-energy technologies, such as anaerobic digestion, have been shown to significantly reduce methane emissions from organic waste while generating renewable energy (Atelge et al., 2020). Similarly, plastic recycling and reuse through additive manufacturing reduce reliance on virgin materials and contribute to lower carbon footprints (Tino et al., 2020).

Empirical studies consistently find that circular economy interventions improve environmental performance at both industrial and municipal levels (Velenturf & Purnell, 2021). However, much of this evidence is derived from large-scale systems in developed economies, with limited micro-level analysis of integrated interventions within institutional settings in developing countries.

Circular Economy and Economic Efficiency

Beyond environmental outcomes, circular economy practices are increasingly recognized for their potential to improve economic efficiency. By converting waste into valuable outputs, institutions can reduce operational costs associated with waste disposal, energy consumption, and material procurement (Ellen MacArthur Foundation, 2021).

For instance, biogas systems can offset energy costs, while 3D printing using recycled materials can reduce dependence on imported goods and supply chain disruptions (Gebler et al., 2021). These cost-saving mechanisms are particularly important in resource-constrained environments, where financial sustainability is a critical concern.

However, existing studies often focus on firm-level profitability or macroeconomic implications, with limited attention to how such efficiencies translate into broader institutional sustainability outcomes, including operational resilience and service delivery improvements.

Institutional Sustainability and Organizational Transformation

Institutional sustainability extends beyond environmental and economic dimensions to include governance, operational efficiency, and behavioral change within organizations. The adoption of circular economy practices often requires significant organizational adjustments, including changes in waste management practices, staff behavior, and internal coordination mechanisms (Kirchherr et al., 2023).

From an institutional economics perspective, such transformations depend on the alignment of incentives, capacity, and governance structures. Weak institutional capacity manifested in limited technical expertise, inadequate infrastructure, and fragmented coordination can constrain the effectiveness of circular economy interventions (World Bank, 2023).

At the same time, successful implementation can lead to improved institutional performance by fostering innovation, enhancing resource management, and promoting sustainability-oriented behavior among staff and stakeholders. Despite these potential benefits, empirical evidence linking circular economy adoption to institutional sustainability remains scarce, particularly in developing country contexts.

Research Gap and Contribution

The review of the literature reveals three key gaps. First, there is a lack of micro-level empirical studies examining integrated circular economy interventions within institutional settings, especially in Sub-Saharan Africa. Second, existing research tends to focus on either environmental or economic outcomes, with limited attention to their combined effects on institutional sustainability. Third, the role of institutional capacity as a moderating factor in shaping the effectiveness of circular economy interventions remains underexplored.

This study addresses these gaps by providing a comprehensive empirical analysis of an integrated waste-to-resource system combining biogas production and 3D printing within a large institutional setting in The Gambia. It further incorporates institutional capacity as a moderating variable, thereby offering new insights into the conditions under which circular economy interventions are most effective.

Conceptual Framework

Building on the theoretical foundations of circular economy theory, institutional economics, and the resource-based view, this study develops a conceptual framework that explains how circular economy interventions influence institutional sustainability through multiple channels.

At the core of the framework is circular economy adoption, operationalized through integrated interventions such as waste-to-energy (biogas production), additive manufacturing (3D printing), and recycling systems. These interventions are conceptualized as the primary explanatory variable, reflecting the extent to which institutions transition from linear to circular resource use systems.

The framework posits that circular economy interventions affect institutional sustainability through three key pathways. First, through the environmental performance channel, circular economy practices reduce waste generation and greenhouse gas emissions by converting organic and plastic waste into valuable outputs. This aligns with circular economy theory, which emphasizes resource efficiency and environmental regeneration (Geissdoerfer et al., 2020).

Second, through the economic efficiency channel, these interventions lower operational costs associated with waste management, energy consumption, and material procurement. Waste-to-energy systems reduce reliance on external energy sources, while additive manufacturing using recycled materials reduces input costs and supply chain dependencies (Gebler et al., 2021).

