Inovasi
Jurnal Ilmiah Ilmu Manajemen
Vol. 12, No. 1, June 2025

P-ISSN 2356-2005
E-ISSN 2598-4950

Eco-Efficiency Assessment at XYZ Hospital: An Analysis Using the Data Envelopment Analysis Method

Satria Putra Perdana[1], **Luluk Widyawati**[2]
University of Indonesia, Indonesia
satriaputraperdana@icloud.com[1], lwidya@ui.ac.id[2]

Submitted: 08th Jan 2025 | **Edited**: 28th March 2025 | **Issued**: 01st June 2025

Cited on: Perdana, S. P., & Widyawati, L. (2025). Eco-Efficiency Assessment at XYZ Hospital: An Analysis Using the Data Envelopment Analysis Method. *INOVASI: Jurnal Ilmiah Ilmu Manajemen, 12*(1), 7-20.

Abstract
This study evaluates the eco-efficiency of Hospital XYZ, identifying strengths and areas for improvement in resource use, waste management, and compliance with environmental policies to support sustainability efforts. A combination of Data Envelopment Analysis (DEA) and Importance-Performance Analysis (IPA) is used. DEA measures eco-efficiency quantitatively using resource inputs and economic outputs, while IPA assesses the perceived importance and performance of environmental management practices through interviews with hospital management. DEA reveals fluctuations in eco-efficiency due to factors like resource use, waste production, and occupancy rates. IPA identifies gaps in waste segregation, energy conservation, and policy compliance. Recommendations include optimizing resource use, enhancing waste management, and strengthening sustainability-focused policies and practices.

Keywords: Eco-efficiency; Data Envelopment Analysis (DEA); healthcare sustainability; resource management

INTRODUCTION

Hospitals play a vital role in society by providing essential medical services, yet their operations significantly impact the environment. Hospitals generate waste that poses risks to patients, staff, and the environment. This waste is categorized into household waste (e.g., packaging, kitchen waste) and hazardous medical waste (e.g., syringes, scalpels). Improperly managed waste contributes to environmental pollution, such as water and soil contamination by heavy metals (e.g., mercury, cadmium) and biochemical waste (Ghali, 2023). With increasing populations, access to healthcare services grows, leading to higher hospital waste generation. Globally, hospitals produce approximately 5.9 million tons of medical waste annually (Campion, 2015). In Indonesia, the National Health Insurance (BPJS-JKN) program launched in 2014 covers 82.3% of the population, increasing healthcare access, especially in remote areas. However, this increased patient intake correlates with higher hospital revenue and waste production (Purwaningsih, 2018). Of the total hospital waste, approximately 15% consists of hazardous materials (B3), while 85% is non-hazardous operational waste. Improperly managed waste leads to significant public health risks, with 5.2 million annual deaths globally attributed to hospital waste, including 4 million children (Rahman, 2020). Environmental impacts

P-ISSN 2356-2005
E-ISSN 2598-4950

include greenhouse gas (GHG) emissions from medical activities, contributing 2.7 Gt CO2eq (5.2% of global emissions) as reported by The Lancet Countdown Report (2022). Other issues include water, air, and soil pollution, and the depletion of natural resources, exacerbating climate change (Sijm-Eeken, 2023).

In response to climate change, sustainability has become a global priority. Initiatives like the European Green Deal (2019), China's Carbon Neutrality Commitment (2020), and the Paris Agreement (2015) demonstrate international commitment to combating climate change. Indonesia, a signatory to the Paris Agreement, commits to sustainable development, as mandated by its Constitution and Environmental Protection Law No. 32/2009 (Rusiana, 2019). Hospitals in Indonesia must align with these sustainability commitments, balancing economic growth and environmental preservation.

Eco-efficiency, defined as minimizing environmental impacts while maximizing efficiency, offers a strategic approach to sustainable operations (Bell & Warren, 2023). This concept encourages optimal resource use, cost reductions, and waste minimization, making it a critical tool for transitioning from unsustainable to sustainable development (Caprian, 2023; Hernandez, 2023). Eco-efficiency in hospitals focuses on delivering healthcare services while minimizing environmental impacts. This involves optimizing energy and water consumption, reducing hazardous chemicals, and enhancing operational sustainability.

