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

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

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Abstract: Costa Rica, renowned for its environmental sustainability, faces a **pressing waste management crisis** that threatens its ecological and public health achievements. This study provides a comprehensive analysis of Costa Rica's waste management challenges, focusing on urban areas like San José, where nearly half of the nation's waste is generated. Key issues include **insufficient landfill capacity**, a **low recycling rate of 9.6%**, and significant regional disparities in waste practices. Employing a hybrid modeling approach with Linear Regression and ARIMA models, the study forecasts **CO2e emissions** and waste minimization trends from 2024 to 2050, highlighting the critical role of public participation and innovative waste management strategies.The introduction of a **Waste Management Innovation Index** allows for a comparative analysis, positioning Costa Rica against global leaders like Germany and South Korea, and identifying areas where significant improvements are needed. The study also incorporates **stakeholder perspectives** to reveal the complex interplay of cultural, economic, and regulatory factors influencing waste management policies.Findings indicate that despite government initiatives like the Environmental Health Route and the National Circular Economy Strategy, success has been limited, particularly in rural areas. The study underscores the necessity of enhancing infrastructure, launching targeted public education campaigns, and adopting advanced technologies such as **AI** and **blockchain** to achieve sustainable waste management. Strategic recommendations are provided to help Costa Rica align its waste management practices with global standards.

Keywords: waste management; recycling rates; environmental sustainability; Costa Rica; circular economy strategies; public participation in recycling

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 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

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success of government initiatives like the Environmental Health Route policy, further underscores the severity of the situation **[8]**.

In response to these challenges, Costa Rica has enacted several legislative measures aimed at reducing waste and promoting sustainable practices. Notably, the "Ley para Combatir la Contaminación por Plástico y Proteger el Ambiente" (Law No. 9786), enacted in 2019, targets the reduction of single-use plastics and the promotion of circular economy practices. This law prohibits the distribution of plastic straws and non-reusable plastic bags, mandates the inclusion of recycled materials in plastic products, and emphasizes public education on plastic waste reduction **[9]**. These efforts underscore the government's commitment to tackling plastic pollution, a critical component of the broader waste management strategy.

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. The historical data, sourced from Universidad Nacional (2010-2014), provided 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 initially used to establish baseline linear trends in variables such as total waste generation and CO2e emissions. These initial projections, executed using R Studio, laid the groundwork for more detailed analysis. Subsequently, ARIMA was applied to the residuals from the LR model to capture non-linear patterns and temporal dependencies, thereby enhancing the robustness of the predictions.

The execution and visualization of these models were performed using **Python and the Spyder IDE**. Residuals analysis played a critical role in the **model validation process**, providing insights into the accuracy of the predictions and identifying patterns not fully captured by the models. **Before finalizing the hybrid model, alternative forecasting methods, including the Exponential Smoothing State Space Model (ETS) and the Prophet Model with custom seasonality, were explored.** Although these models offered valuable insights, the **LR+ARIMA combination proved more 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. The residuals were thoroughly examined to confirm the **accuracy and robustness** of the projections, providing a comprehensive, data-driven roadmap for understanding the potential impact of ongoing and future waste management initiatives in Costa Rica.

However, it is important to acknowledge certain limitations of the chosen methodology. The reliance on historical data may introduce **biases related to past trends**, and the assumptions inherent

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in the LR and ARIMA models could impact the accuracy of future projections under drastically changing conditions. Despite these limitations, the chosen approach was deemed the most suitable for the scope and objectives of this study.

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

Despite its global reputation for environmental sustainability, **Costa Rica faces significant challenges in effectively managing its waste**. Recent studies indicate varying waste generation rates across the country, reflecting diverse socioeconomic conditions and infrastructure capabilities. In the **Metropolitan Area of Costa Rica**, 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]. Similarly, in the **Guácimo municipality**, the average generation rate is slightly lower at **0.55 kg per person per day**, with waste composed of **35% recyclable materials, 45% biodegradable waste, and 20% destined for landfills** [12].

The strain on **landfill capacities is particularly concerning**, with many sites approaching or exceeding their designed capacities, a situation exacerbated by the recent **closure of the Los Pinos landfill in Cartago**. This has forced municipalities to seek alternative solutions, and the issue is further complicated by **regional disparities in waste management practices**: while **urban areas like San José generate nearly 47% of the nation's waste**, placing a substantial burden on existing infrastructure, rural regions struggle with **inadequate waste collection services and limited access to recycling facilities** [3]. Additionally, the implementation of **more accurate leachate movement models tailored to Costa Rica's tropical conditions** is essential to enhance the efficiency and longevity of waste disposal sites [13].

Comparing Costa Rica's waste management system with those of other countries in the region reveals shared challenges, such as **inadequate recycling infrastructure and high rates of waste leakage into the environment** [14]. However, countries like **Colombia and Chile have made significant strides** in improving their waste management systems through **targeted policy reforms and investments in recycling infrastructure**. **Adopting similar best practices from these countries**, particularly in enhancing recycling and waste diversion strategies, could help Costa Rica improve its overall waste management efficiency and better prepare for future increases in waste production [15].

In summary, while Costa Rica has made considerable progress in environmental sustainability, the country's waste management system remains under significant strain, particularly in urban areas like San José. Addressing these challenges requires not only the implementation of advanced waste management models and infrastructure but also the adoption of successful strategies from other nations facing similar issues. By focusing on enhancing recycling rates, improving landfill management, and bridging the urban-rural divide in waste collection services, Costa Rica can take critical steps toward aligning its waste management practices with its broader sustainability goals. This foundational understanding of the current state of waste management sets the stage for the subsequent analysis of specific government initiatives aimed at addressing these challenges.

