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Overcoming Waste Management Challenges in Costa Rica: Evaluating Practices, Government Initiatives, and Future Strategies

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Article

Overcoming Waste Management Challenges in Costa Rica: Evaluating Practices, Government Initiatives, and Future Strategies

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Abstract: Costa Rica, widely acknowledged for its environmental leadership, is now facing a significant challenge in managing waste, a situation that could potentially compromise both its environmental and public health achievements. This analysis delves into the waste management issues in Costa Rica, particularly in urban areas such as **San José, responsible for nearly half of the country's waste**. The study identifies several pressing concerns, including **the heavy burden on landfill capacities**, a **recycling rate of just 9.6%**, and substantial regional differences in waste management practices.To address these challenges, the research employs a **combined methodology**, utilizing **Linear Regression (LR) and AutoRegressive Integrated Moving Average (ARIMA) models** to project **future trends in CO2e emissions and waste minimization from 2024 to 2050**. This method underscores the vital need for public involvement and the introduction of innovative strategies in waste management. The research also introduces a **Waste Management Innovation Index** to compare Costa Rica's practices with those of leading nations like Germany and South Korea, identifying key areas for improvement.Furthermore, the study incorporates insights from stakeholders, revealing the intricate balance of cultural, economic, and regulatory factors that shape waste management policies. Despite efforts by the government, such as the **Environmental Health Route and the National Circular Economy Strategy**, results show limited progress, particularly in rural regions. The study highlights the **urgent need for better infrastructure, targeted public awareness campaigns,** and the use of advanced technologies like **Artificial Intelligence (AI) and blockchain** to enhance sustainable waste management practices. The research provides strategic recommendations to help Costa Rica improve its waste management systems in line with international standards, ensuring long-term environmental sustainability and protection of public health.

Keywords: waste management; recycling rates; environmental sustainability; costa rica; circular economy strategies; public participation in recycling

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1. Introduction

Costa Rica is globally recognized for its exemplary environmental stewardship, particularly in biodiversity conservation and renewable energy. The country generates over 98% of its electricity from renewable sources and has designated more than a quarter of its land as protected, underscoring its commitment to sustainability **[1,2]**. However, beneath this success lies a significant and escalating challenge: waste management. Severe landfill management problems and low public participation in recycling not only threaten to undermine the country's environmental achievements but also pose serious risks to public health and ecosystems **[3,4]**. In 2021, Costa Rica sent over 1.2 million tonnes of waste to landfills, with a recovery rate of only 9.6% **[5]**. These figures highlight the need for comprehensive long-term planning, as current trends indicate that without significant changes, these issues could escalate, placing unsustainable pressure on existing infrastructure.

This study addresses a critical gap in the literature by focusing on Costa Rica's waste management challenges, an area that has received comparatively less attention in both academic and

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policy discussions. While extensive research exists on Costa Rica's achievements in renewable energy and conservation, the waste management sector, particularly in urban areas like San José—which generates nearly 47% of the nation's waste—has been plagued by inefficiencies and inadequate infrastructure **[6,7]**. The closure of major landfills, such as Los Pinos in Cartago, alongside the limited success of government initiatives like the Environmental Health Route policy, further underscores the severity of the situation **[8]**.

Costa Rica has proactively responded to waste management challenges by implementing specific laws aimed at reducing plastic waste and fostering sustainable practices. A notable example is the 2019 legislation known as **'Law No. 9786,'** which targets the reduction of single-use plastics while promoting a circular economy. This law includes measures such as banning plastic straws and single-use plastic bags, mandating the use of recycled materials in plastic manufacturing, and launching public education campaigns focused on reducing plastic waste **[9]**. These legislative steps highlight the government's dedication to addressing plastic pollution as an essential aspect of its comprehensive waste management approach.

In addition to infrastructural and logistical challenges, cultural and social factors contribute to the low levels of public participation in recycling programs, with less than 10% of the population actively engaged **[10]**. This study critiques the effectiveness of current government policies and compares Costa Rica's situation with global waste management practices, particularly those of Germany and Japan, to identify strategies that could be adapted locally. The findings have broader implications for other developing nations facing similar challenges, offering insights into the effective implementation of sustainable waste management practices.

The objectives of this paper are to analyze the current state of waste management in Costa Rica, identify the primary challenges, evaluate the effectiveness of government initiatives, and propose innovative solutions based on successful practices from both local and international contexts. Additionally, the paper introduces the Waste Management Innovation Index as a framework for comparing Costa Rica's practices with global leaders like Germany and Japan, offering tailored recommendations to improve local strategies. The paper is structured into three core sections: an overview of waste management in Costa Rica, an analysis of the challenges leading to the crisis, and an evaluation of government responses and policies. Through this structured approach, the study aims to contribute valuable insights into the intersection of waste management and environmental sustainability in developing countries.

2. Methodology

This study employed a hybrid modeling approach combining Linear Regression (LR) and AutoRegressive Integrated Moving Average (ARIMA) models to forecast trends in waste management practices and CO2e emissions in Costa Rica. Historical data from Universidad Nacional (2010-2014) served as the foundation for projecting laboratory waste minimization practices, while broader environmental trends were informed by data from the OECD Environmental Performance Reviews and the Estado de la Nación reports. The LR model was first utilized to establish baseline linear trends in variables such as total waste generation and CO2e emissions, laying the groundwork for more detailed analysis. Subsequently, ARIMA was applied to capture non-linear patterns and temporal dependencies, thus enhancing the robustness of the predictions.

The execution and visualization of these models were conducted using **Python** and the **Spyder IDE**. The **LR+ARIMA combination** proved effective in capturing both **linear trends** and **complex temporal dynamics**. **Cross-validation techniques** were employed to ensure the reliability of the models, with the dataset divided into **training and testing subsets**.

In addition to this hybrid modeling approach, **simulation techniques were employed** to explore the potential outcomes of different waste management strategies. These simulations focused on projecting the remaining waste under four distinct scenarios: **Baseline Scenario, Enhanced Recycling Scenario, Waste-to-Energy (WtE) Scenario, and a Combined Scenario (Recycling + WtE)**. The simulations, conducted using **Python**, utilized key parameters derived from **real data** such as **waste generation rates, recycling rates, and CO2e emissions**. The **simulation results** provided critical insights into the effectiveness of various waste management strategies, revealing that the **Combined Scenario** presented the **most significant reduction in remaining waste**, offering a clear path to alleviating pressure on landfill capacity.

Nevertheless, it is essential to recognize some limitations associated with the selected methodology. The use of **historical dat**a may carry biases linked to previous trends, and the assumptions built into the **Linear Regression (LR), ARIMA**, and simulation models could affect the precision of future predictions, especially under significantly changing circumstances. Despite these challenges, the chosen approach was considered the most appropriate for the study's scope and objectives, particularly in its capacity to combine various data sources and forecasting methods to tackle the complex issues of waste management in Costa Rica

Ethical considerations were not applicable to this study as it exclusively utilized publicly available environmental data, and no human participants were involved.

3. Current State of Waste Management

3.1. Overview of Waste Production

Costa Rica, despite its reputation for environmental sustainability, faces significant challenges in managing its waste effectively. **Recent studies reveal considerable variation in waste generation rates across the country**, reflecting diverse socioeconomic conditions and infrastructure capabilities. For instance, in the Metropolitan Area, the average waste generation rate is approximately **0.59 kg per person per day**, with organic waste comprising **55.9% of the total waste stream** [11]. In Guácimo, the rate is slightly lower at **0.55 kg per person per day**, with waste composition including **35% recyclable materials, 45% biodegradable waste, and 20% destined for landfills** [12].

The strain on landfill capacities is particularly acute, with many sites nearing or exceeding their designed limits, a situation worsened by the **recent closure of the Los Pinos landfill in Cartago**. This closure has compelled municipalities to seek alternative waste management solutions. **Urban areas like San José, which generate nearly 47% of the nation's waste**, place a substantial burden on existing infrastructure, while rural regions struggle with inadequate waste collection services and limited access to recycling facilities [3].

Addressing the inefficiencies in waste disposal, particularly in Costa Rica's tropical conditions, necessitates the development of more accurate **leachate movement models** [13]. A comparison with other Latin American countries highlights shared challenges, such as insufficient recycling infrastructure and high levels of waste leakage into the environment [14]. However, countries like Colombia and Chile have made notable progress through targeted policy reforms and investments in recycling. **Costa Rica could enhance its waste management efficiency by adopting similar best practices**, particularly in recycling and waste diversion strategies [15].