This thesis evaluates the eco-efficiency of Hospital XYZ, recognized by the government for its exemplary environmental management practices and its role as a model for other healthcare facilities in West Java. The study aims to assess how eco-efficiency practices in Hospital XYZ contribute to sustainable healthcare operations, providing insights for the broader healthcare sector. Through this evaluation, the study will measure the hospital's effectiveness in waste reduction, energy and water conservation, and hazardous material management without compromising service quality. The findings align with Indonesia's sustainable development commitments and global environmental goals, such as the Paris Agreement, and will highlight areas for improvement. Ultimately, this research aims to support discussions on enhancing eco-efficiency in Indonesia's healthcare sector for long-term sustainability

LITERATURE REVIEW

Eco-efficiency is a crucial management philosophy that seeks to balance economic performance with environmental sustainability (Kero & Bogale 2023). At its core, the concept aims to create more value while minimizing environmental impact through innovative approaches to resource use and production. Multiple experts have proposed definitions that converge on a central theme: eco-efficiency is a strategic approach to creating goods and services while using fewer resources, generating less waste, and reducing pollution (Zhang & Jin, 2024). It represents a paradigm shift in how businesses view their environmental responsibilities. Rather than seeing environmental considerations as a hindrance to economic growth, eco-efficiency positions sustainability as a key driver of innovation and competitive advantage. The fundamental principles of eco-efficiency include minimizing environmental

P-ISSN 2356-2005
E-ISSN 2598-4950

damage; maximizing economic efficiency; reassessing the entire product lifecycle; focusing on resource optimization; and encouraging shared responsibility between producers and consumers (Kosen, 2022).

The World Business Council for Sustainable Development has outlined seven primary objectives for eco-efficiency. These goals fundamentally aim to create a balance between ecological preservation and economic development (Liu, et al., 2023). By implementing eco-efficiency strategies, organizations can achieve positive environmental impacts while maintaining economic viability. Key objectives include preserving natural resources for future generations, reducing solid waste and emissions, lowering potential pollution risks, improving product and service quality, driving technological innovation, enhancing competitive capabilities, as well as reducing operational costs.

Eco-efficiency links economic performance with environmental sustainability by creating value while reducing environmental impacts (Wagner, et al., 2023). It integrates economic, environmental, and social goals, emphasizing that they are interconnected rather than competing. Synergies include cost reductions, resource conservation, and improved quality of life, while barriers involve policy gaps, market limitations, high initial costs, lack of expertise, and organizational resistance. Caiado et al. (2017) stress that eco-efficiency alone cannot guarantee sustainable development. Achieving it requires ongoing collaboration among stakeholders and tailored strategies that address regional and sectoral differences.

Eco-efficiency in hospitals focuses on delivering healthcare services while minimizing environmental impacts by reducing resource consumption and waste generation. Kim (2018) analyzed hospitals in South Korea using Data Envelopment Analysis (DEA), measuring inputs like water, energy, waste, and hazardous chemicals, and outputs such as revenue and patient numbers. The study showed an increase in eco-efficiency scores from 0.830 in 2012 to 0.902 in 2015, with 12 out of 21 hospitals achieving perfect scores due to government initiatives like the Greenhouse Gas and Energy Target Management System (GETMS) and Emission Trading System (ETS). However, gaps remain in hazardous chemical use and waste management, highlighting the need for further improvements.

Research on hospitals often emphasizes energy efficiency, given the high energy consumption from 24/7 operations and patient care needs. Studies by Psillaki (2023) and others focus on energy-saving technologies like cogeneration systems, improved HVAC, efficient lighting, and renewable energy, particularly solar photovoltaics. Building design improvements, such as enhanced windows and natural lighting, also reduce energy usage. While energy efficiency is critical, it is only one aspect of achieving overall eco-efficiency in hospitals.