3.1. Landfill Capacities and Regional Waste Management Practices

The concentration of waste production in urban areas, particularly **San José**, underscores the **urgent need for targeted waste management solutions**. Effective waste management is crucial to 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].

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

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significant 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, it is essential to implement targeted improvements in waste recovery infrastructure and policies. Projections for 2050 suggest that, with significant interventions, the proportion of recoverable waste could increase by up to 30-40%, alleviating pressure on landfill capacities and contributing to more sustainable waste management practices [16].

The capacity of landfills in Costa Rica has reached a critical point, with many sites **nearing or exceeding their maximum limits**. Major landfills, such as **La Carpio and Aserrí**, each manage approximately **600 tonnes of waste daily** and are on the brink of collapse after decades of service, with waste accumulation far exceeding their original design capacities. The recent **closure of the Los Pinos landfill in Cartago in January 2024**, due to its full capacity and geological risks, underscores the severity of the situation [17]. **Figure 3** illustrates the geographic locations of these key landfill sites, highlighting their proximity to urban areas and the environmental challenges they present.

Given the current circumstances, Costa Rica must urgently develop new waste disposal methods to alleviate the pressure on landfills and mitigate greenhouse gas emissions. With **94% of solid waste in the country ending up in landfills, open dumps, or designated waste disposal sites**, the risks to surface and groundwater quality are substantial. In urban areas like San José, while waste collection services are more accessible, their efficiency and frequency vary, leading to **inconsistent waste management**. Rapid urban expansion has exacerbated environmental degradation, exposing **groundwater to nitrate pollution** and contributing to **air pollution-related diseases**. In contrast, **rural regions face even greater challenges due to logistical issues and inadequate infrastructure**, resulting in improper disposal practices such as burning or burying waste. These practices not only pose environmental hazards but also have **severe public health implications**, as unregulated waste management can lead to soil and water contamination [18,19].

In summary, 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 will be essential to safeguarding both environmental and public health as the nation moves forward.

4. Government Initiatives and Policies

Costa Rica is widely recognized for its commitment to environmental sustainability, particularly in the areas of biodiversity conservation and renewable energy. However, the country faces significant challenges in waste management, prompting the government to introduce 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 objectives, the policy outlines specific sub-goals such as reducing per capita waste generation by **10% by 2025**, expanding public education campaigns on waste separation, and developing new infrastructure for waste sorting and processing in underserved areas [20]. Complementing these efforts is the **National Circular Economy Strategy**, launched in 2023. This strategy seeks to transform waste management practices and reduce emissions by promoting a **circular economy model**, where materials are reused, recycled, and repurposed to minimize waste. Specific initiatives under this strategy include promoting the use of **reusable bags and containers**, incentivizing businesses to adopt sustainable packaging, and fostering the development of markets for recycled materials. The strategy not only encourages businesses and consumers to adopt more sustainable practices but also emphasizes the importance of **reducing single-use plastics** and improving recycling infrastructure [21,22].

Adding to these initiatives, Costa Rica implemented the **'Ley para Combatir la Contaminación por Plástico y Proteger el Ambiente' (Law No. 9786)** in 2019. This law aims to drastically reduce the use of single-use plastics through various measures, such as **banning plastic straws and non-reusable plastic bags**, promoting reusable materials, and integrating plastic waste education into the national curriculum. The law also mandates the creation of special programs for research and

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innovation to support the transition away from plastics, aligning with the circular economy strategy's goals. The alignment of these initiatives with **Law No. 9786** underscores Costa Rica's commitment to reducing waste generation through a **comprehensive, multi-faceted approach** [8].

These initiatives highlight the government's proactive stance in addressing the multifaceted challenges of waste management. The **Environmental Health Route policy** and the **National Circular Economy Strategy** are central to this effort, establishing ambitious targets for recycling and waste reduction while also focusing on expanding infrastructure and public education. The success of these initiatives depends heavily on **effective implementation, public participation, and ongoing evaluation**.

Progress has been made in several areas, such as the **ban on plastic bags**, which has seen varying levels of success across different communities. In some regions, **reusable alternatives** have been widely adopted, while in others, challenges remain due to **limited access to sustainable options**. The expansion of waste collection services under the **Environmental Health Route policy** has also made significant strides, particularly in urban areas, although rural regions continue to face difficulties with inconsistent service delivery.

The government's dedication to these initiatives reflects a deep understanding of the need for **tailored solutions that 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**. By integrating immediate and long-term goals, these policies aim to minimize environmental impact, promote public health, and drive sustainable economic growth. The emphasis on circular economy practices further underscores the **strategic importance of reducing waste generation through innovative approaches**. However, the effectiveness of these programs will ultimately depend on overcoming barriers such as **public awareness, funding constraints, and technological limitations**. **Table 1** summarizes these government initiatives and their goals.

Table 1. Government Initiatives and Goals.

Initiative	Goal	Target Year	Reference
Environmental Health Route Policy	Increase recycling rate to 25%	2033	[20]
Environmental Health Route Policy	Ensure regular garbage collection in 34% of the territory	2023	[20]
Environmental Health Route Policy	Reduce per capita waste generation by 10%	2025	[20]
National Circular Economy Strategy	Promote circular economy practices	Ongoing	[21,22]
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 represent Costa Rica's comprehensive approach to addressing the complexities of waste management. The **Environmental Health Route policy** and **National Circular Economy Strategy** are at the forefront of these efforts, setting the stage for significant advancements in recycling and waste reduction while also focusing on the expansion of infrastructure and public education. By integrating immediate and long-term goals, these policies aim to minimize environmental impact, promote public health, and drive sustainable economic growth. As Costa Rica continues to refine and implement these initiatives, it stands poised to strengthen its environmental stewardship and serve as a model for other nations facing similar challenges.

