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A Proposed Circular Economy Model for Hospital Bio-Waste Management in Municipal Settings

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Abstract: This paper presents a proposed circular economy (CE) model for hospital bio-waste management, using Athens as a case study to demonstrate its applicability in urban environments. The model incorporates waste segregation at the source, resource recovery methods such as composting and anaerobic digestion, and data-driven tools to enhance the efficiency and sustainability of healthcare waste management. The study investigates the transition from linear to CE practices, focusing on structured collection strategies, collaborative efforts between hospitals and municipal authorities, and continuous tracking of waste flows. A comprehensive analysis of bio-waste volumes from participating hospitals over a three-year period is conducted, utilizing multi-criteria decision-making (MCDM) tools such as TOPSIS to evaluate the system's effectiveness. The results indicate a significant increase in hospital participation, improved waste separation, and optimized resource recovery, offering a scalable framework for other municipalities seeking to implement CE-based waste management practices in healthcare settings.

Keywords: climate change; sustainable healthcare; sustainable cities; circular economy; urban sustainability; sustainable development goals; bio-waste management; decision-making methodology; TOPSIS method

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1. Introduction

Transitioning to a CE model in the context of hospital bio-waste management is far from straightforward, as it demands not only a shift in waste processing but also a fundamental change in how hospitals approach sustainability. By addressing the challenges of resource recovery and waste minimization, this study demonstrates how CE principles could be more realistically applied in the hospital setting. Hospital bio-waste, including infectious, hazardous, and organic materials, poses significant environmental and public health risks if not managed effectively [1]. Traditional linear models, characterized by waste disposal without resource recovery, are inadequate for addressing the rising waste volumes generated by healthcare facilities [2]. This research delves into how circular economy (CE) principles can revolutionize hospital bio-waste management within cities, responding to the limitations of conventional models by prioritizing resource recovery and sustainable practices.

While the traditional "take–make–dispose" model has long dominated waste management, its environmental and economic shortcomings are becoming increasingly apparent, especially in sectors like healthcare where waste streams are often hazardous. This model, particularly in the healthcare sector, is becoming increasingly unsustainable due to the growing volume of bio-waste generated by hospitals. Linear approaches often lead to the incineration or landfilling of bio-waste, causing significant environmental impacts, including greenhouse gas emissions and the depletion of valuable resources [3]. The adoption of CE principles within hospital waste management contributes to urban sustainability by reducing environmental impacts, enhancing resource efficiency, and supporting circular resource flows [4]. By adopting CE principles, the model transforms hospital bio-waste into resources like compost or energy, contributing to the broader objectives of urban sustainability and circular resource use [5].

The selection of the TOPSIS method in this study is driven by its capability to address multi-criteria decision-making challenges, particularly in complex systems such as hospital bio-waste management. TOPSIS offers a systematic framework to evaluate and rank alternatives based on their closeness to an ideal solution, making it particularly suitable for comparing the performance of waste management strategies across multiple sustainability criteria. This approach ensures robust and objective decision-making, aligning with the primary objectives of circular economy principles. The choice of TOPSIS is further justified by its ability to manage complex decision-making processes involving multiple, often conflicting criteria. In the context of hospital bio-waste management, where factors such as environmental impact, cost efficiency, and resource recovery hold varying levels of priority, TOPSIS ensures a balanced and transparent evaluation. Its computational efficiency and proven applicability in sustainability-related studies make it particularly suitable for urban waste management scenarios. This method allows stakeholders to assess alternatives systematically, thereby aligning decisions with circular economy principles while addressing both environmental and operational goals.

In the context of sustainable cities, it is essential for healthcare facilities to integrate with urban bio-waste management systems to enhance overall efficiency and effectiveness. Partnerships between healthcare providers and municipal waste management services are crucial for aligning waste management practices with broader sustainability goals [6]. Furthermore, sustainable procurement practices in hospitals, such as choosing suppliers that prioritize eco-friendly products and sustainable practices, can significantly contribute to reducing the overall environmental impact of healthcare facilities [7]. This holistic approach promotes a culture of sustainability within the healthcare sector, ensuring a sustainable future for cities and communities.

Municipalities adopting CE models in hospital waste management can see reductions in greenhouse gas emissions and improvements in public health. This approach not only reduces the environmental footprint of waste management but also aligns with broader sustainability goals, such as reducing greenhouse gas emissions and promoting resource efficiency [8]. The healthcare sector, with its large volume of hazardous and organic waste, presents a significant opportunity for municipalities to apply CE models effectively [9].

The transition to a circular model in hospital bio-waste management also offers potential economic benefits for municipalities. By investing in composting facilities and advanced waste segregation systems municipalities can reduce the cost of waste disposal while generating new revenue streams from recovered resources [10]. Moreover, the integration of CE models fosters stronger collaboration between hospitals and municipal authorities, encouraging innovation in waste handling practices and improving overall public health outcomes [11].

This research uniquely contributes to the existing literature by providing a comprehensive framework that integrates circular economy principles with advanced decision-making methodologies, specifically TOPSIS, to address the critical challenges of hospital bio-waste management in urban contexts. The study raises an important question: Can the principles of circular economy truly transform the way hospital bio-waste is managed, especially within densely populated urban settings? Our objective is to assess if and how these principles can contribute not only to resource recovery but also to creating healthier and more resilient cities. The study utilizes a three-year dataset of bio-waste volumes from hospitals in Athens to assess the CE model's impacts on waste management efficiency and sustainability. By analyzing these trends through the TOPSIS multi-criteria decision-making tool, we aim to quantify the model's effectiveness in fostering sustainable practices in urban healthcare waste systems

Following this introduction, Section 2 delves into the existing literature, focusing on the limitations of linear models and the opportunities that circular systems present for hospital waste management. Section 3 elaborates on the circular economy (CE) model applied in Athens, describing the bio-waste collection system, the collaboration between hospitals and municipal authorities, and the integration of advanced tracking technologies. Section 4 presents the methodology, outlining data collection procedures and the application of the TOPSIS decision-making tool to evaluate the impact of the CE model. Section 5 offers a discussion of the results, situating the findings within the broader context of related research, and identifying the primary successes and ongoing challenges of the model's implementation. Finally, Section 6 provides conclusions and explores the implications for expanding CE-based waste management practices in urban healthcare systems.