Costa Rica's waste management system, particularly in urban areas, remains under significant strain. Enhancing recycling rates, improving landfill management, and bridging the urban-rural divide in waste collection services are critical steps toward aligning the country's waste management practices with its broader sustainability goals.

3.2. Landfill Capacities and Regional Waste Management Practices

In 2021, Costa Rica's Ministry of Health reported that **1,282,057 tonnes of waste were sent to landfills**, yet only **9.6% of this waste was recoverable**. This low recovery rate highlights the challenges in meeting the country's waste recovery goals, with only **3.9% allocated for recycling, 2.7% for composting, and 2.4% for co-processing**. Given the critical situation as of 2024, targeted improvements in waste recovery infrastructure and policies are essential [16,17].

The concentration of waste production in **urban areas, particularly San José**, underscores the urgent need for targeted waste management solutions. Effective management is crucial for preserving environmental health and ensuring sustainability, especially as **Costa Rica experiences rapid urban growth**. Notably, organic waste constitutes **58% of San José's waste stream**, presenting a significant opportunity for composting and organic waste treatment initiatives [7,10].

Costa Rica urgently needs to develop innovative waste management strategies to reduce the overwhelming reliance on landfills and mitigate the associated greenhouse gas emissions. **A significant 94% of the country's solid waste currently ends up in landfills, open dumps, or other disposal sites**, which poses serious risks to both surface and groundwater resources. In urban areas, such as **San José**, waste collection services are more accessible, yet their effectiveness varies, leading to inconsistencies in waste management practices. Rapid urbanization exacerbates these issues, resulting in **nitrate pollution in groundwater and an increase in health problems linked to air quality deterioration**. In contrast, rural regions struggle even more due to logistical challenges and insufficient infrastructure, often resorting to unsafe disposal methods like burning or burying waste. These practices not only harm the environment but also create significant public health risks by contaminating soil and water **[18,19]**.

Costa Rica's current landfill capacities are at a critical juncture, with urban areas like San José bearing the brunt of waste production. Addressing these challenges through improved infrastructure, policy interventions, and regional collaboration is essential to safeguarding both environmental and public health as the nation moves forward.

3.3. Technlogical Advancements

Recent advancements in waste management and recycling technologies offer promising avenues for improving Costa Rica's waste management systems, aligning with the nation's broader environmental goals, such as achieving a **25% national recycling rate by 2033** and advancing the **National Circular Economy Strategy**.

Technological Innovations: Costa Rica can leverage developments in hydrological modeling, such as **HydroGeoSphere** and **MODFLOW**, to improve landfill management in its tropical climate. By integrating models like **HYDRUS-2D/3D** with local climate and soil data, the country could enhance leachate estimation accuracy and improve overall landfill efficiency **[20,21]**. These tools have been successful in similar tropical settings, such as Brazil, reducing groundwater contamination risks by **25% over five years [22,23]**.

Innovative Financing and Collaboration: The variability in waste management financing across Costa Rican municipalities presents an opportunity for adopting **Pay-as-You-Throw (PAYT) systems**, which have been successfully implemented in South Korea and parts of the United States, achieving waste reduction of **30% within three years [24,25]**. Additionally, fostering **Public-Private Partnerships (PPPs)**, as seen in Singapore, could attract private investment and enhance financial sustainability in municipal waste management **[26]**. These partnerships have significantly increased recycling rates and reduced landfill use, offering a model for Costa Rica to emulate.

Emerging Technologies: Costa Rica's collaboration with countries like the **Netherlands** has facilitated technology transfers essential for developing sustainable business models. To further this progress, expanding collaborations with **Denmark** and **Finland**, leaders in circular economy practices, could support sectors such as construction and manufacturing **[27–29]**. Moreover, integrating **Artificial Intelligence (AI)** and **blockchain technology** into waste management could revolutionize operations. AI has optimized waste collection routes and improved recycling efficiency in Sweden, reducing costs by **20%** and increasing recycling rates by **15%**. Blockchain can provide secure, immutable records of recycling activities, ensuring transparency and accountability **[30]**.

By embracing these technological advancements, Costa Rica can enhance its waste management systems, supporting the **Environmental Health Route policy** and **National Circular Economy Strategy**. These initiatives will minimize environmental impact, promote economic growth, and position Costa Rica as a leader in sustainable waste management, serving as a model for other nations facing similar challenges.

3.4. Costa Rica's Recycling Challenge: A Global Perspective

Previous sections have highlighted Costa Rica's current waste management challenges, including a low recycling rate of only **9.6%,** with **83.8%** of waste ending up in landfills. This section further examines these challenges by comparing Costa Rica's recycling rate to global averages, highlighting key differences that underscore the need for robust reforms. This comparative analysis will identify potential areas for improvement and inform recommendations for advancing Costa Rica's waste management system toward greater sustainability.

Table 1 presents recycling rates from various regions and countries, illustrating where Costa Rica stands compared to global standards. Countries like Germany and Sweden boast high recycling rates due to advanced infrastructure, robust public engagement, and effective enforcement of recycling policies. In contrast, Costa Rica's heavy reliance on landfills and its underdeveloped recycling infrastructure contribute significantly to its lower recycling rate. Germany, for instance, achieves a recycling rate of around **69.3%,** driven by stringent waste separation and recycling regulations, while Sweden integrates **Waste-to-Energy (WtE)** technologies, enabling a recycling rate of **50%.**

Table 1. Global Recycling Rates.

Region/Country	Recycling Rate (%)	Key Contributing Factors	References
European Union	46% (2020)	Varies across member states; strong policies and infrastructure	[31]
Germany	69.3% (2024)	Stringent waste separation, strong regulations	[32]
United States	21% (2024)	State-level variations, mixed public participation	[33]
Japan	20% (2023)	Meticulous waste sorting, but lower recycling infrastructure	[34]
Brazil	4% (2024)	Driven by informal sector, lack of formal infrastructure	[35]
South Korea	69% (2023)	Public involvement, advanced waste sorting systems	[36]
Sweden	50% (2024)	High integration of Waste-to-Energy (WtE) technologies	[37]
Costa Rica	9.6%	High landfill dependency, minimal recycling infrastructure	[17]

The data reveal significant variations in recycling rates across different regions and countries. **Countries like South Korea and Germany** have achieved high recycling rates through **public engagement, advanced sorting systems, and strong regulatory frameworks**. Costa Rica, on the other hand, faces challenges such as **inadequate infrastructure, limited financial resources,** and an **underdeveloped formal recycling sector**, compounded by heavy reliance on informal waste pickers and cooperatives. For instance, the closure of the Los Pinos landfill in Cartago and inadequate waste collection services in rural areas illustrate systemic issues within Costa Rica's waste management framework. **Costa Rica's "Ley para Combatir la Contaminación por Plástico y Proteger el Ambiente" (Law No. 9786)** plays a crucial role in reducing single-use plastics and promoting sustainable alternatives. This law contributes to improving recycling rates and reducing the burden on landfills by fostering a shift towards more sustainable consumption and waste management practices [8].

4. Government Initiatives and Policies

Costa Rica faces significant challenges in waste management, prompting the government to implement several key initiatives aimed at enhancing sustainability. One of the most critical of these is the **Environmental Health Route policy**, introduced in **April 2023**. This policy sets ambitious targets, including achieving a **25% national recycling rate by 2033** and ensuring regular garbage collection services for at least **34% of the national territory by the end of 2023**. To reach these

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objectives, the policy outlines specific sub-goals such as reducing per capita waste generation by **10% by 2025**, expanding public education on waste separation, and developing new infrastructure for waste sorting and processing in underserved areas [38].

The National Circular Economy Strategy, introduced in 2023, aims to revolutionize waste management by promoting a circular economy model. This approach focuses on reusing, recycling, and repurposing materials to significantly reduce waste. Key actions include encouraging the use of reusable bags and containers, incentivizing businesses to adopt sustainable packaging, and fostering the development of markets for recycled materials. A major focus of the strategy is on decreasing the use of single-use plastics and enhancing recycling infrastructure [39,40].