5. Results and Discussion

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5.1. Waste Management Projections and Strategic Analysis

To effectively address the critical challenges in Costa Rica's waste management system, it is essential to prioritize the expansion of recycling programs, invest in composting infrastructure, and explore alternative waste treatment technologies such as waste-to-energy. **These strategies have the potential to transform the country's waste management system from one reliant on landfills to one focused on resource recovery and sustainability by 2050.** The introduction of waste-to-energy technologies, including anaerobic digestion, gasification, and incineration, can play a crucial role in this transformation by reducing landfill use while contributing to renewable energy generation, aligning with Costa Rica's broader environmental goals.

Figure 1 details projections for total waste, recoverable waste, and recovery rates in Costa Rica from 2021 to 2050. The data illustrate a significant increase in total waste sent to landfills, underscoring the need for enhanced waste recovery infrastructure and policies to alleviate the pressure on these facilities. **With targeted interventions, the recovery rate is expected to improve, potentially reaching 25% by 2033.**

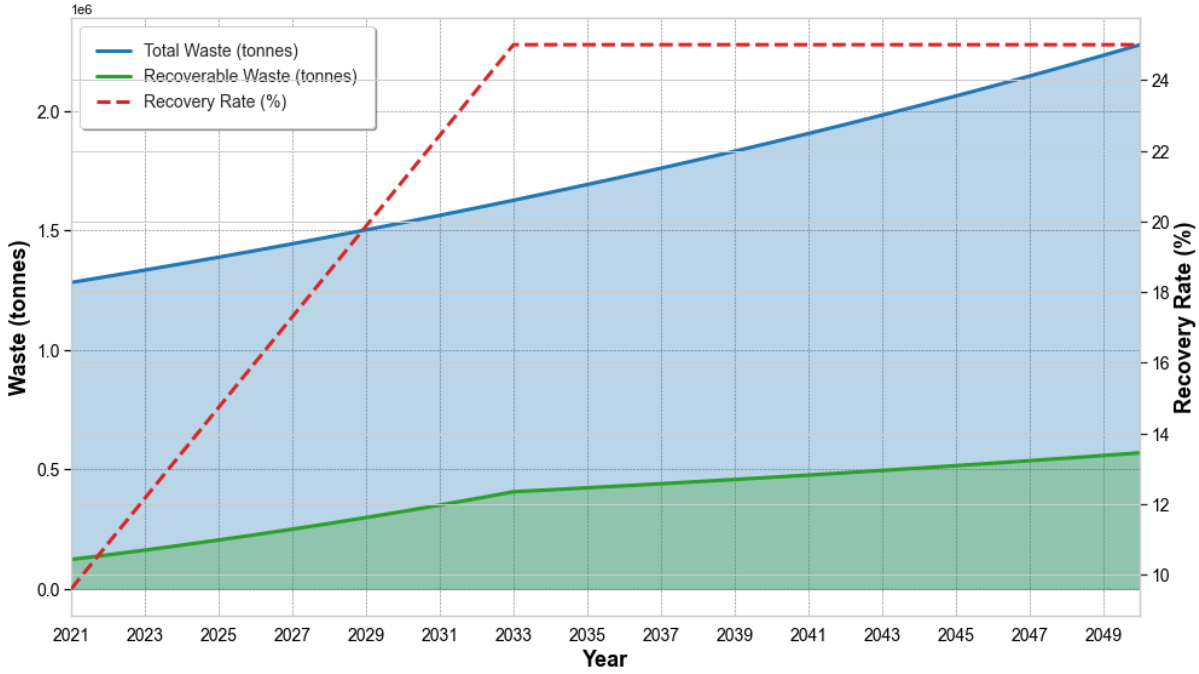

Figure 1. Projections for Total Waste, Recoverable Waste, and Recovery Rate in Costa Rica (2021-2050). **Caption:** The figure illustrates the projected increase in total waste sent to landfills and recoverable waste from **2021 to 2050**. It also shows the expected improvement in the recovery rate, 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 such as paper, cardboard, and plastic. These changes reflect the potential impact of ongoing and future waste management initiatives, suggesting improvements in composting and recycling practices over time