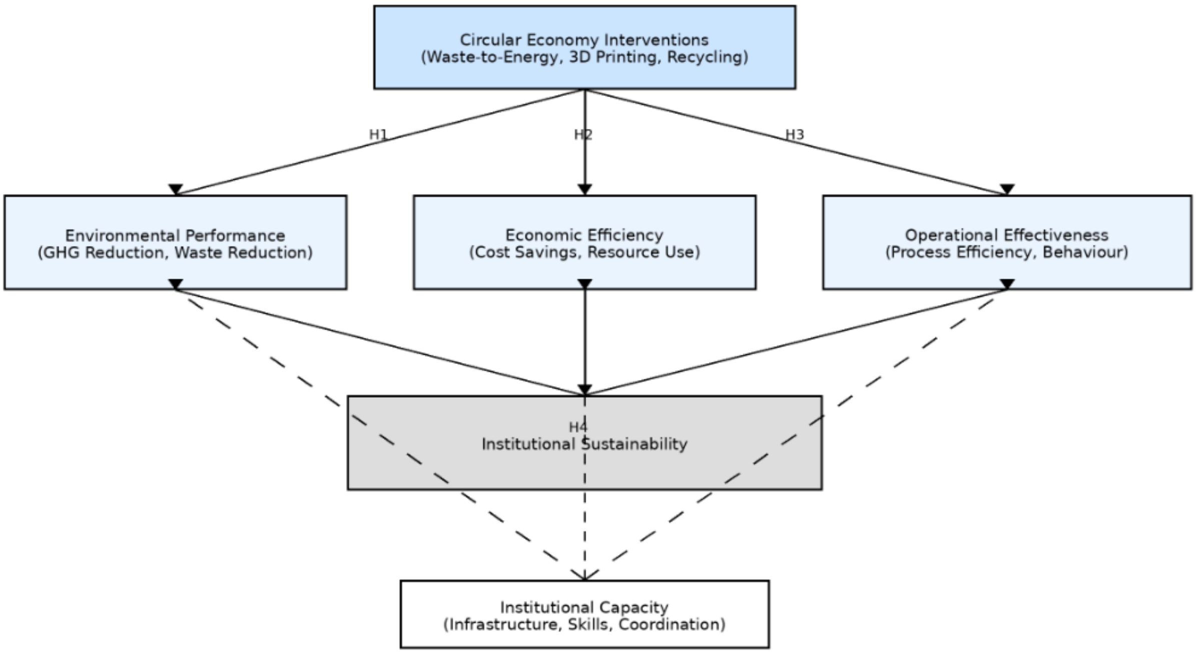
Third, through the operational and organizational channel, circular economy adoption improves institutional processes and promotes sustainability-oriented behavior among staff. This includes better waste segregation practices, improved workflow efficiency, and increased awareness of resource utilization. These changes contribute to broader improvements in institutional performance and governance.

These three channels collectively determine institutional sustainability, which is conceptualized as a multidimensional outcome encompassing environmental performance, cost efficiency, and operational effectiveness.

Importantly, the framework recognizes that the effectiveness of circular economy interventions is not uniform across institutions. The relationship between circular economy adoption and sustainability outcomes is moderated by institutional capacity, which includes factors such as infrastructure availability, technical expertise, and coordination mechanisms. Institutions with higher capacity are better positioned to implement, manage, and scale circular economy interventions, thereby strengthening their impact.

Based on this framework, the study hypothesizes that circular economy interventions positively influence environmental performance (H1), economic efficiency (H2), and overall institutional sustainability (H3), while institutional capacity moderates these relationships (H4).

Figure 1. Conceptual Framework of Circular Economy Interventions and Institutional Sustainability



The framework provides the basis for the empirical model specified in the next section.

Hypotheses Development

Based on the theoretical framework and literature reviewed, the following hypotheses are proposed:

H1: Circular economy interventions positively influence environmental performance.

This hypothesis is grounded in circular economy theory, which emphasizes waste reduction and resource efficiency as key outcomes of circular practices (Geissdoerfer et al., 2020).

H2: Circular economy interventions positively influence economic efficiency.

By converting waste into valuable outputs, circular economy systems reduce operational costs and improve resource utilization (Ellen MacArthur Foundation, 2021).