Through this analysis, we aim to demonstrate the feasibility and benefits of integrating circular economy principles into healthcare waste management and to provide a framework for other cities and healthcare systems to adopt similar models. The study underlines how a holistic CE approach can facilitate the transformation of waste management practices, ensuring both environmental and economic gains.

2. Literature Review

Municipalities today face mounting pressures to adopt sustainable waste management systems, making the transition from a linear economy to a circular economy (CE) model especially urgent when it comes to managing hospital bio-waste. This shift responds directly to the pressing need for environmental and economic resilience within urban settings. Unlike linear models, CE emphasizes resource recovery, reducing landfill dependency and environmental impacts, which are particularly critical in urban hospital settings. This transition not only promotes recycling and waste reduction but also aligns with broader urban sustainability goals, helping cities address the environmental challenges posed by increased waste volume [12].

Amid intensifying regulatory mandates and public calls for greener practices, municipalities are facing increasing pressure to rethink traditional waste approaches—especially in high-risk areas like healthcare waste. Linear disposal methods fail to fully mitigate the hazards posed by bio-waste, often compromising public health and ecological integrity. Circular economy models offer a solution by promoting resource recovery and reducing landfill dependency, thus minimizing the environmental footprint and enhancing urban resilience [13,14]. Moreover, multi-criteria decision-making (MCDM) tools such as TOPSIS have been widely utilized to evaluate and prioritize waste management strategies based on sustainability criteria, providing a systematic approach to addressing complex urban challenges [15,16].The high costs associated with hazardous waste disposal and the need for safer, more efficient waste management further drive municipalities towards CE principles, which enable economic savings and environmental protection through sustainable bio-waste processing.

Furthermore, studies and efforts underscore the environmental and economic advantages of shifting from linear to circular waste management, especially for sectors like healthcare where waste generation is substantial and complex [17,18]. In adopting CE models, municipalities can implement advanced segregation and treatment technologies that not only ensure safe disposal but also facilitate the recovery of resources, such as energy from biogas or organic fertilizers from compost [19]. TOPSIS has also been employed to evaluate trade-offs among conflicting criteria, such as cost efficiency, environmental impact, and resource recovery, providing actionable insights for implementing circular economy principles [19]. This shift aligns with global sustainability targets and helps municipalities address the dual challenges of increasing waste volumes and stringent environmental standards [20,21].

Healthcare bio-waste, though not classified as hazardous waste, raises significant concerns due to its potential environmental and public health impacts [22]. European researchers emphasize that improper disposal practices can adversely affect urban ecosystems and human health, particularly in densely populated cities, where the risk of contamination and pollution is heightened [23]. In response, a shift toward circular economy (CE) models is essential, emphasizing waste treatment systems that not only ensure safe disposal but also facilitate resource recovery. CE models that have been implemented and several future scenarios encourage municipalities to adopt structured, sustainable waste management practices, including segregation, treatment, and the repurposing of bio-waste into valuable resources like compost or energy [24,25].

Assessment strategies play a pivotal role in optimizing waste collection schemes in urban areas, enabling municipalities to refine their approaches and improve efficiency [26]. The literature highlights several key strategies that municipalities should adopt when transitioning from linear to CE models in hospital bio-waste management. These include collection systems, waste segregation at source, and frequent collection schedules to minimize contamination and ensure efficient processing [27]. For instance, Seruga (2016) outlines the benefits of door-to-door waste collection in the case of rural areas with various standard bins being used, where bio-waste from multiple spots is processed at a single facility equipped with advanced technologies such as anaerobic digestion and composting [28].

Policy frameworks are pivotal in establishing a foundation for CE in healthcare waste management, as documented in numerous case studies [19]. In addition to robust policy frameworks, MCDM tools like TOPSIS play a crucial role in aligning municipal waste management practices with sustainability goals, offering a structured framework to assess and optimize diverse waste management [29]. Such frameworks not only drive compliance but also encourage proactive innovation, pushing hospitals and municipalities toward sustainable practices through incentives and regulatory requirements. Governments must establish regulations that encourage sustainable waste management practices, such as providing financial incentives for hospitals that adopt eco-friendly technologies The successful implementation of CE models in hospital bio-waste management is also closely tied to innovation and technological advancements. According to the World Economic Forum (2020), the use of advanced waste treatment technologies, such as autoclaving and anaerobic digestion, has been crucial in reducing the environmental impact of bio-waste [30]. These technologies not only ensure the safe disposal of hazardous waste but also enable the recovery of valuable resources, such as biogas [31].

Athens, for instance, illustrates the tangible benefits of integrating hospital bio-waste with city-wide waste systems, achieving notable improvements in sustainability and significant cost savings. The Athens model also highlights the efficiencies gained through municipal oversight, helping ensure regulatory compliance while enhancing operational synergy [32]. In conclusion, the CE model for managing hospital bio-waste not only presents a pathway to sustainable urban development but also sets a compelling precedent for cities worldwide. By adopting CE principles, cities can reduce waste, promote recycling, and minimize the environmental risks associated with hospital bio-waste. The literature strongly supports the assertion that municipalities need to prioritize CE models, particularly in the healthcare sector, to ensure long-term sustainability [33].

Globally, several cities and municipalities have adopted circular economy (CE) principles to manage hospital bio-waste, showcasing a wide range of strategies and technologies. Municipal authorities have integrated composting facilities to handle bio-waste from healthcare institutions, significantly reducing the volume of waste sent to landfills [34]. In Germany, the integration of bin collection systems with local treatment facilities has significantly enhanced waste diversion rates in urban hospitals. This approach has led to improved segregation and recycling outcomes, aligning with the country's stringent waste management regulations [35]. The "Closed Substance Cycle Waste Management Act" mandates the prevention, recycling, and disposal of waste, emphasizing the importance of proper waste segregation at the source. Hospitals are required to designate responsible personnel to ensure adherence to these regulations, incorporating waste management into their quality management systems. By implementing these measures, German hospitals have achieved more efficient waste processing and increased recycling rates, contributing to environmental sustainability [36].

In Spain, government-led initiatives have fostered public–private partnerships to promote circular economy (CE) models in hospital waste management. The "España Circular 2030" strategy outlines objectives to reduce resource consumption and waste generation, encouraging collaboration between public and private sectors [37]. Public–private partnerships have proven instrumental in advancing CE practices, especially in urban settings where resource constraints and logistical challenges require collaborative solutions. These partnerships enable cities to leverage private sector expertise and resources, enhancing the scalability and efficiency of waste management systems. As seen in other CE implementations, such collaborations facilitate smoother integration of circular practices, fostering a culture of sustainability across sectors.