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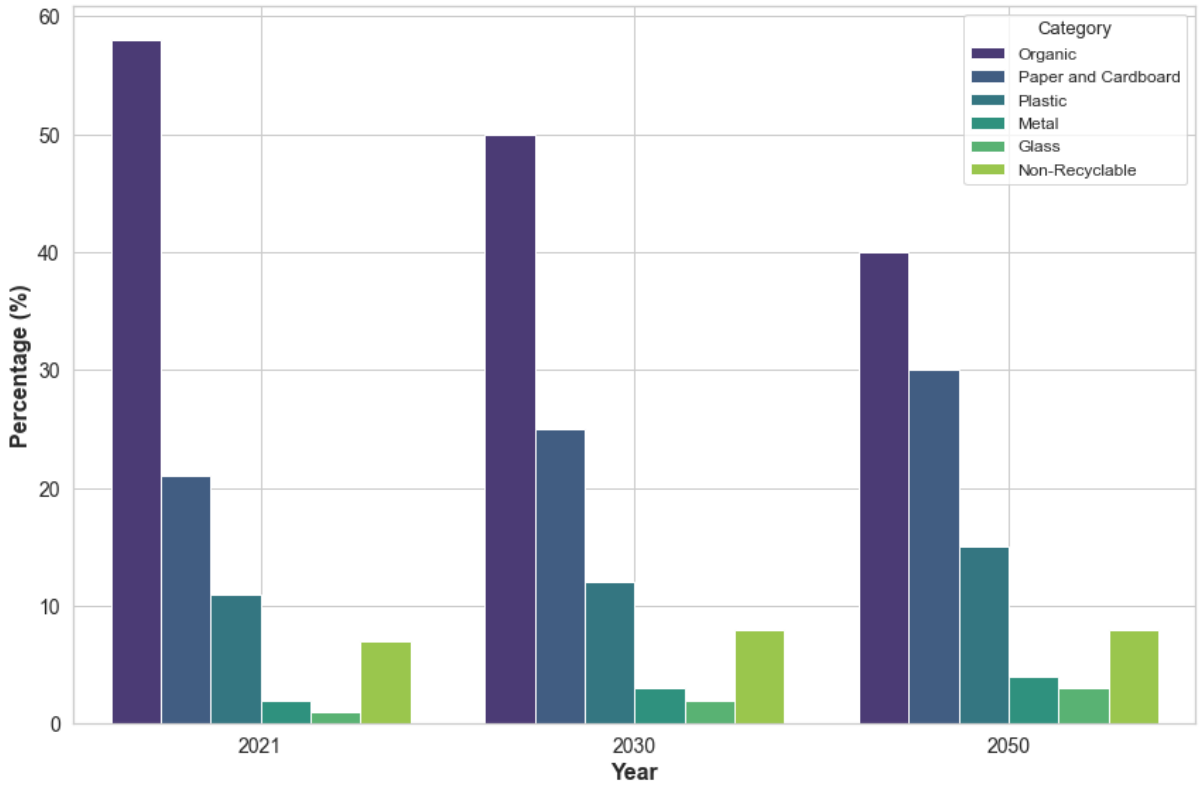

Figure 2. Projected Waste Composition in San José for the Years 2021, 2030, and 2050. **Caption:** The figure shows the waste composition in San José, with significant changes projected for **2030** and **2050**. It highlights a reduction in organic waste and an increase in recyclable materials like 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** that could arise based on varying rates of technological adoption, policy implementation, or global events. **For instance, if Costa Rica accelerates its adoption of waste-to-energy technologies and enhances its recycling infrastructure beyond current projections, the recovery rate could exceed 30% by 2033,** further reducing landfill dependency. Conversely, delays in policy implementation or economic downturns could slow progress, resulting in only modest improvements in recovery rates and increased pressure on landfills. **These scenarios highlight the importance of flexible and adaptive policy-making** that can respond to changing circumstances.

The projections presented are based on the assumption of steady progress and successful implementation of proposed strategies. However, several factors could introduce **uncertainty** into these projections, including sudden policy changes, shifts in global economic conditions, or technological advancements. **For example, a global recession could limit funding for waste management initiatives,** slowing progress and leading to higher landfill use than anticipated. Alternatively, a breakthrough in waste processing technology could significantly enhance recovery rates and reduce waste generation. **By acknowledging these uncertainties, we can better understand the potential range of outcomes** and prepare for various contingencies.

The waste management projections discussed not only impact environmental sustainability but also have broader socio-economic implications. For instance, improved waste recovery and recycling rates could lead to job creation in the waste management sector, particularly in rural areas where economic opportunities are limited. Additionally, reducing landfill dependency could enhance public health by minimizing exposure to landfill-related pollutants and reducing greenhouse gas emissions. Moreover, equitable access to waste management services can promote social equity,

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ensuring that all communities, particularly underserved areas, benefit from these advancements. As Costa Rica works toward its sustainability goals, it is essential to consider these socio-economic outcomes to maximize the benefits of waste management initiatives.

In summary, the projected increase in total waste highlights the **urgency of implementing waste recovery strategies**. The anticipated rise in the recovery rate to **25% by 2033** suggests that with appropriate interventions, Costa Rica can make substantial progress in reducing its landfill dependency and enhancing sustainability. **By considering alternative scenarios, acknowledging uncertainties, and linking these projections to broader socio-economic outcomes,** we gain a more comprehensive understanding of the potential impacts and benefits of Costa Rica's waste management strategies.

5.2. Landfill Capacities and Geographic Considerations

The challenges in waste management are particularly acute in urban areas like **San José**, where waste production is concentrated, and landfill capacities are under severe strain. **Current data indicates that San José's waste recovery rate is low**, with a significant portion of waste, estimated at **58%**, being organic. This highlights the potential for improvement through the expansion of recycling programs and the development of composting infrastructure.

Key landfill sites, including La Carpio and Aserrí, each receive approximately 600 tonnes of waste daily, with an estimated remaining life of **2 to 5 years** [11]. The **Los Pinos landfill**, which was officially closed in January 2024 due to reaching full capacity, exemplifies the challenges faced by these facilities [17]. These data points underscore the urgency of addressing landfill capacities through enhanced waste management practices.

Figure 3 presents the geographic locations of key landfill sites in Costa Rica, including **La Carpio, Aserrí, and the recently closed Los Pinos landfill**. These sites are in close proximity to urban areas, particularly San José, underscoring the environmental challenges posed by landfill operations in densely populated regions. The closure of the Los Pinos landfill in January 2024 due to reaching full capacity and structural failures further illustrates the limitations of current landfill capacities.