Similarly, the **Ley para Combatir la Contaminación por Plástico y Proteger el Ambiente** (Law No. 9786), implemented in 2019, seeks to drastically reduce the use of single-use plastics. The law enforces measures such as banning plastic straws and non-reusable plastic bags, promoting reusable materials, and integrating plastic waste education into the national curriculum. It also mandates the creation of programs for research and innovation to support the transition away from plastics, aligning with the goals of the circular economy strategy **[8].**

The government's commitment to these initiatives reflects an understanding of the need for tailored solutions to address the distinct challenges faced by both urban and rural areas. **As Costa Rica continues to advance these efforts, it has the potential to serve as a model for other nations** confronting similar waste management challenges. These policies aim to minimize environmental impact, promote public health, and drive sustainable economic growth through immediate and long-term goals. However, their effectiveness will ultimately depend on overcoming barriers such as public awareness, funding constraints, and technological limitations. **Table 2** summarizes these government initiatives and their goals.

Table 2. Government Initiatives and Goals.

Initiative	Goal	Target Year	Reference
Environmental Health Route Policy	Increase recycling rate to 25%	2033	[38]
Environmental Health Route Policy	Ensure regular garbage collection in 34% of the territory	2023	[38]
Environmental Health Route Policy	Reduce per capita waste generation by 10%	2025	[38]
National Circular Economy Strategy	Promote circular economy practices	Ongoing	[39,40]
Law No. 9786 (Ley para Combatir la Contaminación por Plástico y Proteger el Ambiente)	Drastically reduce single-use plastic usage and promote sustainable alternatives	2019	[8]

These strategies reflect Costa Rica's holistic approach to tackling the challenges of waste management. The **Environmental Health Route** and the **National Circular Economy Strategy** are central to these efforts, aiming to achieve substantial progress in recycling and waste reduction while also prioritizing the development of infrastructure and public education. By combining immediate actions with long-term objectives, these policies seek to reduce environmental impact, enhance public health, and foster sustainable economic growth. As Costa Rica continues to develop and implement these measures, the country is well-positioned to reinforce its commitment to environmental stewardship and serve as an example for other nations facing similar challenges.

5. Results and Discussion

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5.1. Strategic Approaches and Future Outlook in Waste Management

Costa Rica is currently confronted with significant waste management challenges, highlighting the need to **expand recycling initiatives**, **invest in composting infrastructure**, and explore innovative waste treatment technologies such as **waste-to-energy solutions**. By **2050**, these strategies have the potential to revolutionize the country's waste management system, moving away from heavy reliance on landfills towards a model centered on **resource recovery and sustainability**. Waste-to-energy technologies, including **anaerobic digestion** and **gasification**, are pivotal in this transition, as they help decrease landfill use while contributing to **renewable energy production**, in line with Costa Rica's broader environmental objectives.

Projections indicate a significant increase in total waste sent to landfills, emphasizing the urgent need for enhanced waste recovery infrastructure and policies. With targeted interventions, recovery rates could reach 25% by 2033. However, alternative scenarios suggest that faster adoption of advanced technologies could push recovery rates beyond 30%, further reducing landfill dependency, while delays in policy implementation might slow progress. These projections not only impact environmental sustainability but also have broader socio-economic implications, such as job creation and improved public health outcomes. Figure 1 details projections for total waste, recoverable waste, and recovery rates in Costa Rica from 2021 to 2050.

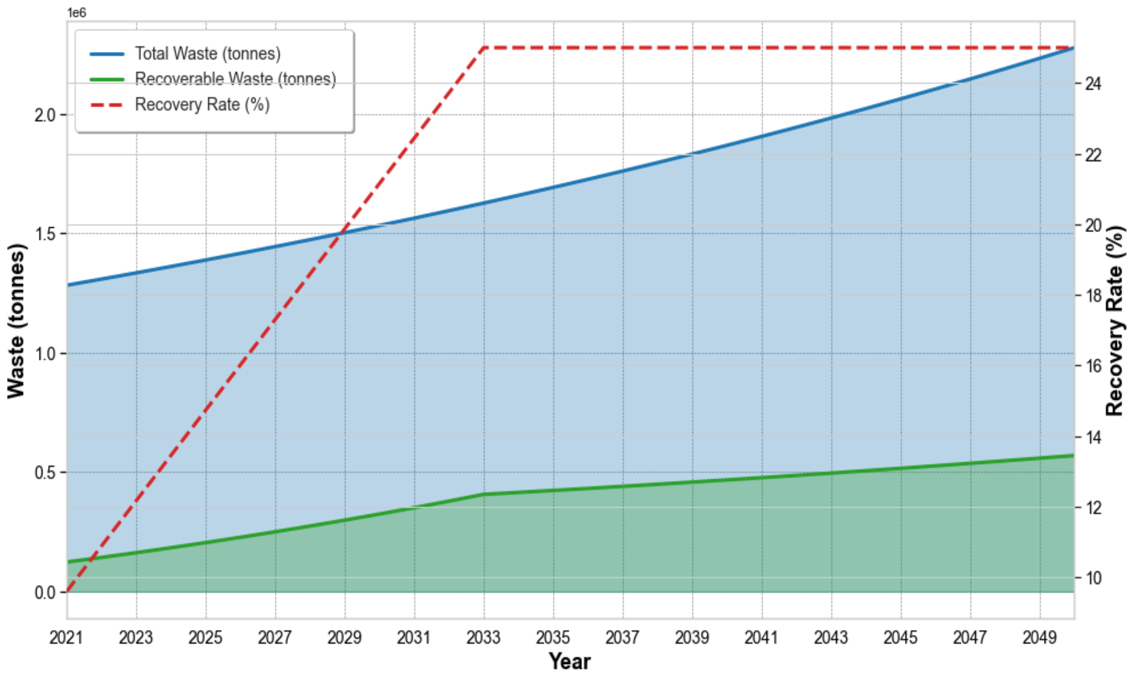

Figure 1. Projections for Total Waste, Recoverable Waste, and Recovery Rate in Costa Rica (2021-2050). **Caption:** The figure illustrates the projected increase in total waste sent to landfills and recoverable waste from **2021 to 2050**. It also shows the expected improvement in the recovery rate, reaching **25% by 2033**, assuming the implementation of targeted waste management strategies. The data underscores the growing need for enhanced waste recovery infrastructure and policies to alleviate the pressure on landfills.

Figure 2 presents the projected waste composition in San José for the years **2021, 2030, and 2050**, highlighting a reduction in organic waste and an increase in recyclable materials. These projections reflect the potential impact of ongoing and future waste management initiatives on composting and recycling practices.

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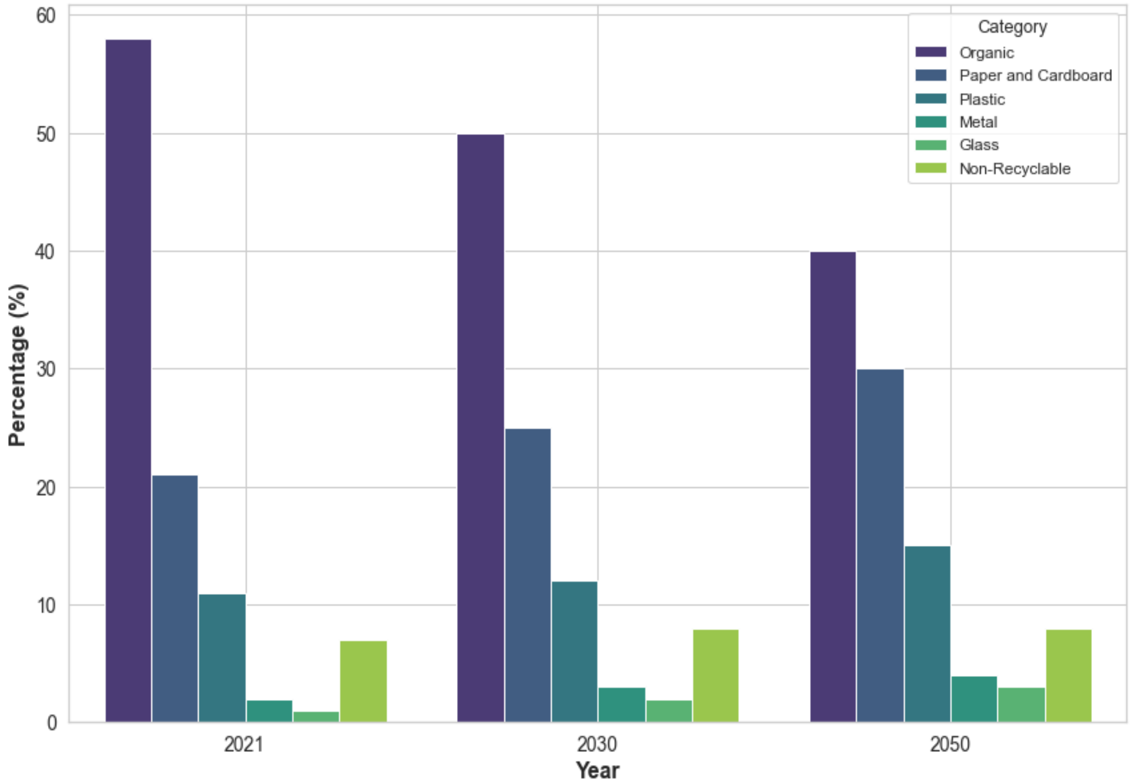

Figure 2. Projected Waste Composition in San José for the Years 2021, 2030, and 2050. **Caption:** The figure shows the waste composition in **San José**, with significant changes projected for **2030 and 2050**. It highlights a reduction in organic waste and an increase in recyclable materials like paper, cardboard, and plastic, reflecting the impact of ongoing and future waste management initiatives. These changes indicate potential improvements in composting and recycling practices over time.