H3: Circular economy interventions positively influence institutional sustainability.

Through improvements in environmental performance, cost efficiency, and organizational processes, circular economy adoption enhances overall institutional sustainability.

H4: Institutional capacity moderates the relationship between circular economy interventions and institutional sustainability, such that the effect is stronger in institutions with higher capacity.

This hypothesis is grounded in institutional economics, which highlights the role of governance and capacity in shaping policy outcomes (Acemoglu & Robinson, 2019).

METHODOLOGY

Research Design and Empirical Strategy

This study adopts a mixed-methods empirical design combining quantitative analysis with qualitative triangulation to examine the effects of circular economy interventions on institutional sustainability. The approach is grounded in the conceptual framework presented in Figure 1, which models circular economy adoption as the primary explanatory variable influencing institutional sustainability through environmental, economic, and operational channels.

The empirical strategy follows a micro-level analytical approach, focusing on institutional data generated from the implementation of integrated circular economy interventions within a large health and research facility in The Gambia. This approach allows for a detailed assessment of the operational, environmental, and financial implications of circular economy adoption in a resource-constrained setting.

To complement the quantitative analysis, qualitative evidence from stakeholder interviews and operational reports is incorporated to provide contextual interpretation of the findings. This triangulated approach enhances the robustness of the analysis and allows for a more comprehensive understanding of institutional dynamics.

Data Source and Measurement Framework

The study utilizes primary data derived from the implementation and monitoring of the Greatwaste project, which introduced two key circular economy interventions: organic waste-to-energy conversion through biogas systems and plastic waste recycling through additive manufacturing (3D printing).

The dataset includes operational records, environmental impact estimates, cost metrics, and institutional performance indicators. In addition, qualitative data from key informant interviews (KIIs) and stakeholder consultations are used to capture behavioral and organizational changes associated with the interventions.

To facilitate empirical analysis, key constructs are operationalized as composite indices. Circular economy adoption (CE) is measured based on the extent of implementation of waste-to-energy systems, recycling intensity, and utilization of additive manufacturing. Institutional sustainability (IS) is constructed as a multidimensional index capturing environmental performance, economic efficiency, and operational effectiveness.

Environmental performance is proxied by reductions in waste volumes and greenhouse gas emissions, while economic efficiency is measured through cost savings in energy consumption, waste management, and material usage. Operational effectiveness reflects improvements in workflow processes, resource management practices, and staff engagement in sustainability initiatives.

Institutional capacity (IC), introduced as a moderating variable, is measured using indicators such as infrastructure availability, technical expertise, and coordination mechanisms within the institution.

Model Specification

To empirically test the relationships proposed in the conceptual framework, the study employs Ordinary Least Squares (OLS) regression models. The baseline specification examines the direct effect of circular economy adoption on institutional sustainability outcomes.

The general model is specified as follows:

$$IS_i = \alpha + \beta_1 CE_i + \beta_2 X_i + \varepsilon_i$$

where IS_i represents institutional sustainability for observation i, CE_i captures the level of circular economy adoption, X_i is a vector of control variables, and ε_i is the error term.

To capture the multidimensional nature of sustainability, the analysis is extended to estimate separate models for each outcome channel.

Environmental Performance Model (H1)

$$ENV_i = \alpha + \beta_1 CE_i + \beta_2 X_i + \varepsilon_i$$

Economic Efficiency Model (H2)

$$ECO_i = \alpha + \beta_1 CE_i + \beta_2 X_i + \varepsilon_i$$

Institutional Sustainability Model (H3)

$$IS_i = \alpha + \beta_1 CE_i + \beta_2 X_i + \varepsilon_i$$

Moderation Model

To test the moderating role of institutional capacity, interaction terms are introduced into the model. This allows the study to assess whether the effectiveness of circular economy interventions varies depending on institutional readiness.

$$IS_i = \alpha + \beta_1 CE_i + \beta_2 IC_i + \beta_3 (CE_i \times IC_i) + \beta_4 X_i + \varepsilon_i$$

where IC_i represents institutional capacity and $(CE_i \times IC_i)$ captures the interaction effect.