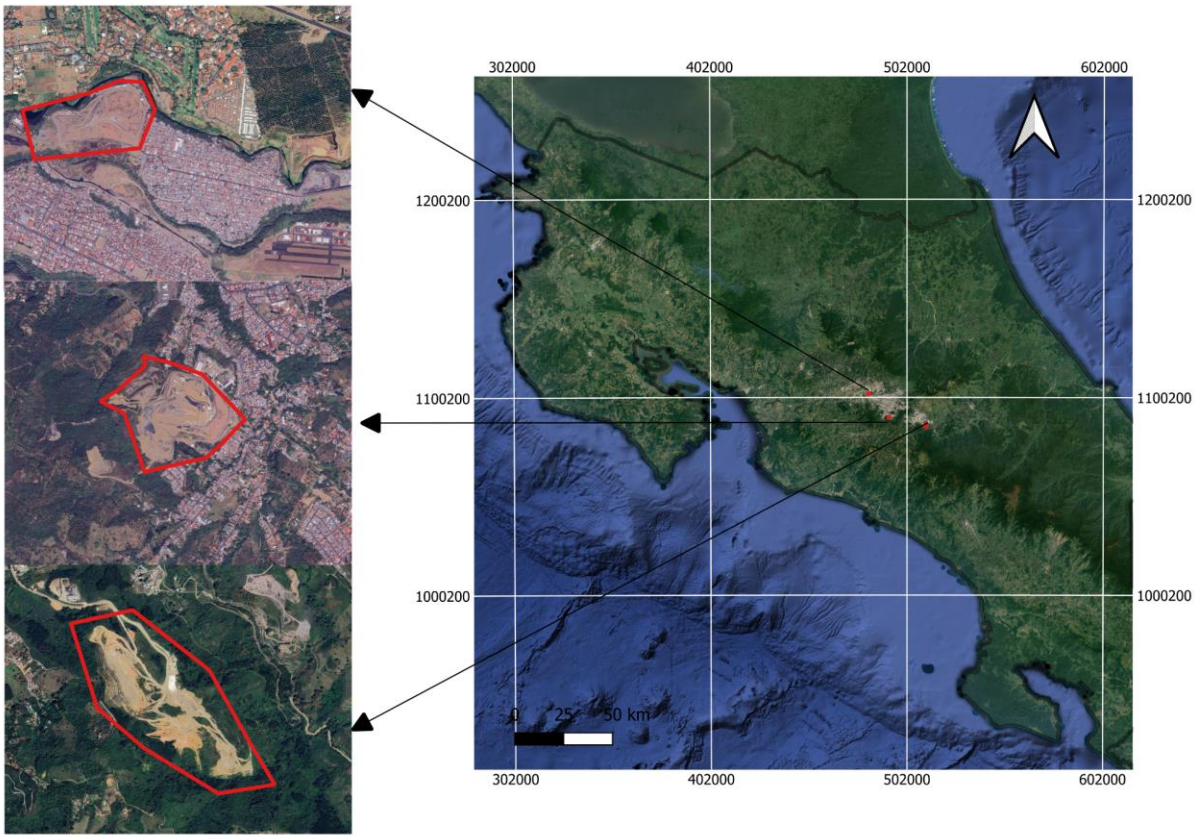

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Figure 3. Satellite imagery of major landfill sites in Costa Rica: (a) La Carpio Landfill, (b) Aserrí Landfill, and (c) Los Pinos Landfill. The Los Pinos landfill was officially closed in January 2024 due to reaching full capacity and structural failures.

Data on landfill management practices indicates that improving the management of existing landfills is critical. Current practices such as compaction techniques, the use of liners to prevent leachate contamination, and gas collection systems to capture methane emissions are essential for mitigating environmental risks. However, these measures alone may not be sufficient to address the growing waste management needs.

The data on landfill capacities and geographic considerations underscore the critical need for immediate and 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 becoming unsustainable, particularly with key sites like Los Pinos reaching full capacity and closing. Addressing these challenges requires not only improving the management of current landfills but also expanding recycling and composting infrastructure to reduce landfill dependency. By prioritizing these measures, Costa Rica can mitigate the environmental risks associated with landfill operations and move closer to achieving its broader sustainability goals.

5.3. Public Participation and the Ecoins Program

Public participation is critical for achieving **Costa Rica's ambitious waste management goals**, including the target of a **25% national recycling rate by 2033**. To address the current low participation rate (**less than 10% of the population**) [**5**], the **ecoins program** was launched in **2017**. The program aims to increase recycling by offering a technological and economic reward system that encourages citizen involvement in solid waste management.

The **ecoins program** has already established **520 collection sites** and attracted **46,162 registered users** ("Ecofans") by **2023**, collecting **3,762 tonnes** of recyclable waste and avoiding **4,592 tonnes of CO2 emissions** [**16**]. **Projected values** based on the program's growth trajectory suggest that by **2030**, the number of collection sites could increase to approximately **1,127**, with the program collecting **8,151 tonnes** of recyclable waste and avoiding **9,949 tonnes of CO2 emissions**. By **2050**, the program could potentially expand to **2,860 collection sites**, involve **253,891 registered users**, and significantly boost Costa Rica's recycling rates, with an estimated **20,691 tonnes** of recyclable waste collected and **25,256 tonnes of CO2 emissions avoided** [**17**].