While the baseline projections offer a clear path forward, it is crucial to consider alternative scenarios, such as the accelerated adoption of waste-to-energy technologies or enhanced recycling infrastructure, which could further improve recovery rates. Conversely, delays in policy implementation or economic challenges could hinder progress, increasing pressure on landfills. These scenarios underscore the importance of flexible and adaptive policy-making to respond to changing circumstances. The projections are based on the assumption of steady progress; however, various factors, such as economic shifts or technological advancements, could introduce uncertainty. By acknowledging these uncertainties, we can better prepare for a range of potential outcomes. Moreover, the socio-economic implications of these projections are significant: improved waste recovery rates could lead to job creation, particularly in rural areas, and reduce public health risks associated with landfill-related pollutants. Additionally, ensuring equitable access to waste management services can promote social equity, benefiting all communities as Costa Rica works toward its sustainability goals.

5.2. Landfill Capacities and Geographic Considerations

The challenges in waste management, particularly in urban areas like San José, are exacerbated by the concentration of waste production and the severe strain on landfill capacities. San José's low waste recovery rate, with 58% of its waste being organic, underscores the potential for improvement through expanded recycling programs and enhanced composting infrastructure. Key landfill sites, such as La Carpio and Aserrí, currently receive approximately 600 tonnes of waste daily and face an estimated remaining life of 2 to 5 years [7]. The closure of the Los Pinos landfill in January 2024 due to reaching full capacity and structural failures exemplifies the critical challenges these facilities face

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[17].Figure 3 presents the geographic locations of major landfill sites in Costa Rica, emphasizing the environmental challenges posed by landfill operations in close proximity to urban areas.

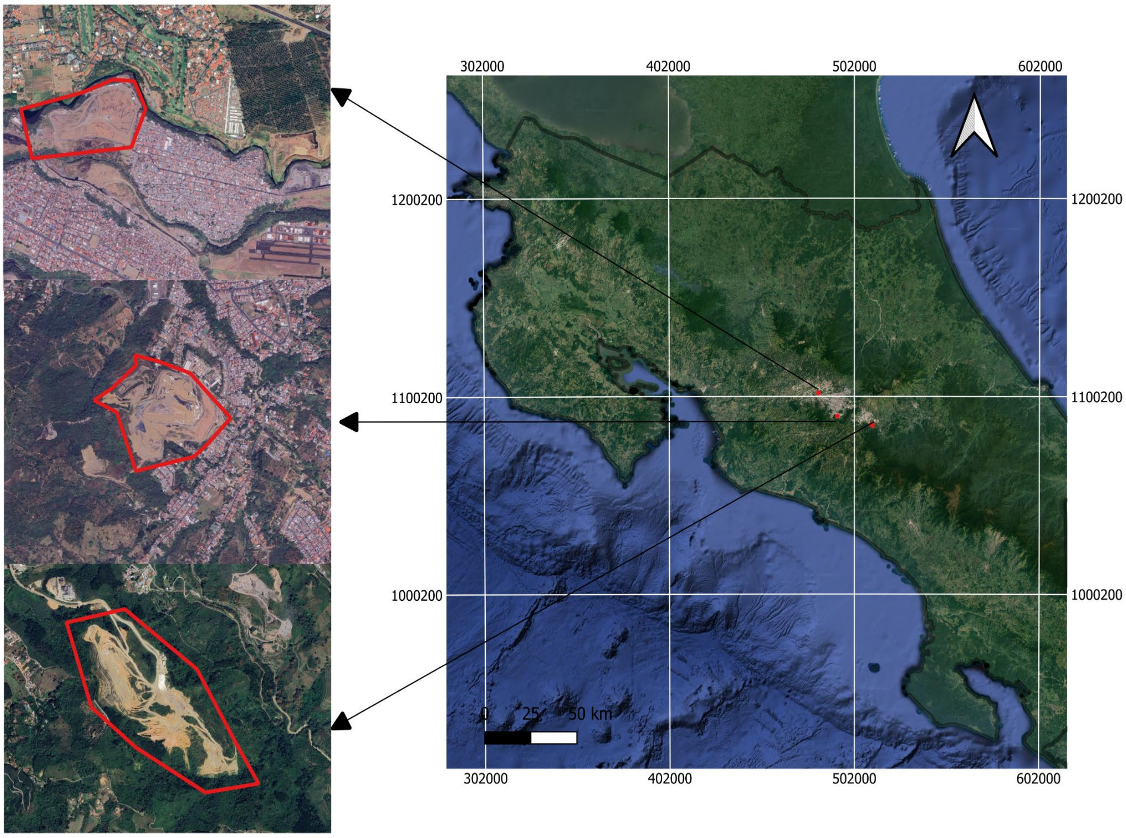

Figure 3. Satellite imagery of major landfill sites in Costa Rica: (a) La Carpio Landfill, (b) Aserrí Landfill, and (c) Los Pinos Landfill. The Los Pinos landfill was officially closed in January 2024 due to reaching full capacity and structural failures.

Improving landfill management practices is essential, including techniques such as waste compaction, the use of liners to prevent leachate contamination, and gas collection systems to capture methane emissions. However, these measures alone may not be sufficient to meet the growing waste management demands. The data underscores the critical need for immediate strategic interventions in Costa Rica's waste management system. As urban areas like San José continue to generate significant waste volumes, the pressure on existing landfills is unsustainable. Expanding recycling and composting infrastructure is crucial to reducing landfill dependency and mitigating the environmental risks associated with landfill operations, thereby aligning with Costa Rica's broader sustainability goals.

5.3. Public Participation and the Ecoins Program

Public participation is critical for achieving **Costa Rica's waste management goals**, particularly in increasing the recycling rate. To address the current **low participation rate (less than 10%)** [5], the **Ecoins program** was launched in **2017**, offering a technological and economic reward system to encourage citizen involvement in solid waste management. As of **2023**, the program has established **520 collection sites** and attracted **46,162 registered users** ("Ecofans"), collecting **3,762 tonnes of recyclable waste** and avoiding **4,592 tonnes of CO2 emissions** [16]. Projections suggest that by **2030**, the program could expand to **1,127 collection sites**, collecting **8,151 tonnes of recyclable waste** and avoiding **9,949 tonnes of CO2 emissions**. By **2050**, the program could involve **253,891 registered users** and collect **20,691 tonnes of recyclable waste**, significantly boosting Costa Rica's recycling rates [17].

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These projections highlight the Ecoins program's potential, but realizing this requires continued investment and development, particularly in expanding the program's reach in **rural areas**. Innovative incentive structures, such as **gamification** and **blockchain technology**, could further engage and motivate the population. Integrating the Ecoins program with other national initiatives, like the **Environmental Health Route policy** and the **National Circular Economy Strategy**, could amplify its impact. **Table 3** highlights the program's achievements from 2017 to 2023, as well as the projected impact for 2030 and 2050.

Table 3. Impact of the Ecoins Program (2017-2023) and Projections for 2030 and 2050.