A positive and significant coefficient for the interaction term (β_3) would indicate that higher institutional capacity strengthens the impact of circular economy adoption on sustainability outcomes, consistent with Hypothesis H4.

Estimation Technique and Diagnostic Tests

The choice of OLS estimation is appropriate given the continuous nature of the constructed indices and the study's focus on estimating linear relationships between variables. To ensure the reliability of the results, robust standard errors are employed to correct for potential heteroskedasticity.

Diagnostic tests are conducted to assess model validity, including checks for multicollinearity, model specification, and residual distribution. Variance Inflation Factors (VIF) are used to evaluate the presence of multicollinearity among explanatory variables, while residual plots are examined to ensure the assumptions of linear regression are not violated.

Although the cross-sectional nature of the data limits causal inference, the inclusion of relevant control variables and the use of a structured analytical framework strengthen the credibility of the estimated relationships.

Integration of Qualitative Evidence

To complement the econometric analysis, qualitative data from key informant interviews and project documentation are systematically integrated into the interpretation of results. These insights provide evidence on operational challenges, behavioral responses, and institutional constraints that are not fully captured by quantitative measures.

For instance, qualitative findings related to staffing limitations, infrastructure constraints, and implementation delays are used to contextualize the moderating role of institutional capacity. This mixed-methods approach enhances the explanatory power of the study and provides a richer understanding of the mechanisms through which circular economy interventions influence institutional outcomes.

Alignment with Conceptual Framework and Hypotheses

The econometric models specified above are directly derived from the conceptual framework presented in Figure 1. Circular economy adoption serves as the central explanatory variable, influencing environmental performance (H1), economic efficiency (H2), and overall institutional sustainability (H3). The inclusion of interaction terms allows for testing the moderating effect of institutional capacity (H4).

This alignment ensures coherence between theory, empirical strategy, and hypothesis testing, thereby strengthening the analytical rigor and internal consistency of the study.

RESULTS

Descriptive and Operational Overview

The implementation of circular economy interventions under the Greatwaste project provides important preliminary insights into institutional performance. The integrated system combining waste-to-energy (biogas) and additive manufacturing (3D printing) resulted in measurable environmental, economic, and operational improvements.

From an environmental perspective, the interventions contributed to an estimated 4.8% reduction in greenhouse gas (GHG) emissions, primarily through the diversion of organic waste from landfill and substitution of conventional energy sources with biogas. At the same time, plastic waste recycling through 3D printing reduced material waste streams and supported localized production.

Economically, the system generated cost savings in energy consumption and material procurement, although these savings varied depending on operational efficiency and system utilization rates. Operationally, improvements were observed in waste segregation practices, workflow efficiency, and institutional awareness of sustainability practices.

These preliminary observations provide descriptive support for the hypothesized relationships and motivate the econometric analysis that follows.

Descriptive Statistics

Table 1. Descriptive Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Institutional Sustainability (IS)	120	3.42	0.68	1.80	4.80
Circular Economy Adoption (CE)	120	3.15	0.72	1.50	4.70
Environmental Performance (ENV)	120	3.58	0.64	2.00	4.90
Economic Efficiency (ECO)	120	3.21	0.70	1.70	4.60
Institutional Capacity (IC)	120	2.95	0.75	1.40	4.50

The descriptive statistics indicate moderate levels of circular economy adoption and institutional sustainability. Environmental performance exhibits relatively higher mean values, reflecting the immediate benefits of waste diversion and energy substitution. In contrast, institutional capacity shows comparatively lower levels, suggesting constraints in infrastructure, technical expertise, and coordination.

Correlation Analysis

Table 2. Correlation Matrix

Variables	CE	ENV	ECO	IS	IC
CE	1				
ENV	0.51***	1			
ECO	0.47***	0.42***	1		
IS	0.58***	0.49***	0.46***	1	
IC	0.39***	0.35***	0.33***	0.44***	1

*Notes: *** $p < 0.01$*

The correlation results show strong positive associations between circular economy adoption and all outcome variables. The strongest correlation is observed between circular economy adoption and institutional sustainability (r = 0.58), providing preliminary support for the central hypothesis of the study.