These projections underscore the **ecoins program's potential** to enhance public participation in recycling, contributing significantly to **Costa Rica's broader waste management goals**. However, to realize this potential, continued **investment and development** are crucial. This includes expanding the program's reach, particularly in rural areas, and exploring innovative incentive structures, such as **gamification and blockchain technology**, to further engage and motivate the population. Additionally, integrating the program's efforts with other national initiatives like the **Environmental Health Route policy** and the **National Circular Economy Strategy** could amplify its impact and help Costa Rica achieve its sustainability objectives. **Table 2** highlights the program's achievements from 2017 to 2023, as well as the projected impact for 2030 and 2050.

Table 2. 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	[23]
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]

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The ecoins program represents a significant step toward increasing public participation in recycling by providing tangible incentives. However, the overall participation rate remains low, indicating that further efforts are needed to enhance engagement. Comparative analysis with similar programs from other countries, such as **Brazil's EcoPontos** and **South Korea's Eco Mileage Program**, could provide valuable insights into different incentive structures and their effectiveness. For instance, EcoPontos offers discounts on goods and services, which contributed to a 20% increase in recycling rates during its first year **[24]**. Similarly, South Korea's program resulted in a 15% reduction in household energy consumption by rewarding users for eco-friendly behaviors **[25]**.

To further boost participation, innovative approaches such as gamification and blockchain technology could be explored. Gamification, as demonstrated by **Estonia's Trash and Seek app**, can make recycling more engaging and educational by rewarding users for correct sorting and recycling activities **[26]**. Additionally, integrating 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 **[27]**.

Expanding the digital presence of the ecoins program through a dedicated mobile app could also be an effective strategy. An app similar to **Japan's Pirika**, which tracks recycling habits, offers real-time feedback, and connects users with local recycling initiatives, could significantly improve participation rates **[28,29]**. 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, along with the integration of innovative technologies and expanded reach, could position Costa Rica as a leader in sustainable waste management. Such efforts would not only contribute to the nation's Environmental Health Route policy and National Circular Economy Strategy but also inspire other nations to adopt similar approaches in tackling their own waste management challenges.

5.4. Technological 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 [30–32]. These tools have been successful in similar tropical settings, such as Brazil, reducing groundwater contamination risks by **25%** over five years [33].

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, successfully implemented in South Korea and parts of the United States, where waste reduction reached **30%** within three years [37,39]. Additionally, fostering Public-Private Partnerships (PPPs), as seen in Singapore, could attract private investment and enhance financial sustainability in municipal waste management [40,42]. 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 [44,45]. 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%** [46,47]. Blockchain can

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provide secure, immutable records of recycling activities, ensuring transparency and accountability [48,49].

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.

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, based on data sourced from **Supplementary Tables S1, S2, S3, and S4**.

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.