Metric	2017-2023	Projected 2030	Projected 2050	Ref
Collection Sites	520	1126.67	2860	[41]
Recyclable Waste Collected (tonnes)	3,762	8,151	20,691	[17]
CO2 Emissions Avoided (tonnes)	4,592	9,949.33	25,256	[17]
Registered Users ("Ecofans")	46,162	100,017.7	253,891	[17]

The **Ecoins program** is a significant initiative to boost public participation in recycling by offering tangible incentives. However, the overall participation rate remains low, indicating a need for further efforts to enhance engagement. Comparative analysis with similar programs from other countries, such as Brazil's **EcoPontos** and South Korea's **Eco Mileage Program**, offers valuable insights. **EcoPontos** increased recycling rates by **20%** in its first year by offering discounts on goods and services **[42]**, while South Korea's program achieved a **15% reduction in household energy consumption** by rewarding eco-friendly behaviors **[43]**.

To further boost participation, exploring innovative approaches like **gamification** and **blockchain technology** could be beneficial. For instance, **Estonia's Trash and Seek app** demonstrates how gamification can make recycling more engaging and educational by rewarding correct sorting and recycling activities **[44]**. Additionally, blockchain technology could enhance transparency and accountability within the Ecoins program by providing immutable records of recycling activities and ensuring the fair distribution of rewards **[45]**.

Expanding the digital presence of the Ecoins program through a dedicated mobile app, similar to Japan's **Pirika**, which tracks recycling habits and offers real-time feedback, could significantly improve participation rates **[46,47]**. These strategies, combined with comprehensive educational campaigns and targeted outreach, particularly in rural areas, could foster a stronger and more inclusive recycling culture across Costa Rica.

The projected growth of the Ecoins program underscores its potential to significantly enhance Costa Rica's recycling rates by 2050. Continued investment in the program, alongside the integration of innovative technologies and expanded reach, could position Costa Rica as a leader in sustainable waste management, contributing to the **Environmental Health Route policy** and **National Circular Economy Strategy**, and inspiring other nations to adopt similar approaches.

5.5. Waste Minimization Practices

Minimizing waste generated in laboratories is crucial for supporting Costa Rica's national goal of achieving a **25% national recycling rate by 2033** and promoting a **circular economy model**. These practices are also key for reducing the strain on landfills, which remains a critical challenge in Costa Rica. This section examines the adoption of waste minimization practices in laboratories across Costa Rica, highlighting trends from 2015 to 2050.

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The data indicate a significant increase in the adoption of six key waste minimization practices over the years: substituting nonhazardous materials (SNM), chemical treatment (CT), distillation (D), redistributing surplus chemicals (RSC), reducing the scale of experiments (RS), and purchasing less (PL) (Figure 4a). Additionally, there has been a noticeable rise in laboratories adopting five other practices, including purchase control (PC) and computer simulation (CS) (Figure 4b).

The annual percentage variation for these waste minimization practices demonstrates the effectiveness of training and policy implementation over time. While the adoption continues to grow, the rate of increase gradually stabilizes as these practices become standard within laboratories (Figure 4c and 4d). However, the data reveal that the percentage variation for some practices, such as **computer simulation (CS)** and **chemical treatment (CT)**, has slowed, indicating potential barriers to wider implementation. These barriers may include high costs, lack of awareness, and challenges in sourcing alternative materials, which can hinder the broader adoption of these practices.

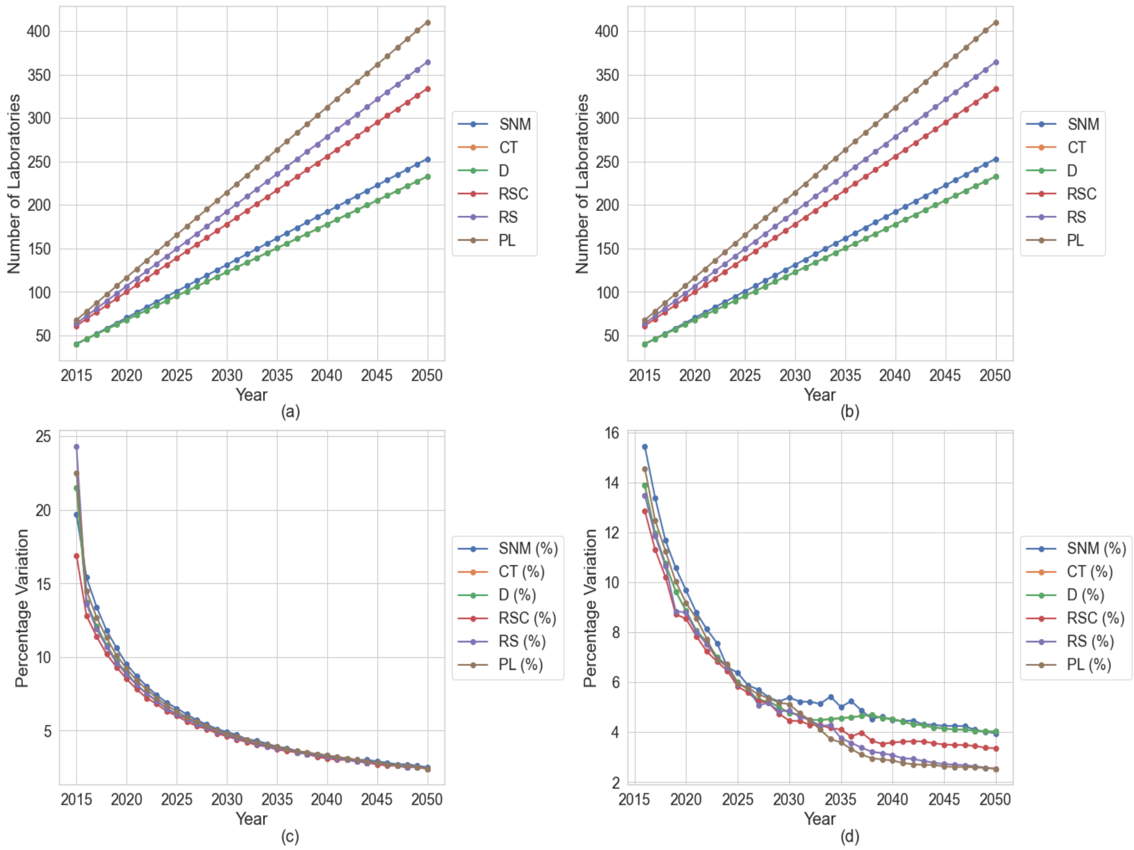

Figure 4. [1] Number of laboratories performing waste minimization practices and annual percentage variation (2015-2050). **Caption:** The figure illustrates the trends in the number of laboratories performing six and five waste minimization practices from 2015 to 2050, as well as the annual percentage variation in these practices. **Notably, while the overall adoption of these practices has increased, Figure 4d shows that the percentage variation for some practices, such as computer simulation (CS) and chemical treatment (CT), has slowed, indicating potential barriers to wider implementation. Overall, the figure highlights the effectiveness of current strategies and the importance of continued focus on improving waste management practices across the country.**

Costa Rica, recognized globally for its environmental sustainability efforts, still faces substantial challenges in effective waste management. The growing implementation of waste minimization strategies in laboratories throughout the country signals progress toward more sustainable practices. Notable increases in activities such as substituting non hazardous materials and redistributing

[1] **Figure 4** derived from **Supplementary Tables S1, S2, S3, and S4**.

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surplus chemicals highlight the success of current training programs and policy measures. Nonetheless, to further advance waste minimization efforts, it is crucial to continuously identify and address areas needing improvement, particularly for practices with slower adoption rates.

By embedding a culture of sustainability within laboratories and other institutions and embracing cutting-edge waste management techniques, Costa Rica has the opportunity to further solidify its leadership in environmental protection. **Emphasizing these approaches** will allow Costa Rica to **cut down on waste production**, advance towards its **recycling targets, support a circular economy**, and reduce the environmental impact of its waste management practices. Addressing challenges, particularly in **chemical treatment (CT)** and **computer simulation (CS)**—areas with slower adoption rates—through focused research and strategic measures will be crucial. These efforts are key to accelerating the implementation of these practices and realizing the country's ambitious goals in waste management.

6.1. Waste Management Innovation Index Table

To provide a more nuanced comparison of waste management practices, this section introduces the concept of a **"Waste Management Innovation Index."** This index measures countries' effectiveness in adopting innovative waste management practices, considering factors such as technological advancements, policy innovation, public engagement, infrastructure development, and sustainability impact. By applying this index, Costa Rica's waste management practices can be more precisely compared with those of global leaders. For instance, **Germany and South Korea** score high on this index due to their integration of cutting-edge technologies and strong regulatory frameworks. In contrast, Costa Rica's reliance on traditional methods and its underdeveloped infrastructure place it lower on this index, highlighting the areas where innovative approaches are urgently needed.