Regression Results: Environmental Performance (H1)

Table 3. OLS Results – Environmental Performance

Variable	Coefficient	Std. Error	p-value
Circular Economy (CE)	0.42	0.06	0.000
Institutional Capacity (IC)	0.21	0.05	0.001
Constant	1.18	0.24	0.000
R^2	0.36		

The results indicate that circular economy adoption has a positive and statistically significant effect on environmental performance (β = 0.42, p < 0.01), supporting H1. This finding confirms that waste-to-energy and recycling interventions contribute to measurable environmental improvements, including emission reductions and waste minimization.

The significance of institutional capacity suggests that environmental gains are partially dependent on the availability of infrastructure and technical expertise.

Regression Results: Economic Efficiency (H2)

Table 4. OLS Results – Economic Efficiency

Variable	Coefficient	Std. Error	p-value
Circular Economy (CE)	0.35	0.07	0.000
Institutional Capacity (IC)	0.27	0.06	0.000
Constant	1.05	0.26	0.000
R^2	0.31		

Circular economy adoption is found to have a positive and statistically significant effect on economic efficiency (β = 0.35, p < 0.01), supporting H2. This indicates that waste-to-resource systems reduce operational costs, particularly in energy and material usage.

However, the magnitude of the coefficient is smaller than that observed for environmental performance, suggesting that economic benefits may take longer to materialize or depend more heavily on system optimization.

Regression Results: Institutional Sustainability (H3)

Table 5. OLS Results – Institutional Sustainability

Variable	Coefficient	Std. Error	p-value
Circular Economy (CE)	0.48	0.05	0.000
Institutional Capacity (IC)	0.29	0.06	0.000
Constant	0.92	0.22	0.000
R^2	0.44		

The results show that circular economy adoption has the strongest effect on institutional sustainability ($\beta = 0.48$, $p < 0.01$), supporting H3. This suggests that the combined environmental, economic, and operational benefits translate into broader institutional improvements.

This finding reinforces the argument that circular economy interventions function as institutional transformation mechanisms, rather than isolated technical solutions.

Moderation Analysis: Institutional Capacity (H4)

Table 6. Moderation Effects

Variable	Coefficient	Std. Error	p-value
CE	0.31	0.07	0.000
IC	0.24	0.06	0.000
CE × IC	0.18	0.05	0.002
Constant	0.88	0.21	0.000
R^2	0.49		

The interaction term (CE × IC) is positive and statistically significant ($\beta = 0.18$, $p < 0.01$), providing strong support for H4. This indicates that institutional capacity enhances the effectiveness of circular economy interventions.

In practical terms, institutions with better infrastructure, technical skills, and coordination mechanisms are more capable of translating circular economy adoption into sustainability outcomes.

Qualitative Triangulation

The quantitative findings are strongly supported by qualitative evidence. Interviews with stakeholders reveal that staffing constraints, technical limitations, and infrastructure gaps affected the speed and efficiency of implementation.

For example, respondents noted that delays in waste segregation and processing reduced the efficiency of the biogas system, while limited technical expertise constrained the full utilization of 3D printing technologies. At the same time, respondents emphasized increased awareness and improved waste management practices, indicating positive behavioral change.

These insights reinforce the econometric findings, particularly the moderating role of institutional capacity.

Summary of Findings

Overall, the results provide consistent evidence that circular economy interventions significantly improve environmental performance, economic efficiency, and institutional sustainability. However, the effectiveness of these interventions is strongly influenced by institutional capacity.

The findings suggest that while circular economy adoption delivers immediate environmental benefits, its broader institutional impact depends on the ability of organizations to effectively implement and manage these systems.

DISCUSSION

This study set out to examine whether circular economy interventions improve institutional sustainability within a resource-constrained setting, using micro-level evidence from an integrated waste-to-energy and additive manufacturing system. The findings provide strong empirical support for the central premise that circular economy adoption generates multidimensional benefits, while also highlighting the critical role of institutional capacity in shaping these outcomes.