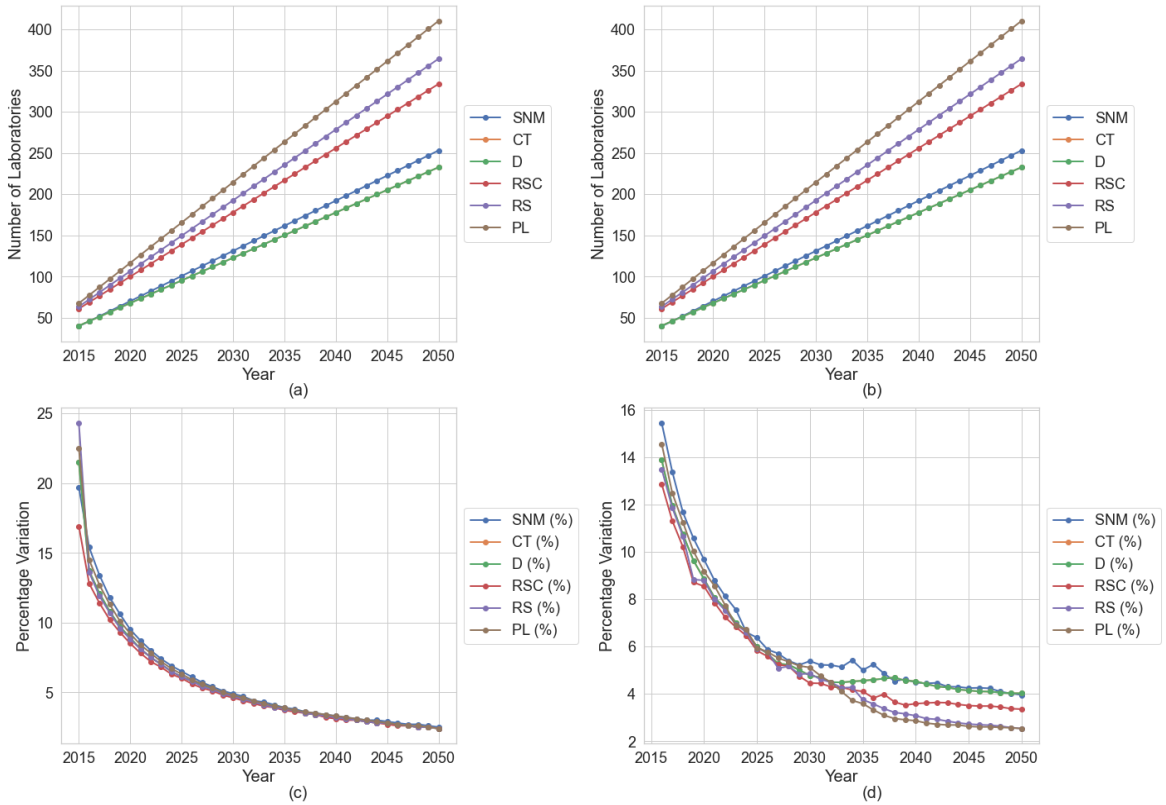

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Figure 4. Number of laboratories performing waste minimization practices and annual percentage variation (2015-2050). **Caption:** The figure illustrates the trends in the number of laboratories performing six and five waste minimization practices 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 nonhazardous materials and redistributing 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 fostering a culture of sustainability within laboratories and other institutions and embracing innovative waste management practices, Costa Rica can further strengthen its leadership in environmental stewardship. **By prioritizing these practices, Costa Rica can not only reduce waste generation but also contribute to achieving its ambitious targets for recycling, promoting a circular economy, and mitigating the environmental impact of its waste management system. Addressing these challenges, particularly for practices like chemical treatment (CT) and computer simulation (CS) that have shown slower adoption rates, through targeted research and strategic interventions will be critical for accelerating the adoption of these practices and achieving the country's ambitious waste management goals.**

6. 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 3 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 3. Global Recycling Rates.

Region/Country	Recycling Rate (%)	Key Contributing Factors	References
European Union	46% (2020)	Varies across member states; strong policies and infrastructure	[41]
Germany	69.3% (2024)	Stringent waste separation, strong regulations	[42]
United States	21% (2024)	State-level variations, mixed public participation	[43]

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Japan	20% (2023)	Meticulous waste sorting, but lower recycling infrastructure	[44]
Brazil	4% (2024)	Driven by informal sector, lack of formal infrastructure	[45]
South Korea	69% (2023)	Public involvement, advanced waste sorting systems	[46]
Sweden	50% (2024)	High integration of Waste-to-Energy (WtE) technologies	[47]
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].

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**[1] below, 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

[1]**Table 4** is derived from **Supplementary Table 6**,

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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

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)	[41,42]	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 involvement	Germany, Japan	[42,44]	Launch public education	Raising public awareness is	Increased awareness

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	and education campaigns significantly increase recycling participation.			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.	essential for increasing participation in recycling programs, especially in rural and under-served areas of Costa Rica.	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	[42,46,47]	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 and address Costa Rica's infrastructure deficiencies.	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.
Economic Incentives	Financial incentives, such as deposit return schemes and tax breaks,	US (state programs), EU (deposit return schemes)	[41,43]	Introduce tax breaks for companies engaged in recycling and explore the potential of	Implementing economic incentives will make recycling more attractive to businesses and	Could increase recycling participation by 15% within three years.

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	boost recycling efforts.			deposit return schemes to incentivize recycling. This approach could make recycling more attractive to businesses and consumers, increasing participation rates.	consumers, driving higher participation rates.	
Cultural Norms	Strong cultural norms around waste reduction contribute to higher participation in recycling.	Japan, South Korea	[44,46]	Promote cultural shifts towards sustainability through community-driven initiatives and public recognition of recycling efforts. This could help normalize sustainable practices and embed recycling in the daily routines of Costa Ricans.	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.
Market for Recycled Materials	A robust market for recycled materials provides economic value and incentivizes recycling activities.	EU, United States	[41,43]	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

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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**[2] 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**. **Figure 5(a)** 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 **Linear Regression and ARIMA models** predict a continued upward trajectory, with the ARIMA model introducing 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 [7].

In contrast, **Figure 5(b)** 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.

Alternative Scenarios and Uncertainty Analysis: While the baseline projections offer a clear path forward, it is crucial to consider alternative scenarios that could arise based on varying rates of policy adoption, technological advancements, or global economic conditions. For instance, if Costa Rica accelerates its adoption of waste-to-energy 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 result in less effective waste management practices, leading to higher than anticipated emissions. These scenarios highlight the importance of adaptive and flexible policy-making that can respond to changing circumstances.

The stark contrast between the **increasing emissions from landfills** and the **decreasing emissions from recycling** underscores the **urgent need for a more comprehensive approach** to waste management in Costa Rica. The data suggests that simply expanding current recycling efforts will not be sufficient to counterbalance the rising emissions from landfills. By **2050**, landfill emissions are projected to reach approximately **1,725 thousand tonnes of CO2e**, while recycling efforts could potentially reduce emissions by about **26 thousand tonnes of CO2e**. This significant disparity emphasizes the need for innovative strategies that extend beyond recycling. Such strategies could include **waste reduction at the source**, **enhanced waste diversion practices**, and the development of **alternative waste treatment technologies** capable of significantly lowering the overall carbon footprint of Costa Rica's waste sector [9].

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[2] **Figure 5** is derived from **Supplementary Table 7**,