METHOD

This study focuses on XYZ hospital, a general hospital in West Java, Indonesia, that provides outpatient and inpatient healthcare services. As the hospital grows, it faces challenges in managing the environmental impacts of its operations, particularly in waste management and resource use. The research aims to evaluate the hospital’s eco-efficiency by examining both quantitative

P-ISSN 2356-2005
E-ISSN 2598-4950

and qualitative factors. The research employs a Mixed Method Single Case Study, combining quantitative and qualitative approaches for a comprehensive understanding of eco-efficiency. The quantitative aspect involves the analysis of numerical data, such as patient numbers, waste generation, and resource consumption (e.g., electricity and water), to calculate eco-efficiency using the Data Envelopment Analysis (DEA) method. The qualitative aspect includes interviews with hospital staff to explore factors influencing eco-efficiency trends and the hospital's strategies for resource and waste management. Although integrating quantitative and qualitative data presents challenges, this method is expected to provide rich, contextual insights.

Data for the study is obtained from both primary and secondary sources. Primary data are collected through interviews with hospital personnel responsible for managing electricity, water, and waste. Secondary data are derived from hospital records, including operational reports and documented resource usage, supporting the quantitative calculations. Together, these data provide a foundation for analyzing the hospital's eco-efficiency. Interviews are conducted with key informants, including management and staff directly involved in waste and resource management. These informants include individuals with strategic oversight, policy coordination responsibilities, and operational waste management duties.

The key data points for eco-efficiency analysis include outputs, such as hospital revenue and patient numbers, and inputs, including electricity and water usage, associated costs, and waste production. More about the details of these variables are listed in Table 1 below.

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E-ISSN 2598-4950

Table 1. Details of the input and output variables used for the DEA analysis

Category	Component	Unit	Details
INPUT	Electricity Usage (E_N)	kWh	Hospitals that use less electricity while maintaining the same level of service are considered more efficient. This is because reducing electricity consumption lowers operating costs and reduces environmental impact.
	Water Usage (W_N)	m^3	Efficient water management is crucial due to limited water resources. Hospitals that use less water while providing the same level of care are more efficient. This also helps conserve resources and reduce costs.
	Solid Medical Waste (S_N)	kg	Proper management of solid waste, especially medical waste, is essential for environmental protection. Hospitals that generate less waste and dispose of it responsibly demonstrate efficient waste management practices.
	Liquid Medical Waste (L_N)	l	Liquid waste from hospitals can contain harmful substances. Hospitals that minimize the production of liquid waste and treat it properly are more efficient and environmentally friendly.
OUTPUT	Revenue (R_N)	Millions of Rupiahs	Revenue is a key indicator of a hospital's financial performance. Hospitals that generate more revenue while using the same or fewer resources are considered more efficient
	Number of Hospitalized Patients (P_N)	Persons	This measures the social impact of a hospital by indicating the number of patients served. Hospitals that treat more patients with the same or fewer resources are considered more efficient in terms of serving the community.

Source : Research Data, 2024

These data enable the calculation of annual eco-efficiency values, while the interviews provide qualitative insights into the hospital's environmental management policies, their implementation, and internal perspectives on resource consumption and waste trends. This mixed-method approach ensures a comprehensive evaluation of RS XYZ's eco-efficiency.

This study incorporates Importance-Performance Analysis (IPA) as a complementary method to understand the perceived importance and actual performance of various environmental management (EM) indicators at Hospital XYZ. While the primary analysis utilizes Data Envelopment Analysis (DEA) to measure the hospital's eco-efficiency based on quantitative data (e.g., resource consumption like water, energy, waste, chemicals, and economic outputs such as revenue and patient numbers), DEA does not capture subjective staff perceptions about the importance of specific EM practices. IPA bridges this gap by integrating qualitative insights from hospital management interviews.

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Inspired by Kim (2018), the IPA analysis assesses items from the Environmental Information Disclosure System (EIDS), a framework used in South Korea. These items are categorized as follows on Table 2.

Hospital management rates the importance and performance of these EIDS items during interviews. The resulting scores are plotted on an IPA matrix, identifying areas requiring improvement or maintaining excellence. By combining IPA with DEA, this research provides a holistic view of eco-efficiency at Hospital XYZ. DEA quantitatively identifies efficient hospitals, while IPA highlights EM practices deemed crucial by hospital staff, offering actionable recommendations for improvement. This integrated approach combines quantitative and qualitative insights, enhancing the ability to improve environmental management practices effectively.