As detailed in **Table 4**[2] The Waste Management Innovation Index ranks several countries based on their advancements in waste management. **Germany, South Korea, and Sweden** are leaders in waste management innovation, scoring high across all categories, including technological advancements, policy innovation, public engagement, infrastructure development, and sustainability impact. These countries serve as benchmarks for Costa Rica's future waste management strategies. The **United States** and **Japan** also show strengths in various areas, though with some regional or systemic limitations that result in moderate overall scores. **Brazil** ranks lower on the index, reflecting significant challenges in its waste management systems, while **Costa Rica** scores modestly, indicating considerable room for improvement.

Table 4. Waste Management Innovation Index.

Region/Country	Technological Advancements	Policy Innovation	Public Engagement	Infrastructure Development	Sustainability Impact	Overall Index Score
Germany	High	High	High	High	High	9/10
United States	Moderate	Moderate	Low	High	Moderate	6/10
Japan	High	High	High	Moderate	Moderate	8/10
Brazil	Low	Low	Low	Low	Low	3/10
South Korea	High	High	High	High	High	9/10
Sweden	High	High	High	High	High	9/10
Costa Rica	Low	Moderate	Moderate	Low	Low	4/10

[2]Table 4 is derived from Supplementary Table 6,

This index highlights the significant gaps in Costa Rica's waste management approach, particularly in technological advancements and infrastructure development. While Costa Rica has begun to implement important legal frameworks and foster public engagement, the overall effectiveness of these efforts is limited by the current infrastructure and technological limitations. **Germany, South Korea, and Sweden** provide useful models for Costa Rica to emulate in future waste management strategies.

6.2. Driving Recycling: Policy, Public Engagement, and Infrastructure

This section further examines these challenges by comparing Costa Rica's recycling rate to global averages, highlighting key differences that underscore the need for robust reforms. This comparative analysis will identify potential areas for improvement and inform recommendations for advancing Costa Rica's waste management system towards greater sustainability.

Table 5 presents factors influencing recycling rates from various regions and countries, illustrating where Costa Rica stands in comparison to global standards. Countries like Germany and South Korea boast high recycling rates due to advanced infrastructure, robust public engagement, and effective enforcement of recycling policies. In contrast, Costa Rica's heavy reliance on landfills and its underdeveloped recycling infrastructure contribute significantly to its lower recycling rate.

Table 5. Factors Influencing Recycling Rates.

Factor	Impact	Examples	References	Potential Strategies for Costa Rica	Rationale	Projected Impact
Legislation and Policy	Stringent regulations, such as mandatory recycling quotas and financial penalties for non-compliance, lead to higher recycling rates.	Germany (Pfand system), EU (Green Dot system)	[31,32]	Implement mandatory recycling quotas, strengthen enforcement of waste separation laws, and develop a deposit return system for beverage containers. This could drive higher recycling rates and accountability, similar to the success seen in Germany.	Costa Rica should adopt a more robust approach to enforcing its existing waste separation laws, as seen in Germany, to increase accountability and drive higher recycling rates.	Could lead to a 10% increase in recycling rates within two years.
Public Awareness	High public	Germany, Japan	[32,34]	Launch public	Raising public	Increased awarenes

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	involvement and education campaigns significantly increase recycling participation.			education campaigns, including school programs, community events, and media outreach, to raise awareness about recycling and waste reduction. This could lead to a significant increase in public participation in recycling programs, especially in rural and underserved areas.	awareness is essential for increasing participation in recycling programs, especially in rural and under-served areas of Costa Rica.	s could lead to a 10% increase in recycling participation in urban areas.
Infrastructure and Technology	Advanced recycling facilities and systems enhance the capacity to process and recycle materials efficiently.	Germany, South Korea, Sweden	[32,36,37]	Invest in modern Material Recovery Facilities (MRFs), particularly in urban and high-waste-generating areas, and explore advanced sorting technologies. This strategy could dramatically improve recycling efficiency	Investing in infrastructure, especially in urban centers, can improve the efficiency of recycling and help address Costa Rica's infrastructure deficiencies.	Could increase recycling efficiency by 20% within five years.

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				and address Costa Rica's infrastructure deficiencies.		
Economic Incentives	Financial incentives, such as deposit return schemes and tax breaks, boost recycling efforts.	US (state programs), EU (deposit return schemes)	[31,33]	Introduce tax breaks for companies engaged in recycling and explore the potential of deposit return schemes to incentivize recycling. This approach could make recycling more attractive to businesses and consumers, increasing participation rates.	Implementing economic incentives will make recycling more attractive to businesses and consumers, driving higher participation rates.	Could increase recycling participation by 15% within three years.
Cultural Norms	Strong cultural norms around waste reduction contribute to higher participation in recycling.	Japan, South Korea	[34,36]	Promote cultural shifts towards sustainability through community-driven initiatives and public recognition of recycling efforts. This could help normalize sustainable	Cultivating a recycling culture in Costa Rica will require community involvement and the normalization of sustainable practices.	Could lead to a 5% increase in recycling rates within five years.

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				practices and embed recycling in the daily routines of Costa Ricans.		
Market for Recycled Materials	A robust market for recycled materials provides economic value and incentivizes recycling activities.	EU, United States	[31,33]	Develop markets for recycled materials, including partnerships with businesses to create demand for recycled products. Building a strong market for recycled materials could provide economic incentives and reduce waste sent to landfills.	Building a market for recycled materials in Costa Rica can provide economic incentives and reduce waste sent to landfills.	Could reduce waste sent to landfills by 10% within five years.

Given these findings and the significant challenges related to infrastructure and public engagement, Costa Rica should prioritize investments in modern recycling facilities and the implementation of extensive public education campaigns to achieve its ambitious recycling goals. Strengthening waste management policies, including the enforcement of waste separation laws and the introduction of economic incentives like deposit return schemes, will also be crucial. By following these guidelines, Costa Rica can aim to significantly increase its recycling rate to **35% by 2035** and to **50% by 2050**, thereby strengthening its position as a global leader in environmental stewardship, contributing to a more circular economy, fostering sustainable economic growth, and enhancing its international standing as a model for sustainable development. Regular monitoring and evaluation of these initiatives will be crucial to ensure effectiveness, address any challenges that arise, and adapt strategies to maximize their impact.

7. The Carbon Footprint of Waste: Modeling the Future

The forecasts in **Figure 5**[3] and **Figure 6** provide crucial insights into the projected trends in CO2e emissions associated with sanitary landfills and the potential mitigation offered by recycling activities in Costa Rica from 2010 to 2050.

[3] **Figure 5 and Figure 6** derived from **Supplementary Tables S8, S9**

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Figure 5 illustrates a steady increase in emissions from sanitary landfills, rising from approximately **1,195 thousand tonnes of CO2e in 2010** to about **1,409 thousand tonnes of CO2e by 2024**, with further increases projected to reach around **1,725 thousand tonnes of CO2e by 2050**. This trend mirrors the growth in waste generation across the country and suggests that current waste management practices are insufficient to curtail the rise in emissions. Both the **Linear Regression** and **ARIMA** models predict a continued upward trajectory. The **ARIMA model** introduces a degree of uncertainty through its **95% confidence interval**, indicating potential variability in these long-term projections. This variability could be influenced by changes in waste management practices, advancements in technology, or the implementation of more stringent policies.