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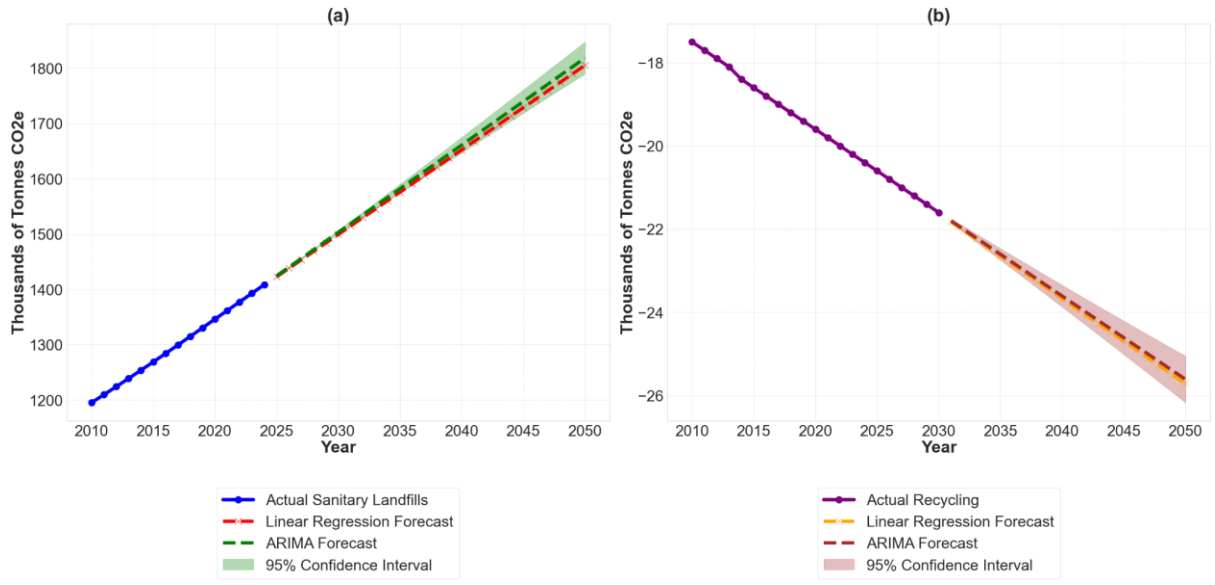

Figure 5. Projected CO2e Emissions from Sanitary Landfills and Recycling Activities in Costa Rica (2010-2050). Caption:(a) Sanitary Landfills Forecast: Forecast of CO2e emissions from sanitary landfills in Costa Rica from 2010 to 2050. The blue line represents the actual data from 2010 to 2024, the red dashed line indicates the linear regression forecast, and the green dashed line indicates the ARIMA forecast. The green shaded area represents the **95% confidence interval** for the ARIMA forecast. (b) **Recycling Forecast:** 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. These forecasts provide insights into the future impact of waste management practices on greenhouse gas emissions in Costa Rica.

The data presented highlight the contrasting trends in CO2e emissions from sanitary landfills and the potential reductions achievable through enhanced recycling efforts. The **steady increase in emissions** from landfills underscores the **urgent need for more aggressive waste management strategies**, particularly in reducing landfill dependency. In contrast, the **projected reduction in emissions** due to recycling activities emphasizes the **effectiveness of current recycling initiatives** but also points to the **limitations** of relying solely on recycling to mitigate greenhouse gas emissions. The significant disparity between the emissions from landfills and the reductions achieved through recycling suggests that **Costa Rica must adopt a multifaceted approach** that includes waste reduction at the source, improved waste diversion practices, and the development of alternative waste treatment technologies. This integrated strategy will be crucial for achieving Costa Rica's broader environmental goals and reducing the overall carbon footprint of its waste management system.

7.1. 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 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].

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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, on the other hand, support economic incentives, such as tax breaks and subsidies, to encourage corporate investment in recycling infrastructure. Their willingness to invest, provided there is adequate regulatory support, highlights the potential for **public-private partnerships (PPPs)** to drive innovation in waste management. **Costa Rica could implement similar economic strategies to those in Chile,** fostering greater corporate participation in sustainable waste management through targeted tax incentives and subsidies, as noted by Araya-Córdova et al. (2021) [50].

Advanced Methodologies: To further understand and enhance stakeholder engagement, advanced methodologies such as Social Network Analysis (SNA) and Geographic Information Systems (GIS) could be employed. SNA could map relationships and uncover power dynamics among stakeholder groups, providing insights into communication pathways that influence policy implementation and engagement. This could lead to policies that specifically target key influencers in the waste management system, thereby improving policy rollouts. Similarly, GIS tools could inform the spatial planning of waste management infrastructure by identifying regions with the most urgent needs, ensuring that investments are strategically allocated [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 urgent need for targeted reforms in Costa Rica's waste management system, particularly in addressing the persistently low recycling rates and the heavy reliance on landfills. Despite the government's commendable commitment to environmental sustainability, significant challenges persist, especially in rural areas where infrastructure deficits and limited public participation hinder progress. The **Waste Management Innovation Index** further highlights the areas where Costa Rica lags behind global leaders, particularly in technological advancements and infrastructure development.

Moving forward, the expansion of recycling infrastructure, enhanced public education initiatives, and the fostering of public-private partnerships are critical steps toward modernizing waste management practices. **Stakeholder perspectives** reveal the importance of tailoring these reforms to local cultural contexts, emphasizing the need for adaptable policies and community-

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driven approaches. Integrating advanced technologies, such as AI-driven sorting systems and the use of biodegradable materials, will be essential to achieving these goals.

However, the successful implementation of these strategies requires adaptability to local contexts and robust legislative frameworks to ensure their long-term impact. It is important to recognize that these efforts may face challenges, including financial constraints, cultural resistance, and technological limitations, which must be addressed through continuous evaluation and policy adjustments. **Advanced methodologies like Social Network Analysis (SNA) and Geographic Information Systems (GIS)** can further support these efforts by providing deeper insights into stakeholder dynamics and the spatial distribution of waste management needs.

By focusing on these areas, Costa Rica can overcome its current waste management challenges and set a global example of sustainable practice. Through strategic reforms, technological integration, and community engagement, Costa Rica has the potential to not only safeguard its environmental legacy but also to lead by example in the global movement towards a circular economy and sustainable development.

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