While technological advancements in bio-waste treatment remain crucial to the success of the CE, their efficacy depends heavily on adaptation to local contexts and ongoing stakeholder engagement. Anaerobic digestion (AD), a process that converts organic waste into biogas, has been widely adopted across Europe. In Finland, companies have integrated waste management systems that utilize sorted bio-waste to produce electricity and heat, thereby creating a closed-loop system. Several biogas plants operate in Finland and Sweden, processing biodegradable waste into renewable energy and recycled fertilizers; this approach not only reduces landfill waste but also contributes to energy production, exemplifying the principles of a circular economy [38].

In recent years, the integration of digital tools into waste management systems has become crucial for improving efficiency. Smart waste tracking technologies enable municipalities to monitor waste flows in real time, optimizing collection schedules and ensuring that waste is treated at appropriate facilities. Several studies highlight the role of data-driven decision-making in reducing operational costs and improving waste management outcomes. For instance, IoT-based intelligent waste management systems utilize sensors to gather data on waste bin levels, facilitating timely collection and reducing overflow incidents. Additionally, data analytics frameworks support decision-makers in implementing, monitoring, and optimizing smart waste management systems by analyzing trends and patterns in waste generation. These data-driven approaches have been shown to reduce operational costs and improve waste management outcomes, contributing to more sustainable urban environments [39–41].

In the Netherlands, hospitals have implemented advanced waste management systems that monitor bio-waste from its point of origin to its final treatment, ensuring adherence to circular economy (CE) principles and reducing waste volumes. For example, the University Medical Center Utrecht (UMC Utrecht) has adopted the Sterilwave solution, which decontaminates medical waste on-site, transforming it into a safe, inert material suitable for recycling or disposal. This system enhances waste traceability and minimizes the need for external waste processing, aligning with CE objectives [42]. Additionally, initiatives like the Pharmafilter system have been installed in several Dutch hospitals, including Erasmus University Medical Center. This system processes hospital waste and wastewater on-site, converting organic waste into biogas and reducing the overall waste footprint [43]. These examples demonstrate healthcare institutions' commitment to utilizing smart waste management technologies, thereby promoting sustainability and resource efficiency.

The economic benefits of transitioning to circular economy (CE) models have been well documented in various studies. By adopting resource recovery methods, such as composting and biogas generation, municipalities can offset the costs associated with waste disposal while generating revenue from the sale of these by-products. For instance, the European Biogas Association highlights that several municipalities across the EU separately collect and digest organic municipal waste in biogas plants, resulting in multiple greenhouse gas emission savings and the production of renewable energy and organic fertilizers [44]. Additionally, the integration of composting innovations has been shown to transform waste into valuable products, contributing to a circular economy. These practices not only reduce landfill usage but also create economic opportunities through the commercialization of compost and biogas, thereby enhancing municipal revenue streams [45].

The transition to circular economy (CE) models significantly diminishes dependence on landfills and incineration, thereby reducing both the environmental and the economic burdens associated with waste management. For instance, the NHS Clinical Waste Strategy aims to transform waste management by eliminating unnecessary waste and finding innovative ways to reuse materials, ensuring waste is processed in the most cost-effective, efficient, and sustainable manner. Implementing such bio-waste treatment systems based on CE principles has led to substantial cost savings and environmental benefits [46].

In light of the growing environmental and economic challenges associated with hospital bio-waste, the transition to circular economy (CE) models has emerged as a necessary step for municipalities and healthcare institutions. The existing literature demonstrates the effectiveness of CE principles in improving resource recovery, reducing waste, and minimizing environmental risks. However, despite the advancements in technologies and policies, there remains a gap in understanding with regard to how these models can be systematically evaluated and optimized, particularly in urban settings.

This study addresses this gap by focusing on the application of a CE model for hospital bio-waste management in Athens. The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) methodology will be employed to evaluate the performance of this model, comparing various factors. The use of TOPSIS in this study provides a validated approach for prioritizing hospital bio-waste management strategies, ensuring that the selected solutions align with the principles of the circular economy. Through this approach, we aim to provide a comprehensive framework that can be adapted by other municipalities seeking to adopt CE models for sustainable urban development.

3. Material and Methods

This section outlines the strategic methodology applied to evaluate and optimize the bio-waste collection network in Athens's hospitals, designed within the framework of the circular economy (CE) model. Emphasizing waste minimization, resource recovery, and sustainability, our analysis employs the TOPSIS multi-criteria decision-making methodology to prioritize management strategies based on critical factors, including environmental impact, cost efficiency, resource recovery, scalability, and stakeholder acceptance.

3.1. Method Research Structure—Scientific Questions and Research Objectives

The focus of this research is to evaluate the application of a circular economy (CE) model for hospital bio-waste management within an urban context, with the city of Athens serving as the primary case study. The primary objective is to measure the environmental and economic benefits that can be achieved through CE principles in hospital bio-waste management, specifically examining stakeholder collaboration and resource recovery. The methodology's structured multi-criteria decision-making process aids in comparing the relative effectiveness of composting and landfill as bio-waste strategies. The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) methodology was selected to prioritize bio-waste management strategies based on multiple criteria, including environmental impact, cost efficiency, resource recovery, scalability, and stakeholder acceptance [47].

The research methodology follows a structured multi-criterion decision-making approach. This involves defining the relevant criteria and alternatives, assigning weights to each criterion, applying the TOPSIS method, and ranking the alternatives based on their relative closeness to the ideal solution. The choice to evaluate only two alternatives, composting and sanitary landfill, stems from their dominance in the existing Greek waste management systems. Composting represents an advanced, CE-compliant method that prioritizes resource recovery, while sanitary landfill reflects the basic option that, despite its drawbacks, remains a prevalent practice in urban settings. This binary focus ensures a clear and focused comparison between the innovative CE-aligned approach and the widely used traditional method.