A key finding of the study is that circular economy interventions have a significant and positive effect on environmental performance, as evidenced by reductions in waste volumes and greenhouse gas emissions. This aligns closely with circular economy theory, which emphasizes the transformation of waste into valuable inputs as a mechanism for reducing environmental externalities (Geissdoerfer et al., 2020). The observed GHG reduction reinforces existing empirical evidence that waste-to-energy systems can play a meaningful role in mitigating emissions, particularly in contexts where landfill disposal remains the dominant waste management strategy (Atelge et al., 2020). Importantly, the results demonstrate that even relatively small-scale institutional interventions can generate measurable environmental gains, thereby supporting the scalability of such approaches in similar settings.

The analysis also reveals that circular economy adoption contributes positively to economic efficiency, although the magnitude of this effect is comparatively smaller than that observed for environmental outcomes. This finding is consistent with prior research suggesting that while circular economy systems can reduce operational costs, these benefits often depend on utilization rates, technological maturity, and economies of scale (Gebler et al., 2021). In the context of this study, the modest effect size reflects the early-stage implementation of the interventions, where initial setup costs and operational constraints may limit immediate financial gains. Nevertheless, the results confirm that circular economy practices can enhance resource efficiency and reduce institutional expenditure over time, particularly in energy and material usage.

The most compelling finding of the study is the strong effect of circular economy interventions on institutional sustainability, which encompasses environmental, economic, and operational dimensions. This result extends the literature by demonstrating that circular economy adoption functions not merely as a technical or environmental intervention, but as a broader mechanism of institutional transformation. From a resource-based perspective, the integration of biogas systems and additive manufacturing represents a strategic capability that enhances organizational performance through innovation, cost optimization, and improved resource management (Barney, 1991). At the same time, from an institutional economics perspective, these interventions signal a shift toward more efficient and sustainable governance practices.

The moderation analysis further underscores the importance of institutional capacity in determining the effectiveness of circular economy interventions. The positive and significant interaction effect indicates that institutions with stronger infrastructure, technical expertise, and coordination mechanisms are better able to translate circular economy adoption into sustainability outcomes. This finding is consistent with the broader literature on institutional performance, which emphasizes that the success of policy interventions depends critically on implementation capacity (Acemoglu & Robinson, 2019; World Bank, 2023). In practical terms, this suggests that the same circular economy intervention can yield vastly different outcomes depending on the institutional context in which it is implemented.

The qualitative evidence provides important insights into the mechanisms underlying these relationships. Reports of staffing limitations, technical constraints, and coordination challenges highlight the operational barriers that can reduce the efficiency of circular economy systems. At the same time, improvements in waste segregation practices and increased awareness among staff indicate that circular economy interventions can foster behavioral and organizational change, which are essential components of long-term sustainability.

Taken together, these findings contribute to the literature in several important ways. First, the study provides micro-level empirical evidence on the effectiveness of integrated circular economy interventions within an institutional setting in Sub-Saharan Africa, a context that remains underrepresented in existing research. Second, it advances the conceptualization of circular economy by demonstrating its multidimensional impact, extending beyond environmental outcomes to include economic efficiency and institutional performance. Third, it highlights the role of institutional capacity as a critical moderating factor, thereby bridging the gap between technological adoption and governance outcomes.

From a policy perspective, the results suggest that circular economy interventions should be viewed not only as environmental solutions but also as strategic tools for institutional strengthening. Investments in waste-to-energy systems and recycling technologies can generate multiple co-benefits, including cost savings, improved operational efficiency, and enhanced sustainability performance. However, the effectiveness of such investments depends on complementary improvements in institutional capacity, including infrastructure development, technical training, and coordination mechanisms.

At the same time, the findings caution against assuming that circular economy adoption will automatically lead to optimal outcomes. Without adequate capacity and institutional support, the benefits of these interventions may remain limited or unevenly distributed. This underscores the need for a more integrated approach that combines technological innovation with institutional development.

Overall, the study demonstrates that circular economy interventions have significant potential to improve institutional sustainability in resource-constrained settings. However, realizing this potential requires not only the adoption of appropriate technologies but also the strengthening of institutional capacity and governance structures. In this regard, the findings provide valuable insights for policymakers, development partners, and institutional leaders seeking to scale circular economy solutions in similar contexts.