Table 2. EIDS Reporting Items

Category	EIDS Reporting Items
Environmental management	Establishment of a vision and strategy for environmental management
	Organization of task team for environmental management and task assignment
	Guideline and compliance with green purchasing
Resource/energy management and reduction activities	Management of water use and reduction activity
	Management of energy use and reduction activity
	Investment in new and renewable energy and the introduction of technology
GHG emissions and environmental pollution management and reduction activities	Management of GHG emissions and reduction activity
	Management of water pollutants and reduction activity
	Management of waste generation and reduction activity
	Management of hazardous chemical use and reduction activity
Social/ethical responsibility compliance	Compliance with domestic and international environmental laws and regulations
	Publication of environmental report and environmental information disclosure
	Response to stakeholder requests for environmental information

Source : Research Data, 2024

RESULT

This section analyzes the eco-efficiency measurements of XYZ Hospital using the Data Envelopment Analysis (DEA) approach. The evaluation uses data from 2019 to 2023, with several input and output variables. DEA based on Constant Return to Scale (CRS) is applied, focusing on the input and output variables listed in Table 3. Using data from 2019 to 2023 as Decision Making Units (DMUs), Excel was used to solve the DEA model. This forms the basis for analyzing resource consumption, waste management, and their relationship to hospital output in the form of treated patients and revenue. The DEA results for eco-efficiency at XYZ Hospital from 2019 to 2023 are shown on Table 4.

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Table 3. DEA inputs and outputs for eco-efficiency assesment at XYZ Hospital from 2019 to 2023

Year	Electricity Usage (kWh)	Water Usage (m^3)	Solid Medical Waste (kg)	Liquid Medical Waste (l)	Revenue (Millions of Rp)	Number of Hospitalized Patients
2019	1,056,569	7,689	19,850	3,625	Rp73,094.61	9,224
2020	919,449	9,236	20,105	3,710	Rp56,559.84	5,368
2021	924,680	12,985	21,051	3,798	Rp56,229.86	5,619
2022	979,036	16,527	20,569	3,652	Rp66,188.41	6,160
2023	1,049,133	24,150	17,722	4,337	Rp66,366.80	6,940

Source : Research Data, 2024

The DEA analysis using two outputs—hospital revenue and number of inpatients—shows fluctuating efficiency from 2019 to 2023. Optimal efficiency scores (1.00) were achieved in 2019 and 2023, reflecting effective resource utilization to maximize output. However, efficiency dropped during the pandemic in 2020 (0.88) and improved progressively through 2021 (0.92) and 2022 (0.97). Despite a slight decrease in 2023 (0.91), the hospital showed recovery signs. When only revenue is considered as output, efficiency is more stable. Optimal scores (1.00) were recorded in 2019, 2022, and 2023, while efficiency dipped during the pandemic (0.88 in 2020 and 0.92 in 2021). This stability highlights successful financial resource management, likely due to service diversification and cost-saving strategies during challenging times. With patient numbers as the sole output, efficiency fluctuations are more pronounced. Optimal efficiency (1.00) occurred in 2019, 2022, and 2023. However, the pandemic caused a sharp decline in 2020 (0.74), with gradual recovery through 2021 (0.85). These trends underscore the pandemic's impact on patient volume and the hospital's efforts to restore operations.

The next section compares the eco-efficiency of Rumah Sakit XYZ (RS XYZ) in 2019 with 19 hospitals in South Korea in 2016. The comparison is based on the study by Kim (2018), which analyzed the eco-efficiency of 21 South Korean hospitals from 2012 to 2016. The year 2019 was chosen for RS XYZ as it represents the latest available data, while 2016 was the most recent year in Kim's study.

Table 4. DEA results for eco-efficiency at XYZ Hospital from 2019 to 2023

Year	Eco-efficiency (Two Outputs)	Eco-efficiency (Revenue Only)	Eco-efficiency (Patients Only)
2019	1.00	1.00	1.00
2020	0.88	0.88	0.74
2021	0.92	0.92	0.85
2022	0.97	1.00	1.00
2023	0.91	1.00	1.00

Source : Research Data, 2024

This benchmarking aims to evaluate RS XYZ's performance against international standards, providing insights into its relative efficiency. The analysis employs the Data Envelopment Analysis (DEA) method with an input-oriented Constant Returns to Scale (CRS) approach. The analysis considers inputs such as water usage, medical waste generation, and energy consumption, with outputs measured in the number of patients served and