First, the decision matrix was constructed, capturing the performance of each alternative against the defined criteria. The decision-making matrix was constructed based on expert consultations and publicly available data from similar waste management initiatives in European urban contexts. Experts from the Municipality of Athens, waste management authorities, and healthcare professionals provided insights into the performance of composting and sanitary landfill across the five criteria. The decision matrix was normalized to ensure comparability across different criteria, followed by the application of a weighting system. Each criterion was assigned a weight based on its importance to overall sustainability. The weights for the criteria were determined using the Analytical Hierarchy Process (AHP), a structured decision-making framework designed to quantify subjective judgments in multi-criteria scenarios. AHP was particularly suitable for this study due to its ability to integrate expert opinions systematically while maintaining transparency and consistency in the weighting process. Experts from diverse fields—including environmental science, healthcare management, and municipal waste operations—were consulted, ensuring a balanced reflection of environmental, economic, and operational priorities. This approach aligns with recent applications of AHP in sustainable planning, where criteria such as environmental impact and stakeholder acceptance are frequently prioritized to achieve long-term sustainability goals [48]. Next, the ideal solution (best possible outcomes) and negative-ideal solution (worst outcomes) were calculated. Finally, the Euclidean distance between each alternative and the ideal/negative-ideal solutions was determined, and the alternatives were ranked based on their relative closeness to the ideal solution.

The diagram below (Figure 1) provides a visual representation of the research methodology employed in this study, highlighting the key components and processes involved in our approach.

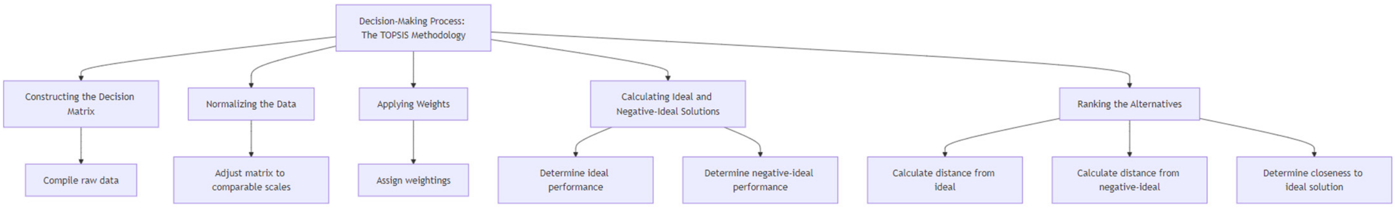

Figure 1. A schematic flowchart of the TOPSIS.

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) methodology was employed in the city of Athens to evaluate and rank bio-waste management strategies in hospitals, framed within the circular economy (CE) model. The two alternatives under consideration—composting and sanitary landfill—were assessed using five carefully selected criteria: environmental impact, cost efficiency, resource recovery, scalability, and stakeholder acceptance. Each criterion within the TOPSIS framework was carefully selected and weighted based on its relevance to sustainability goals. The weightings were determined through stakeholder and expert consultations, reflecting the priority of minimizing environmental impact, maximizing resource recovery, and ensuring cost-efficiency. Specifically, environmental impact and resource recovery were assigned higher weights, underscoring the importance of these factors in sustainable bio-waste management within urban hospital settings.

The initial decision matrix contains the raw performance data for each alternative under each criterion. The values represent the performance of composting and sanitary landfill on a scale relative to each criterion (Table 1).

Table 1. Alternatives' performance against each criterion.

Criterion	Composting	Sanitary Landfill
Environmental Impact	85	45
Cost Efficiency	65	80
Resource Recovery	90	25
Scalability	55	95
Stakeholder Acceptance	70	50

The decision matrix was normalized to adjust for different scales of measurement, allowing for a fair comparison across all criteria (Table 2).

Table 2. Normalized decision values.

Criterion	Composting	Sanitary Landfill
Environmental Impact	0.875	0.462
Cost Efficiency	0.622	0.766
Resource Recovery	0.955	0.265
Scalability	0.500	0.866
Stakeholder Acceptance	0.777	0.555

The weighted normalized matrix, obtained by multiplying each normalized value by its corresponding weight, is shown below (Table 3):

Table 3. Weighted normalized values.

Criterion	Composting	Sanitary Landfill
Environmental Impact	0.262	0.138
Cost Efficiency	0.093	0.115
Resource Recovery	0.191	0.053
Scalability	0.050	0.087
Stakeholder Acceptance	0.194	0.138

The weighting of criteria such as environmental impact, cost efficiency, and resource recovery was instrumental in guiding the decision-making process towards sustainable options. By assigning higher importance to environmental sustainability and stakeholder engagement, this methodology aligns with CE principles, prioritizing options that contribute to long-term urban sustainability.

The first step is shown below. The following five criteria were chosen to evaluate the alternatives based on their relevance to hospital bio-waste management, sustainability goals, and practical applicability. The goal is to rank alternatives for hospital bio-waste management in Athens according to key sustainability criteria that align with the principles of the circular economy (CE).

Environmental impact: Environmental sustainability is central to bio-waste management and the CE model. This criterion evaluates the potential of each alternative to reduce environmental harm, focusing on greenhouse gas emissions, pollution, and reducing landfill use. Composting, for example, is known to reduce methane emissions and return nutrients to the soil, whereas landfills are major contributors to environmental degradation.

Cost efficiency: Financial feasibility is crucial for municipalities and hospitals wishing to adopt any bio-waste management strategy. This criterion considers the overall costs of implementation, including capital investment, operational expenses, and long-term savings. Alternatives that offer cost-effective solutions while maintaining high sustainability standards are rated more favorably.

Resource recovery: A key aspect of the CE model is the reuse and recovery of resources from waste. This criterion evaluates the potential of each alternative to recover valuable materials or produce energy. Composting, which converts organic waste into valuable compost, ranks highly here, while landfills offer minimal resource recovery opportunities.

Scalability: The scalability criterion assesses the ability of each alternative to adapt to different scales of waste generation. Hospitals generate varying amounts of bio-waste depending on their size, so scalability is an important factor. A scalable solution ensures that smaller and larger hospitals alike can participate in the program with ease.

Stakeholder acceptance: The success of any waste management strategy depends on the participation and acceptance of stakeholders, including hospital staff, waste management authorities, and the public. This criterion measures the willingness and ability of key stakeholders to adopt and support the bio-waste management alternative. Composting, for instance, enjoys strong support in communities that prioritize sustainability, while landfill use faces more resistance due to its environmental drawbacks.

The second step of the TOPSIS method is to assign weights to the identified criteria. The weights reflect the relative importance of each criterion. The following two alternatives were implemented and analyzed based on their effectiveness in the local context.

Composting: Composting is a process that breaks down organic materials, such as food waste and biodegradable hospital waste, into nutrient-rich compost. This alternative was chosen due to its alignment with the CE principles of reducing landfill use, recovering valuable resources, and minimizing environmental harm. Composting has been success-fully implemented in various urban settings, and its potential to integrate with existing waste management systems in Greece makes it a viable solution for hospitals.