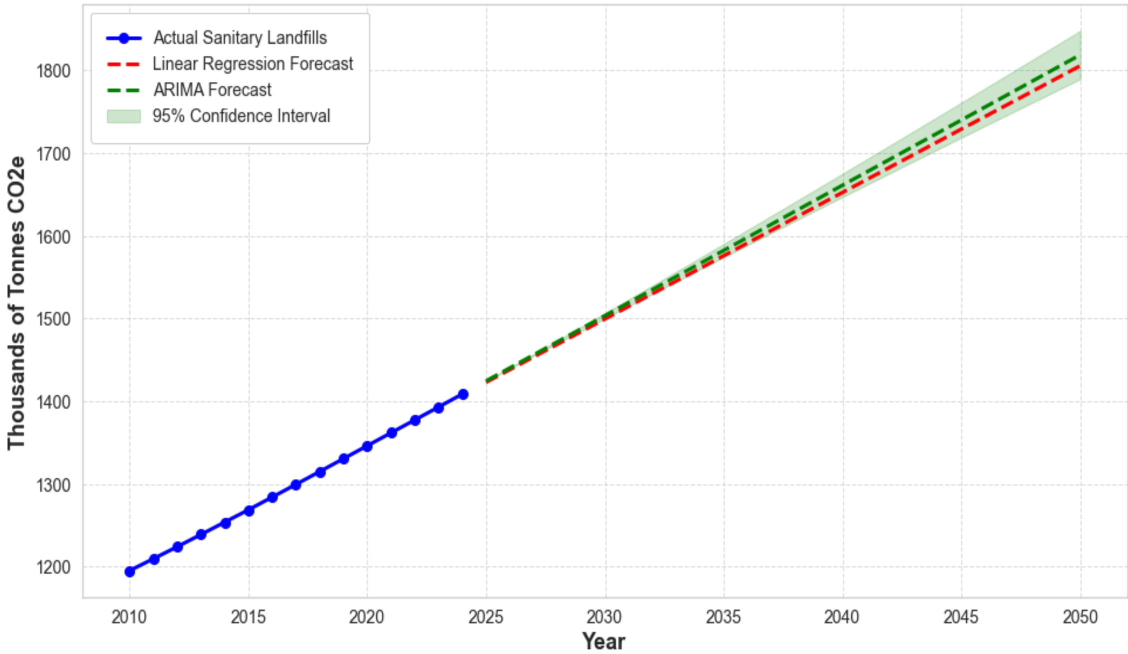

Figure 5. Projected CO2e Emissions from Sanitary Landfills. **Caption**: This figure depicts the projected CO2e emissions from sanitary landfills in Costa Rica, covering the period from 2010 to 2050. The **blue line** shows the recorded emissions from 2010 to 2024, the **red dashed line** represents the emissions forecast using linear regression, and the **green dashed line** reflects the ARIMA model predictions. The **green shaded area** denotes the 95% confidence interval associated with the ARIMA forecast.

In contrast, **Figure 6** shows a consistent reduction in emissions due to recycling activities, reflecting the effectiveness of recycling efforts in mitigating greenhouse gas emissions. The emissions reductions are projected to improve from approximately **-17.5 thousand tonnes of CO2e in 2010** to about **-20.2 thousand tonnes of CO2e by 2024**, with further declines potentially reaching **-26 thousand tonnes of CO2e by 2050**. However, the **ARIMA model's expanding range of uncertainty**, particularly as projections extend toward 2050, suggests that while current recycling efforts are impactful, their future effectiveness could vary considerably depending on factors such as technological advancements, policy shifts, and public participation in recycling programs.

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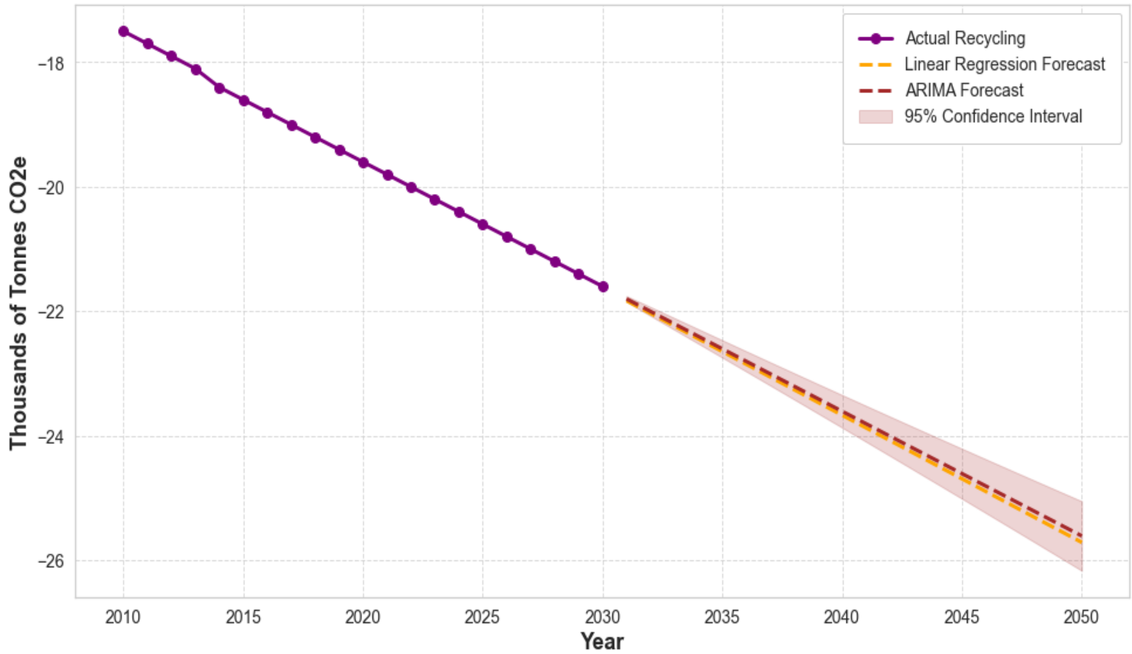

Figure 6. Recycling Forecast. **Caption**: This figure depicts the forecast of CO2e emissions reduction due to recycling activities in Costa Rica from **2010 to 2050**. The **purple line** represents the actual data from **2010 to 2030**, the **orange dashed line** indicates the linear regression forecast, and the **brown dashed line** indicates the ARIMA forecast. The **brown shaded area** represents the **95% confidence interval** for the ARIMA forecast.

7.1. Alternative Scenarios and Uncertainty Analysis

Baseline projections offer a clear initial pathway for waste management, yet it is critical to consider **alternative scenarios** that might emerge due to variations in policy adoption rates, technological advancements, or shifts in global economic conditions. If Costa Rica **accelerates its adoption of waste-to-energy (WtE) technologies** and **enhances its recycling infrastructure** beyond current projections, the reduction in **CO2e emissions** could be significantly greater, potentially mitigating the overall rise in emissions. Conversely, **delays in policy implementation** or **economic downturns** could lead to less effective waste management practices, resulting in **higher-than-anticipated emissions**. These scenarios highlight the importance of **adaptive and flexible policy-making** capable of responding to changing circumstances.

To examine the potential outcomes of different waste management strategies, a simulation was conducted projecting the remaining waste under four distinct scenarios from 2021 to 2050: the **Baseline Scenario**, **Enhanced Recycling Scenario**, **Waste-to-Energy (WtE) Scenario**, and a **Combined Scenario (Recycling + WtE)**. The simulation results, illustrated in **Figure 7**[4], indicate that the **Combined Scenario provides the most significant reduction** in remaining waste, suggesting a clear path to alleviating the pressure on landfill capacity.

In the **Baseline Scenario**, without any improvement in waste management practices, the remaining waste continues to grow, reaching approximately **1.67 million tonnes by 2050**. This trend underscores the insufficiency of current practices to manage escalating waste generation. The **Enhanced Recycling Scenario** shows a notable reduction, with remaining waste leveling off at around **1.85 million tonnes by 2050**, indicating that recycling alone may not be sufficient for long-term sustainability. The **Waste-to-Energy (WtE) Scenario** demonstrates a more substantial reduction, with remaining waste decreasing to approximately **0.84 million tonnes by 2050**. However, the **Combined Scenario** achieves the most significant reduction, with remaining waste projected to be

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[4] **Figure 7** s derived from **Supplementary Table 10**,

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below **0.92 million tonnes by 2050**. This outcome suggests that a **multi-faceted approach** integrating both enhanced recycling and WtE technologies is the optimal strategy for minimizing waste and reducing landfill strain.