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E-ISSN 2598-4950

revenue generated. The data are presented in Table 3, illustrating the operational scale differences between RS XYZ and South Korean hospitals. The eco-efficiency scores derived from the DEA calculation are summarized in Table 4. RS XYZ achieved a perfect score of 1.000, indicating full efficiency, along with four South Korean hospitals (H1, H13, H16, and H18). Other hospitals displayed varying levels of efficiency, with scores ranging from 0.44891 to 0.87432. The comparison highlights significant differences in operational scale, resource allocation, and efficiency strategies. RS XYZ demonstrated resource efficiency, reflected in its low input values for water usage and waste production. Despite its smaller scale, RS XYZ's output in terms of patients served and revenue remains competitive. In contrast, South Korean hospitals, operating at a larger scale, displayed higher input values, potentially due to differences in patient demographics, service offerings, and operational scales.

Efficient hospitals like H13 and H18 benefit from advanced waste management systems and energy-saving technologies. RS XYZ could enhance its eco-efficiency further by investing in similar innovations. Moderately efficient hospitals, such as H6 (score 0.56293), underline the need for standardizing resource allocation and minimizing operational waste. RS XYZ should prioritize maximizing patient care and revenue while maintaining proportional input usage, especially as it considers expanding operations. This comparative analysis reveals that RS XYZ (2019) has outperformed many South Korean hospitals despite its smaller operational scale. Its full efficiency score reflects a balanced approach to resource utilization and service delivery, positioning it as a model for similar institutions in developing countries. However, as RS XYZ scales up its operations, it must address potential inefficiencies by adopting innovative technologies and learning from highly efficient international counterparts.

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Table 5. Input and output data from XYZ Hospital and 19 other hospitals in South Korea for benchmarking.

DMU	Water Usage (ton)	Total Medical Waste (ton)	Energy (ton-hour)	Output (Patient)	Output (Million Won)
RS XYZ (2019)	2.715	23	909	124.842	6.415
H1Korea	8.760	61	281	62.830	7.659
H2Korea	340.094	1.974	7.143	1.194.736	268.547
H3Korea	119.187	609	4.499	357.181	97.813
H4Korea	270.052	23.587	4.983	848.648	171.176
H5Korea	154.797	846	3.340	506.523	71.331
H6Korea	349.163	31.859	6.535	1.148.492	265.330
H7Korea	26.504	1.724	658	125.606	16.098
H8Korea	12.997	1.724	780	64.847	4.765
H9Korea	420.332	9.253	10.242	1.471.829	387.638
H10Korea	1.017.140	51.480	21.846	2.751.328	759.350
H11Korea	396.076	58.978	11.835	46.962	325.512
H12Korea	220.151	21.137	6.779	820.959	201.714
H13Korea	326.081	6.368	6.158	1.922.494	453.302
H14Korea	304.885	5.443	8.399	1.260.091	248.521
H15Korea	145.980	2.722	3.677	608.935	93.470
H16Korea	322.702	1.983	6.586	1.408.000	292.394
H17Korea	423.675	3.629	6.524	350.499	247.608
H18Korea	181.413	61	3.898	716.954	128.355
H19Korea	83.175	2.341	1.807	162.155	87.246

Source : Research Data, 2024

Next, an IPA Analysis is done, and it evaluates environmental management practices at Hospital XYZ using the IPA framework to identify areas of strength and those requiring improvement for better eco-efficiency. The analysis is based on indicators from the Environmental Indicators for Sustainability (EIDS), originally implemented in South Korea and adapted for this research following Kim (2018).

This matrix provides a clear view of the hospital's strengths and areas for improvement, enabling strategic recommendations to enhance eco-efficiency at Hospital XYZ.

The Importance-Performance Analysis (IPA) matrix highlights areas where Hospital XYZ excels and areas needing improvement, guiding strategies to enhance eco-efficiency. This section delves into the factors influencing eco-efficiency, integrating insights from eco-efficiency scores and interviews with hospital management. These factors, categorized into internal and external influences, offer a deeper understanding of their role in enhancing or hindering eco-efficiency.