Sanitary landfill: Despite its environmental drawbacks, sanitary landfill remains a common practice in many countries, including Greece. This alternative was included to provide a comparison with composting, focusing on its cost-effectiveness and scalability. Sanitary landfill is less resource-intensive initially, but it contributes significantly to greenhouse gas emissions and offers no resource recovery. As a baseline alternative, it provides insight into the performance of composting when evaluated against conventional waste disposal methods.

In the TOPSIS method, the positive-ideal solution (PIS) represents the best possible outcome for each criterion, while the negative-ideal solution (NIS) represents the worst possible outcome. These solutions are calculated by selecting the maximum and minimum normalized values for each criterion:

- PIS: This alternative maximizes benefits (offering higher scores for positive criteria like resource recovery) and minimizes costs (lower scores for negative criteria like environmental impact).
- NIS: This alternative minimizes benefits and maximizes costs, representing the least favorable outcome.
- For each criterion, we state the following:
- PIS = {max value for benefit criteria, min value for cost criteria}.
- NIS = {min value for benefit criteria, max value for cost criteria}.

In continuation, the separation values (PIS and NIS) are presented in Table 4. Based on the separation values from the PIS and NIS, we are able to calculate the relative closeness of each alternative to the ideal solution. The formula for calculating the relative closeness is as follows:

$$R_i = \frac{d_i^-}{d_i^- + d_i^+}$$

Table 4. Separation values (PIS and NIS).

Alternative	Distance to PIS	Distance to NIS
Composting	0.345	0.781
Sanitary Landfill	0.652	0.529

To validate the robustness of the TOPSIS results, a sensitivity analysis was conducted by varying the weights of the criteria within a $\pm 10\%$ range [49]. This variation tested the impact of altering the relative importance of environmental impact, cost efficiency, resource recovery, scalability, and stakeholder acceptance on the final ranking. The analysis consistently identified composting as the superior alternative, with its ranking remaining unchanged across all scenarios. This robustness underscores the reliability of the model and its alignment with CE principles, offering a systematic approach to decision-making in urban bio-waste management systems.

3.2. Applying the Decision-Making Methodology to Hospital Bio-Waste Management in the City of Athens

The CE-driven decision-making approach enables an objective evaluation of each bio-waste management strategy, focusing on sustainability impacts and resource efficiency. By employing TOPSIS, a clear, data-driven comparison emerges between composting and landfill. Composting aligns with CE principles by promoting resource recovery, while landfill remains tied to the traditional linear model. To evaluate these strategies, the following weights were assigned based on sustainability priorities: environmental impact

(30%), cost efficiency (15%), resource recovery (20%), scalability (10%), and stakeholder acceptance (25%).

After establishing the ideal and negative-ideal solutions, the Euclidean distance for each alternative was calculated, providing a clear ranking of bio-waste management strategies based on their closeness to the ideal solution.

Composting: Relative closeness = 0.781.
Sanitary landfill: Relative closeness = 0.529.

The analysis identified composting as the more sustainable option for hospital bio-waste, with a relative closeness of 0.781 to the ideal solution, compared to 0.529 for landfill. Composting's performance aligns closely with CE objectives, particularly in terms of environmental impact and resource recovery. The practice of converting hospital bio-waste into valuable organic matter supports Athens's broader sustainability goals, moving away from linear disposal models towards a regenerative, CE-aligned system.

While sanitary landfill scored higher in terms of cost efficiency and scalability, these benefits are overshadowed by its significant environmental drawbacks. The landfill method, though initially more affordable, contributes to greenhouse gas emissions and long-term land use issues, which run counter to the CE objectives of reducing the ecological footprint of urban waste management. For hospitals in Athens, particularly those participating in the bio-waste program, composting presents a far more sustainable solution that not only reduces environmental harm but also supports the city's ambition to integrate waste management into a circular, resource-recovering system.

The close collaboration between hospitals and the Municipality of Athens has been critical in implementing composting as a viable alternative. The high stakeholder acceptance of composting reflects the strong collaboration between healthcare providers and municipal authorities, reinforcing the city's commitment to achieving sustainable waste management under a circular economy framework Composting emerges as the superior choice within a CE framework due to its resource recovery potential and lower environmental impact, while sanitary landfill, despite its cost efficiency, does not align with sustainability targets due to its high emissions and lack of resource utilization. The results suggest that, as the city of Athens continues to scale its circular economy initiatives, composting will play a central role in transforming hospital bio-waste into valuable resources, further integrating hospitals into the city's sustainability framework.

3.3. Evaluation Methodology Description

The evaluation methodology aligns with CE goals by focusing on two core parameters: bio-waste production and stakeholder engagement. These parameters form a comprehensive framework to gauge the network's scalability and sustainability, ensuring that bio-waste is consistently diverted from traditional disposal methods while fostering growing stakeholder participation.

The first evaluation parameter involves tracking the total bio-waste volume produced by participating hospitals. By systematically collecting data over time, this metric reflects the success of waste separation practices and the program's overall impact on reducing landfill dependency. Data gathered at regular intervals provide insight into bio-waste trends across participating hospitals, highlighting whether improved separation practices have led to increased bio-waste diversion from traditional disposal methods.

The second key parameter evaluates the rate of hospital participation in the bio-waste network. Tracking the number of hospitals joining the network over the years offers a measure of the program's scalability, capturing its ability to integrate new facilities within a CE model. Systematic recording of hospital entries, supplemented by surveys and interviews, sheds light on the motivations behind engagement and hospitals' commitment to CE principles.

Evaluating hospital participation offers insight into the program's scalability and reflects the network's success in integrating healthcare facilities into the municipal CE model, enhancing the overall sustainability of urban bio-waste management. In terms of stakeholder engagement, the methodology involves tracking participation rates, identifying hospitals that have joined or exited the program, and determining the impact of these changes on overall bio-waste production. The participation trend will be evaluated using both quantitative measures (number of hospitals involved, bio-waste contributions) and qualitative feedback from hospital stakeholders.

This methodology provides a robust framework for assessing the success of the hospital bio-waste collection network, focusing on key performance indicators such as the volume of bio-waste produced and the expansion of hospital participation. To further validate the model, a comparative analysis was performed against historical data from European CE initiatives in urban bio-waste management. The outcomes were consistent with those reported in similar studies, reinforcing the validity of the methodology [13]. Future work will aim to incorporate real-time data tracking to enhance accuracy and adaptability.