CONCLUSION

This study investigated the extent to which circular economy interventions improve institutional sustainability within a resource-constrained setting, using micro-level evidence from an integrated waste-to-energy and additive manufacturing system. Anchored in circular economy theory, institutional economics, and the resource-based view, the study conceptualized circular economy adoption as a multidimensional intervention influencing environmental performance, economic efficiency, and operational effectiveness.

The findings demonstrate that circular economy interventions significantly enhance institutional sustainability through multiple pathways. While environmental improvements particularly in terms of waste reduction and greenhouse gas mitigation are immediate and pronounced, economic gains are more gradual and contingent on operational efficiency and system utilization. Most notably, the study shows that circular economy adoption contributes to broader institutional transformation by improving resource management practices, enhancing operational processes, and fostering sustainability-oriented behavior.

A central insight of the study is that the effectiveness of circular economy interventions is not uniform but depends critically on institutional capacity. Institutions with stronger infrastructure, technical expertise, and coordination mechanisms are better positioned to translate circular economy adoption into sustained performance gains. This highlights the importance of moving beyond technology-centered approaches toward integrated strategies that combine innovation with institutional strengthening.

Overall, the study advances the literature by demonstrating that circular economy interventions function not only as environmental solutions but also as strategic drivers of institutional sustainability, particularly in developing country contexts where resource constraints and inefficiencies are more pronounced.

POLICY RECOMMENDATIONS

The findings of this study provide several important policy insights for governments, development partners, and institutional leaders seeking to promote circular economy adoption.

First, policymakers should mainstream circular economy interventions within institutional operations, particularly in high-resource-consuming sectors such as health and research facilities. Integrated systems combining waste-to-energy and material recycling should be prioritized, as they generate multiple co-benefits across environmental, economic, and operational dimensions.

Second, there is a need to invest in institutional capacity development as a prerequisite for effective circular economy implementation. This includes strengthening infrastructure, providing technical training, and improving coordination mechanisms. Without these enabling conditions, the potential benefits of circular economy interventions may not be fully realized.

Third, governments and development partners should promote scalable and context-specific circular economy models tailored to resource-constrained environments. Rather than relying on large-scale, capital-intensive systems, emphasis should be placed on adaptable, institution-driven innovations that can be replicated across similar settings.

Fourth, financial and regulatory frameworks should be designed to incentivize circular economy adoption. This may include subsidies for renewable energy systems, support for recycling technologies, and policies that encourage waste segregation and resource recovery within institutions.

Fifth, institutional leadership should prioritize behavioral and organizational change, recognizing that circular economy adoption requires shifts in practices, attitudes, and workflows. Awareness campaigns, staff engagement, and internal accountability mechanisms can enhance the effectiveness and sustainability of interventions.

RESEARCH LIMITATIONS

Despite its contributions, this study is subject to several limitations that should be acknowledged.

First, the analysis is based on a single institutional case study, which may limit the generalizability of the findings to other contexts. While the case provides valuable insights into circular economy implementation in resource-constrained settings, future studies should consider multiple institutions or cross-country comparisons to enhance external validity.

Second, the study relies partly on constructed indices and operational data, which, although appropriate for capturing multidimensional outcomes, may not fully reflect all aspects of institutional sustainability. Measurement challenges, particularly in quantifying behavioral and organizational changes, remain a limitation.

Third, the cross-sectional nature of the data limits the ability to capture long-term effects of circular economy interventions. Economic benefits, in particular, may evolve over time as systems mature and operational efficiencies improve.

Fourth, while qualitative data were used to triangulate findings, there may still be unobserved institutional dynamics such as informal practices or governance constraints that are not fully captured in the analysis.

FUTURE RESEARCH DIRECTIONS

Future research should extend this analysis by employing longitudinal designs to examine how the impacts of circular economy interventions evolve over time. Comparative studies across institutions and sectors would also provide deeper insights into the role of context in shaping outcomes.

Additionally, further work is needed to develop more refined measures of institutional sustainability, particularly in relation to behavioral change and governance processes. Exploring the interaction between circular economy interventions and broader development policies, such as climate finance and green growth strategies, would also enhance understanding of their systemic impact.

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