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E-ISSN 2598-4950

Table 6. Eco-Efficiency Benchmark Calculation Results Between XYZ Hospital and 19 Hospitals in South Korea

DMU No.	DMU Name	*Eco-efficiency*
1	RS XYZ Tahun 2019	1.00000
2	H1 Korea	1.00000
3	H2 Korea	0.87432
4	H3 Korea	0.86318
5	H4 Korea	0.54552
6	H5 Korea	0.67389
7	H6 Korea	0.56293
8	H7 Korea	0.71269
9	H8 Korea	0.44891
10	H9 Korea	0.65544
11	H10 Korea	0.53396
12	H11 Korea	0.57713
13	H12 Korea	0.64217
14	H13 Korea	1.00000
15	H14 Korea	0.59939
16	H15 Korea	0.62503
17	H16 Korea	1.00000
18	H17 Korea	0.69555
19	H18 Korea	1.00000
20	H19 Korea	0.74984

Source : Research Data, 2024

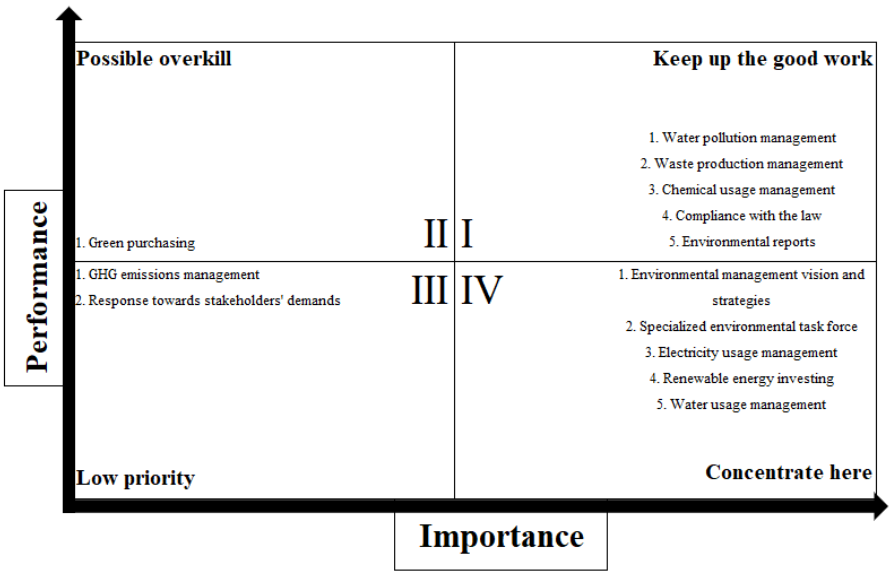

Image 1. IPA Matrix of XYZ Hospital
Source : Research Data, 2024

Efficient resource management is vital for improving eco-efficiency. Electricity and water, essential for hospital operations, directly impact costs and environmental outcomes. Management practices include optimizing energy and water use, such as turning off unused lights and managing water consumption based on needs. Notably, water usage surged post-COVID-19 due to intensified

P-ISSN 2356-2005
E-ISSN 2598-4950

sanitation efforts. Reducing energy and water consumption improves operational efficiency, contributing to higher eco-efficiency scores.

Effective medical waste management is crucial for eco-efficiency. Hospital XYZ must segregate and manage solid and liquid medical waste efficiently to minimize environmental impact. This includes early-stage waste separation and eco-friendly disposal methods, like recycling or non-polluting incineration. Poor waste management increases environmental harm and operational costs. Non-medical waste, such as domestic waste, also affects eco-efficiency. Reducing overall waste production is a critical step toward better eco-efficiency.

Facility utilization, including occupancy rates and patient numbers, significantly influences eco-efficiency. Low patient numbers can lead to resource wastage, such as underutilized electricity, water, and medical supplies. Conversely, higher occupancy rates enhance resource utilization efficiency. The COVID-19 pandemic profoundly affected eco-efficiency. Increased resource consumption (energy, water) and higher medical waste volumes were driven by stricter sanitation protocols. Patient number fluctuations posed challenges in resource management. Hospital XYZ must evaluate the pandemic's impact on eco-efficiency and implement strategies to mitigate resource overuse during unforeseen events.