Applying this methodology to real-world data will help refine the network's operational efficiency, providing a feedback loop that supports continuous improvement and strengthens the city's commitment to sustainable, CE-aligned waste management.

4. Strategic Implementation and Evaluation of the Bio-Waste Collection System for Hospitals in Athens: A Case Study

This section examines the strategic phases and operational challenges involved in implementing the hospital bio-waste collection system in Athens, with a focus on integrating circular economy principles into municipal waste management frameworks. Effective bio-waste management in healthcare facilities is crucial for ensuring environmental sustainability and mitigating the risks associated with improper waste disposal. This section discusses the implementation of bio-waste collection models in hospitals within the city of Athens, focusing on practical strategies and their integration with municipal waste management systems.

Optimizing Processes: The Methodological Framework for a Hospital Bio-Waste Collection System

To ensure effective bio-waste management in hospitals, Athens designed its collection program around phased implementation and source separation strategies. These processes aim to reduce contamination and support sustainability, which are key CE objectives. The Athens bio-waste program was rolled out in phases, initially focusing on organic waste collection from major producers, including hospitals. Phase one prioritized plant-based organic waste, which consistently creates a large waste stream within these facilities.

A primary strategy of the program emphasizes source separation, particularly of food waste, which constitutes a significant portion of hospital bio-waste. Source separation is critical for minimizing contamination and maximizing the quality of recovered materials, aligning directly with CE principles. Hospitals implemented an interior-yard collection system to ensure organic waste was isolated from other waste streams at the source. To support this, the Municipality of Athens provided specialized tools, such as compostable bags and designated bins for food waste, helping to maintain clean collection points. This setup not only minimized contamination but also enhanced hygiene, increasing staff participation in bio-waste management efforts. Recognizing food waste as a major component, the program emphasized segregation at the kitchen level. Participating hospitals received small (140–240 L) bins and compostable bags to facilitate collection within kitchens. Strategically placed bins encouraged convenient and hygienic collection practices. The compostable bags further reduced contamination risk, minimizing cleaning frequency—an important factor in food waste handling, as spoilage and pests are common issues. These measures led to marked improvements in both waste separation quality and overall kitchen hygiene.

The mandatory nature of this system, combined with ongoing training and public awareness campaigns, significantly increased compliance among hospitals and healthcare providers.

Hospitals collaborated closely with the Municipality of Athens, which played a central role in providing infrastructure, including 660 L bins and specialized collection vehicles. The Municipality's support in providing infrastructure has been pivotal in scaling the program, ensuring that hospitals have consistent access to necessary collection tools and transportation resources. These vehicles were designed to handle organic waste safely and efficiently, ensuring timely collection from each hospital. The program's success is largely attributable to the effective integration of hospitals within the broader municipal waste collection framework.

The frequency of bio-waste collection varies depending on climatic conditions and the volume of organic waste generated. In Mediterranean climates, such as that of Athens, frequent collection is necessary to prevent the accumulation of bio-waste that can lead to leachate production and pest infestations. Collection frequencies in Athens ranged from three to six times per week, depending on the hospital's output and the time of year.

Collection vehicles were also adapted to meet the specific needs of bio-waste transport. For example, food waste, which has a low bulk density and high moisture content, required the use of non-compacting vehicles to preserve the integrity of the waste during transportation. The municipality acquired specialized milled-type waste collection vehicles equipped with onboard washing systems to clean the bins immediately after emptying, ensuring high hygiene standards.

Despite the successes, several challenges have emerged during the implementation of bio-waste collection models in Athens' hospitals. One key issue is maintaining consistent participation from all hospitals and ensuring that bio-waste is properly segregated at the source. Challenges such as the high cost of compostable bags and the need for regular maintenance of collection vehicles underscore the ongoing financial and operational investment required to sustain the program.

Continuous education and training sessions were conducted for hospital staff, emphasizing the importance of proper waste segregation and the environmental benefits of bio-waste recycling. These initiatives significantly improved compliance rates and enhanced the overall effectiveness of the program. Further investments in infrastructure, including the expansion of the vehicle fleet and improved bag distribution systems, are also being considered to enhance the overall efficiency of the program.

The implementation of bio-waste collection models in Athens's hospitals, in collaboration with the Municipality of Athens, has provided a valuable case study in sustainable waste management practices. By focusing on source separation, specialized tools, and frequent collection, the program has succeeded in reducing contamination and improving the overall handling of hospital-generated bio-waste. Moving forward, continuous investment in infrastructure and education will be essential to maintaining the program's success and expanding its scope.

The following diagram (Figure 2) visually depicts the implementation framework for the hospital bio-waste collection system in Athens, detailing the strategic phases and core components of the program, from initial design to future planning and evaluation.

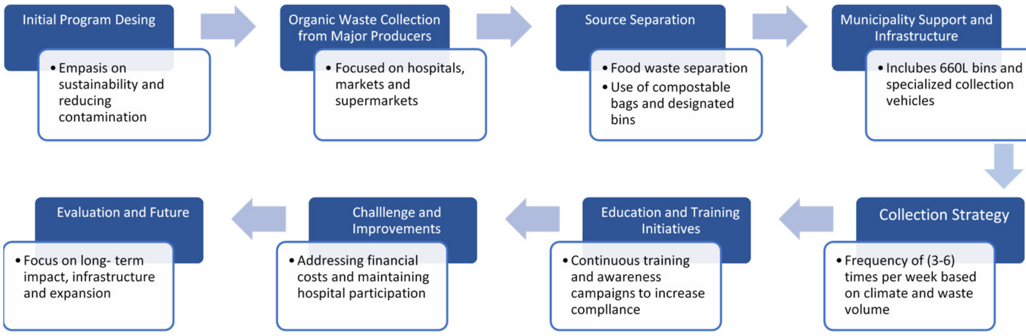

Figure 2. A flowchart of the phased implementation and optimization processes for hospital bio-waste collection in Athens.

Future efforts should focus on enhancing the program's financial sustainability and operational efficiency to ensure its long-term impact on hospital bio-waste management in Athens.

5. Findings. How Is CE Implemented in Hospital Bio-Waste Management?

This section presents the findings from the Athens hospital bio-waste management network, emphasizing trends in participant engagement and bio-waste production. The findings highlight the network's alignment with circular economy (CE) goals, focusing on how stakeholder participation and internal waste practices have evolved from 2021 to 2023.