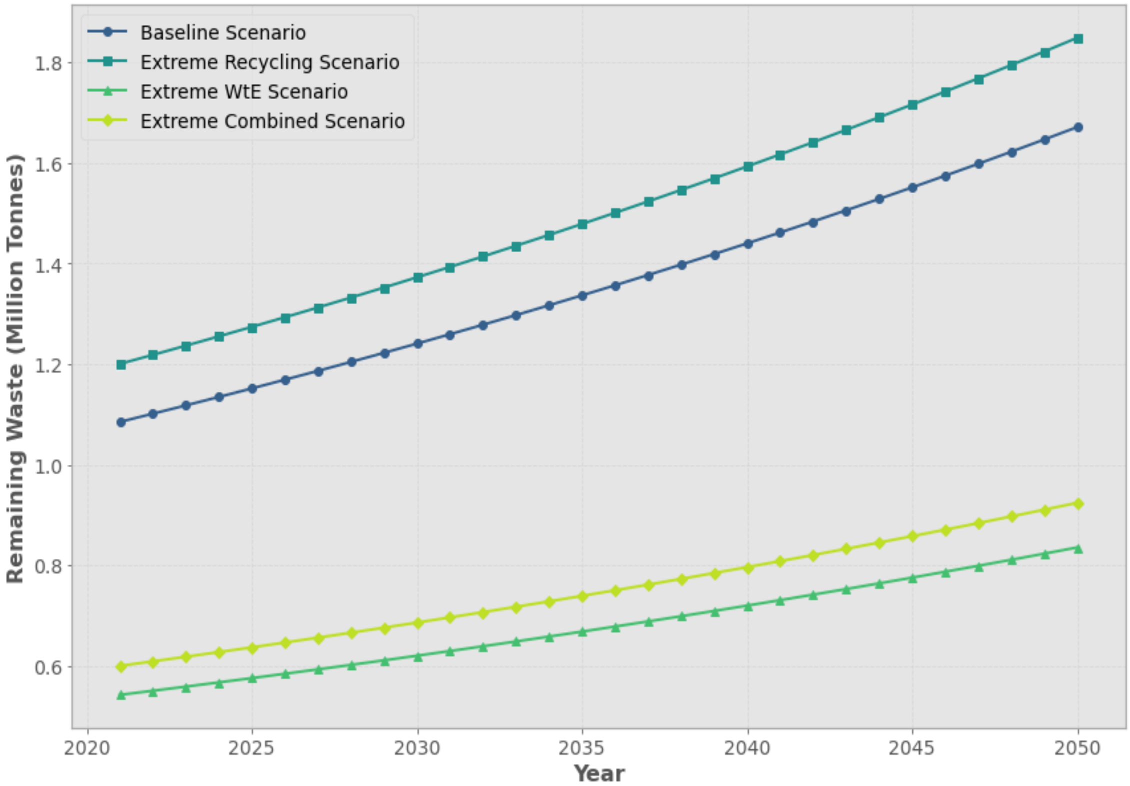

Figure 7. Recycling Scenarios: Projected Remaining Waste (2021-2050). **Caption:** This figure illustrates the projected remaining waste in Costa Rica under four scenarios: Baseline, Enhanced Recycling, Waste-to-Energy, and a Combined Strategy of Recycling and Waste-to-Energy. The **Combined Scenario** shows the greatest reduction in remaining waste, indicating the potential effectiveness of integrating both recycling and waste-to-energy technologies into Costa Rica's waste management strategy.

The significant differences between these scenarios underscore the **critical need for a comprehensive waste management strategy** in Costa Rica. The findings clearly reveal that **enhancing current recycling efforts alone** will not be sufficient to manage the escalating waste generation. By 2050, the **Combined Scenario** emerges as the **most effective approach**, demonstrating that a strategic blend of recycling and waste-to-energy (WtE) technologies can **significantly reduce residual waste**, keeping it within the manageable capacity of existing or potential new landfills. This compelling evidence underscores the **urgency for immediate, integrated policy actions** in waste management to ensure **sustainability and environmental protection** for the future of Costa Rica.

7.2. Stakeholder Perspectives: Shaping Waste Management Policy

Stakeholder perspectives on waste management in Costa Rica reveal a complex interplay of regulatory, cultural, and economic factors that significantly influence the effectiveness of recycling initiatives. Government officials emphasize the necessity for comprehensive policies and stricter enforcement, particularly in rural areas where infrastructure deficiencies and traditional waste disposal practices, such as burning or burying waste, persist. Future legislative actions may include developing more robust rural waste management infrastructure and implementing stricter penalties for non-compliance with recycling regulations. Additionally, these officials advocate for educational

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programs tailored to address cultural barriers in rural communities, ensuring that waste management practices are adapted to local contexts, as observed in Wang et al. (2021) [48].

Environmental groups call for stronger government action and deeper community engagement, arguing that current enforcement mechanisms are insufficient. Without comprehensive public education campaigns that are sensitive to local cultural contexts, they believe recycling initiatives will continue to fall short. These groups may influence the development of policies that integrate Multi-Criteria Decision Analysis (MCDA) frameworks, which balance environmental, economic, and social criteria to create more effective and inclusive waste management strategies, as proposed by Knickmeyer (2020) [49].Expanding on this, it is crucial to consider how local cultural factors influence stakeholder perspectives, particularly in rural and indigenous communities where traditional practices may conflict with modern waste management techniques. For instance, the cultural importance of land and nature in these communities can both support and hinder waste management efforts. Tailoring recycling policies to respect these cultural values while promoting sustainable practices is essential for gaining broader acceptance and effectiveness. Addressing these cultural influences through community-led initiatives and culturally sensitive education programs can significantly enhance the impact of recycling policies.

Businesses, in contrast, are in favor of **economic incentives**, including **tax breaks and subsidies**, to stimulate corporate investment in recycling infrastructure. Their **willingness to invest**, given sufficient regulatory backing, underscores the potential for **public-private partnerships (PPPs)** to lead innovation in waste management. Costa Rica could adopt **similar economic strategies** to those used in Chile, encouraging greater corporate involvement in sustainable waste management through **targeted tax incentives and subsidies**, as highlighted by **Araya-Córdova et al. (2021) [50].**

Utilizing **advanced methodologies** such as **Social Network Analysis (SNA)** and **Geographic Information Systems (GIS)** can significantly enhance the understanding of stakeholder engagement and improve policy execution. **SNA** can analyze the relationships and power structures among stakeholders, revealing important communication channels that impact how policies are adopted and engaged with. This approach can lead to more precise targeting of key influencers within the waste management sector, thereby increasing the effectiveness of policy rollouts. Similarly, **GIS** can support the strategic planning of waste management infrastructure by identifying the areas with the most urgent needs, ensuring that **resources are allocated in the most effective manner** [51].

Predictive modeling techniques, such as System Dynamics Modeling, could also play a crucial role in shaping future waste management strategies by offering a forward-looking assessment of the long-term impact of current policies on stakeholder engagement. For example, machine learning models could analyze historical data to forecast the success of educational programs aimed at changing cultural norms around waste management, enabling policymakers to refine strategies and ensure more effective promotion of sustainable waste management practices across Costa Rica [52].

Overall, integrating stakeholder perspectives into waste management policies in Costa Rica is crucial for developing effective, context-sensitive strategies that address the diverse challenges faced across different regions. By leveraging advanced methodologies and fostering collaboration among government, environmental groups, and businesses, Costa Rica can enhance the effectiveness of its waste management policies, contributing to its broader environmental sustainability goals.

9. Conclusion

This study underscores the **critical need for comprehensive reforms** in Costa Rica's waste management system, particularly in addressing the **persistently low recycling rates** and the **over-reliance on landfills**. Despite the government's strong commitment to environmental sustainability, significant challenges persist, especially in rural areas where **infrastructure deficits** and **limited public participation** continue to hinder progress. The **Waste Management Innovation Index** clearly identifies the areas where Costa Rica lags behind global leaders, particularly in **technological advancements** and **infrastructure development**.

Looking ahead, expanding recycling infrastructure, enhancing public education efforts, and promoting public-private partnerships are essential for modernizing waste management practices.

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The simulation results indicate that combining improved recycling with waste-to-energy (WtE) technologies could significantly reduce landfill pressures, providing a clear pathway for the country's future. Stakeholder insights emphasize the importance of tailoring reforms to local cultural contexts, ensuring that policies remain flexible and community-oriented. Incorporating advanced technologies, such as AI-driven sorting systems and biodegradable materials, will be critical in achieving these goals.

To effectively implement these strategies, a thorough understanding of local contexts and the creation of strong legislative frameworks are essential for ensuring lasting impact. It's important to acknowledge and address potential obstacles, such as financial limitations, cultural resistance, and technological challenges, through ongoing evaluation and policy adjustments. Utilizing advanced tools, such as **Social Network Analysis (SNA) and Geographic Information Systems (GIS**), can offer valuable insights into stakeholder dynamics and the geographic distribution of waste management requirements, thereby strengthening these initiatives.

By prioritizing these key strategies, Costa Rica can successfully overcome its current waste management issues and emerge as a global leader in sustainability. With carefully planned reforms, technological innovations, and active community participation, Costa Rica can ensure the preservation of its environmental legacy and play a pivotal role in the global movement towards a circular economy and sustainable growth.

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