Internal policies and strategies play a pivotal role in achieving eco-efficiency. Hospital XYZ needs clear and robust environmental policies addressing energy management, waste reduction, and efficient resource use. Training programs for staff to promote awareness and sustainable practices are essential. Additionally, adopting eco-friendly medical materials and reducing single-use plastics can improve eco-efficiency outcomes.

Government regulations on emissions reduction, medical waste management, and resource use heavily influence eco-efficiency. Compliance with these regulations not only minimizes environmental impact but also incentivizes the adoption of efficient practices. Hospital XYZ should prioritize adherence to these policies to enhance its eco-efficiency and contribute to broader environmental goals.

In conclusion, combining findings from the IPA matrix with these identified factors provides actionable insights for Hospital XYZ to improve its eco-efficiency. By addressing resource management, waste production, occupancy rates, pandemic impacts, internal policies, and regulatory compliance, the hospital can develop targeted strategies to enhance both environmental and operational performance.

CONCLUSION

This research evaluates the eco-efficiency of XYZ Hospital from 2019 to 2023 using Data Envelopment Analysis (DEA) with a Constant Return to Scale (CRS) approach. The findings reveal that the hospital achieved optimal efficiency in 2019 with an eco-efficiency score of 1.00, reflecting optimal resource utilization before the COVID-19 pandemic. However, in 2020, eco-efficiency dropped significantly to 0.88 due to the pandemic, which increased operational costs, including higher water and electricity usage under stricter health protocols. This decline highlights the challenges of maintaining resource efficiency amid higher costs and reduced patient numbers

P-ISSN 2356-2005
E-ISSN 2598-4950

A gradual recovery occurred in 2021 and 2022, with eco-efficiency scores improving to 0.92 and 0.97, respectively. This recovery indicates the hospital's ability to balance operational needs and resource efficiency, despite significant challenges such as increased water costs. In 2023, eco-efficiency slightly declined to 0.91, but rising patient numbers and revenue suggest positive recovery trends. However, high water costs from shifting to municipal water and increased medical waste due to stringent health protocols continued to impact efficiency. Overall, the study underscores the importance of effective resource management and adaptability to operational changes as key factors for maintaining and improving eco-efficiency.

The Importance-Performance Analysis (IPA) suggests that XYZ Hospital lacks a proactive vision and strategy for sustainability, with efforts focused more on regulatory compliance than long-term initiatives. Drawing inspiration from Ørsted, a Danish energy company, the hospital could adopt strategies such as integrating sustainability across operations, investing in innovative technologies, setting ambitious long-term targets, and engaging stakeholders actively. These measures could enhance resource efficiency, reduce environmental impact, and improve the hospital's reputation as a sustainable healthcare institution. These recommendations address the hospital's challenges and align with global sustainability standards for healthcare services. Implementing these steps could help the hospital excel in the IPA matrix's "Concentrate Here" quadrant, ultimately improving its overall eco-efficiency and sustainability.

This study has research limitations. The study only covers five years (2019-2023), limiting its ability to identify long-term trends or the impact of annual fluctuations on eco-efficiency. A short time frame may affect DEA results, making them less stable for broader efficiency patterns. Next, the research focuses solely on XYZ Hospital, making it difficult to generalize the findings to other hospitals, which may have different structures, resources, and management policies. Also, the study uses a narrow set of variables—electricity costs, water costs, chemical usage, solid medical waste, and liquid medical waste—as eco-efficiency indicators. Other aspects, such as renewable energy use or greenhouse gas management, are not included. Finally, the analysis relies heavily on quantitative DEA methods and lacks qualitative insights from interviews or direct observations, which could provide additional context and reveal challenges and opportunities in eco-efficiency management.

With these limitations in mind, future studies should include longer time frames, such as 10 years or more, to better understand long-term patterns and stable changes in eco-efficiency. On top of that, the research should include multiple hospitals of varying sizes, services, and geographic locations would make the findings more representative. This approach allows for cross-hospital comparisons and tailored policy recommendations. Also, future studies could incorporate variables such as carbon emissions, renewable energy use, indoor air quality, and fuel management in medical equipment. Additionally, variables related to patient satisfaction and service quality could provide insights into the relationship between efficiency and service delivery.

P-ISSN 2356-2005
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