The following Table 5 provides an overview of the annual bio-waste generation per hospital bed across Athens's hospitals that are participating in the management program.

Table 5. Bio-waste generation per hospital bed per year (2021–2023).

Year	Hospitals	Total Beds	Bio-Waste (Kg)	Bio-Waste Per Bed (Kg/Bed)
2021	18	7.224	599.456	83
2022	20	7.857	667.224	85
2023	20	7.843	808.044	103

A detailed analysis of bio-waste production per bed highlights further insights into the network's efficiency. The average annual bio-waste generated per hospital bed was calculated to be approximately 83 kg in 2021, 85 kg in 2022, and 103 kg in 2023 [50]. This steady increase in bio-waste generation per bed, despite the relatively stable number of beds in participating hospitals, underscores the effectiveness of enhanced segregation and internal waste management practices. These findings provide additional evidence of the network's scalability and its ability to optimize resource recovery within existing hospital infrastructure.

The phased initiation began as a pilot program in 2020, with 18 hospitals actively participating by 2021. This gradual inclusion enabled adaptive logistics and infrastructure upgrades, even amid the COVID-19 pandemic's heightened waste handling requirements.

In 2022, with municipal support, the network grew to 20 hospitals. Collection efficiency improved through optimized routes and additional infrastructure, reflecting ongoing refinements in waste management logistics and bin allocation. In 2023, participation was steady, and the network saw a substantial increase in bio-waste volume due to refined segregation practices within hospitals, indicating enhanced internal compliance and resource recovery. These year-on-year trends underline the network's capacity for sustainable bio-waste diversion, demonstrating that a focus on training, infrastructure, and compliance can significantly enhance resource recovery without expanding the network's scope.

Across these years, distinct trends emerge. The phased integration in 2021 led to a gradual increase in bio-waste volumes as more hospitals were brought into the network. By 2022, the focus shifted to refining operations, with collection efficiency improving through optimized routes and frequent collections. In 2023, with participation steady, bio-waste volume continued to rise due to effective segregation practices, underlining the network's success in sustainably managing waste without needing to expand its participant base. This consistent increase despite stable participation reflects the scalability and efficiency of the network, signaling that enhanced training, infrastructure, and compliance measures are key to maximizing bio-waste recovery.

The Municipality of Athens' support was instrumental in these outcomes, through investments in specialized collection vehicles, strategically placed bins, and streamlined routes. The continuous backing from the Municipality provided the structural backbone needed to manage increasing volumes of bio-waste, demonstrating the critical role of municipal support in sustainable CE-aligned waste management. Hospitals found it easier to comply with the collection model, which was strengthened by ongoing staff training and awareness initiatives. This continuous municipal backing allowed the program to absorb increased waste volumes and integrate new hospitals effectively, thereby reinforcing the CE objectives. Stakeholder acceptance, highlighted by high compliance rates among healthcare providers, further contributed to the program's overall success.

The graphical representation (Chart 1) highlights these trends visually, depicting the year-on-year growth in bio-waste volumes and underscoring the network's efficiency gains over time.

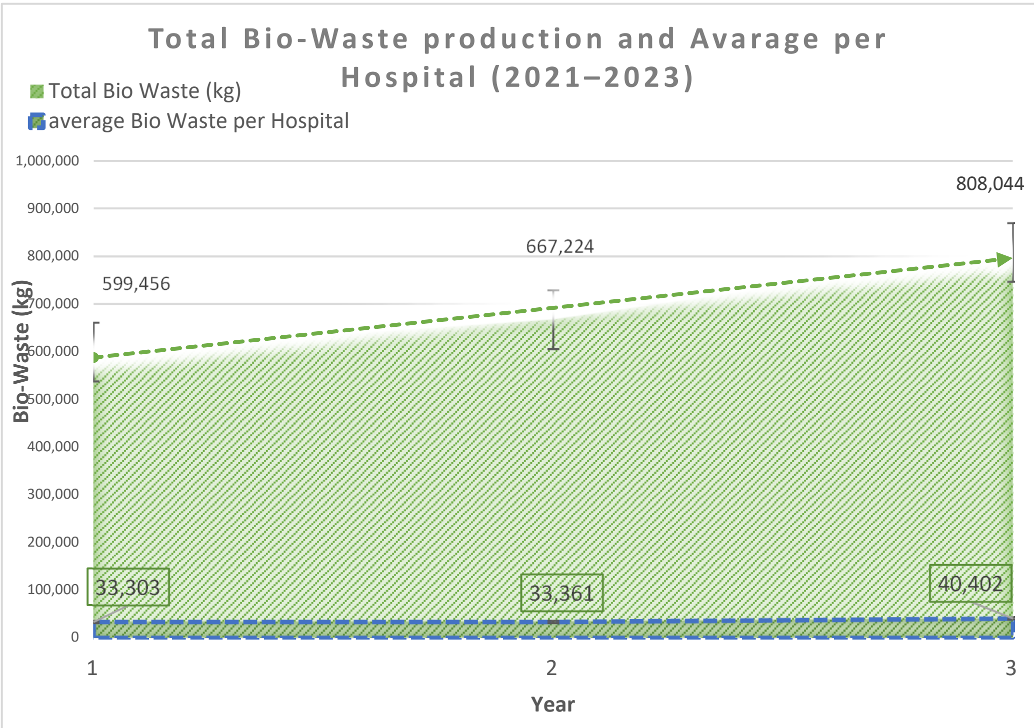

Chart 1. Bio-waste production 2021–2023.

The steady increase in bio-waste volumes, combined with consistent participant numbers, illustrates the model's scalability and adaptability, offering a robust foundation for other cities looking to implement CE-based hospital waste management. Athens' experience showcases a well-integrated, adaptable model that continuously improves through training, infrastructure investment, and alignment with sustainability principles. In summary, the strategic implementation of the bio-waste collection system in Athens's hospitals demonstrates the practical applicability of CE principles in urban waste management. The collaborative approach, continuous stakeholder engagement, and adaptive strategies were key factors contributing to the program's success. These findings set the stage for the subsequent discussion on the broader implications and potential for replication in other urban contexts. Additionally, the bio-waste per bed metric offers a replicable indicator for assessing the efficiency of hospital waste management programs. By incorporating this metric, the Athens model provides a benchmark for comparative analyses with similar CE-based programs globally, allowing municipalities to assess their progress and refine their waste management strategies.

6. Discussion

The analysis of bio-waste collection trends in hospitals across Athens over the three-year period underscores the success of the city's strategic approach to sustainable waste management under the principles of the circular economy (CE). This section discusses the effectiveness of the Athens model, comparing it to similar CE implementations in other urban contexts, and highlights the key factors contributing to its success. The consistent increase in bio-waste volumes, despite the stable number of participating hospitals between 2022 and 2023, highlights the effectiveness of the program's strategies, including enhanced segregation practices, staff training, and integration with municipal waste management systems. This adaptability, even during the COVID-19 pandemic, reflects the model's resilience and scalability in urban waste management contexts [12].

This alignment resonates with broader findings from European municipal waste systems, where CE models have demonstrated the potential for significant improvements in waste diversion and resource recovery [51]. The success of the Athens bio-waste program aligns with general trends observed in other European contexts where CE models have been implemented for urban waste management. Studies emphasize the importance of continuous stakeholder engagement, training, and infrastructure investment as fundamental factors that drive successful CE adoption in waste management systems [30].

The phased integration adopted in Athens, began with a smaller network of 18 hospitals in 2021 and expanded during 2023, reflects the effective expansion strategies observed in other CE implementations. Gradual integration allows for logistical adaptation and incremental optimization of processes, minimizing resistance among stakeholders and facilitating smoother adoption of CE practices [27].

The transition from a linear to a CE model for bio-waste management has resulted in multiple environmental and economic benefits. By promoting segregation at the source, the Athens program has reduced contamination, improved the quality of collected waste, and facilitated more efficient recycling and composting processes. Such practices align with broader CE objectives and have shown to increase waste diversion rates and reduce greenhouse gas emissions in other studies [33].

A notable trend that has been observed is the steady rise in bio-waste volumes between 2022 and 2023, even without the addition of new hospitals. This trend suggests that participating hospitals have optimized their internal waste management processes, contributing to more effective segregation and collection. The ongoing training and awareness campaigns have reinforced these practices, supporting Athens' sustainability goals and aligning with similar efficiencies observed in other urban CE initiatives [37].

The Athens hospital bio-waste program offers a compelling case for how CE principles can transform urban waste management systems. Its adaptability, scalability, and focus on continuous improvement establish a benchmark for similar initiatives. Future developments, including the potential integration of real-time monitoring, are expected to enhance operational efficiency further, supporting Athens' broader sustainability goals and offering a replicable model for other municipalities aiming to adopt CE-based waste management practices [41,44].

The Athens hospital bio-waste program serves as a compelling example of how CE principles can be effectively implemented in urban waste management. Its emphasis on adaptability, scalability, and ongoing improvement underscores the potential for long-term impact in meeting sustainability goals. As other municipalities look to adopt similar CE-based practices, Athens' experience offers valuable insights and a replicable framework that highlights the importance of stakeholder engagement, infrastructure investment, and the integration of advanced monitoring technologies.

7. Conclusions

The hospital bio-waste collection network implemented in Athens serves as a significant case study illustrating the effective integration of circular economy (CE) principles into urban waste management systems. Over the course of three years, the program has achieved steady growth, now involving 20 hospitals, and has consistently increased the volume of bio-waste diverted from conventional disposal methods. The stable hospital participation from 2022 to 2023, coupled with the notable rise in bio-waste volumes, underscores the success of enhanced segregation practices and optimized collection processes.

The strategic expansion that began in 2021—during the challenging COVID-19 pandemic—demonstrated the program's adaptability and resilience. Initially involving 18 hospitals, the phased integration of additional participants allowed the program to develop a robust network that could accommodate scaling and operational adjustments. This approach, marked by careful planning, continuous training, and strong municipal support, serves as a replicable model for other cities transitioning from linear to circular waste management systems.

Transitioning to a CE model in Athens has resulted in multiple environmental and economic benefits, including improved resource recovery, reduced reliance on landfills, and enhanced environmental stewardship. By promoting the separation and composting of bio-waste, the program supports sustainability goals and contributes to a cleaner and healthier urban environment. The observed increase in bio-waste volumes, particularly between 2022 and 2023, suggests that hospitals are actively engaging in Athens' broader initiative to foster resource efficiency and waste minimization.

Despite its successes, the study has certain limitations. First, the evaluation considered only two alternatives—composting and sanitary landfill—which, while reflective of current Greek waste management systems, may not capture the full spectrum of potential strategies. Expanding the analysis to include additional alternatives, such as waste-to-energy, could provide a more comprehensive understanding of CE applications. Second, the dataset, while spanning three years, is limited in its temporal scope. A longer-term dataset might offer greater insights into the program's scalability and resilience under varying conditions. Finally, the reliance on expert opinions for determining criteria weights, while methodologically sound, introduces a degree of subjectivity that could impact the generalizability of the findings.

Building on the findings of this study, future research should explore several avenues to enhance the understanding and application of CE principles in urban waste management. First, incorporating additional waste management alternatives, such as advanced waste-to-energy technologies or decentralized treatment systems, could broaden the analysis and could allow us identify innovative solutions. Second, conducting longitudinal studies that extend beyond three years could better capture the long-term impacts of CE models on urban sustainability. Third, integrating digital tools like IoT-based monitoring systems and predictive analytics could improve the accuracy and efficiency of waste management processes. Lastly, expanding the scope of research to include comparative analyses across multiple cities or regions would help validate the findings and establish universally applicable best practices for CE implementation in healthcare waste systems.

The experiences from Athens' hospital bio-waste collection program underscore the broader potential for CE models in urban settings. By adhering to CE principles, cities can build sustainable waste management systems that address environmental concerns while yielding economic advantages. This program provides valuable insights for municipalities looking to strengthen their waste management practices, highlighting the importance of stakeholder engagement, continuous improvement, and scalability. As more cities adopt similar models, the approach developed in Athens can serve as a blueprint for effective, sustainable bio-waste management strategies in healthcare systems.

In conclusion, the shift from linear to CE-based sustainable bio-waste management models in healthcare systems has proven successful in Athens, demonstrating the feasibility and benefits of integrating CE principles into urban waste management. The consistent growth in bio-waste volumes, effective stakeholder participation, and scalable implementation model underscore the program's achievements and potential for future expansion. As cities worldwide explore CE practices, the Athens CE bio waste model for healthcare system offers an exemplary framework for sustainable urban development that can be adapted to diverse urban contexts.

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