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AN INTEGRATED FRAMEWORK FOR GHG REDUCTION AND SUSTAINABILITY IN THE WATER DISTRIBUTION AND WASTE MANAGEMENT SECTOR OF A SUPER-SPECIALTY HOSPITAL

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ABSTRACT

One of the most resource-intensive systems of the public infrastructure is healthcare institutions, where water and energy usage are high, and solid, liquid, and biomedical waste are constantly produced. These operations are increasing the emission of greenhouse gases (GHG) and environmental degradation, especially in the booming healthcare systems in the low- and middle-income nations. Even though sustainable healthcare has become an increasingly common topic, water, waste, and energy systems remain isolated, even within the environment management of hospitals. This research proposes and implements a combined model of GHG mitigation and sustainability of the water supply and waste disposal industry within a giant super-specialty hospital campus in the southern Indian state. Quantification of the baseline emissions, project emissions, and verified emission reductions through five interdependent sub-projects under ISO 14064-2:2019, such as water

reuse, biogas recovery on effluent treatment plant sludge, plastic waste valorization, organic waste composting, and on-site solar photovoltaic generation are quantified using an attributional Life Cycle Assessment (LCA) and project-based GHG accounting. According to the results of monitoring the data of the period of 2022-2025, the cumulative effect of the integrated framework is a reduction of about 5,228 tCO 2e, of which the largest share is made by renewable electricity generation. The findings indicate that integrated actions between water, waste, and energy systems can provide much greater climate resolutions than single actions. The proposed framework offers a scalable and replicable approach to low-carbon healthcare infrastructure to promote the national climate objectives as well as Sustainable Development Goals on health, water, and climate action.

KEYWORDS: Sustainable Healthcare; Life Cycle Assessment; GHG Accounting; Hospital Waste Management; Water Reuse; Renewable Energy.

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1. INTRODUCTION

The world is unanimously aware that healthcare systems form a crucial part of the social welfare and economic development. Nonetheless, the provision of high-tech medical services is coupled with significant environmental expenses, especially in the sense of high energy use, intensive usage of water, and complicated production of waste (World Health Organization [WHO], 2017). Some of the most resource intensive elements of the healthcare industry are super specialty hospitals, which are highly equipped in terms of diagnostic equipment, advanced surgical units, intensive care services, and operates 24 hours a day. With increasing worries about climate change and environmental degradation issues in most parts of the world, there is increased questioning of the environmental foot print of healthcare institutions and a desperate need to align health service provision with the ideas of sustainability and greenhouse gases (GHG) mitigation.

Healthcare also has a significant contribution to the global GHG emissions by direct energy consumption, indirect emissions related to the electricity purchased, and embedded emissions as a result of water supply, waste treatment, pharmaceuticals, and medical consumables. Hospitals come up with a significant percentage of this footprint as they demand continuous operation and have high standards of hygiene and safety which is regulated by the authorities. High turnover rate, the use of single-use materials, and uninterrupted water and sanitation services are other effects that are compounded in super specialty. The need to focus on environmental sustainability within such facilities is therefore not a strategic necessity but an ethical issue of climate resistant health systems (World Health Organization [WHO] & United Nations Children's Fund [UNICEF], 2020).

The hospital operations are based on water distribution systems, which help in providing clinical care, sanitation, infection control, laundry services, cooling, and food preparation. The energy-consuming processes encompass the abstraction, treatment, pumping, heating, storage and distribution of water which contributes to GHGs when combined. Aging infrastructure, lack of efficient pumping systems, and insufficient monitoring mechanisms that cause mass water loss and wastage of energy are common in most hospitals. In addition, the quality standards on clinical water consumption impose in most cases complex treatment procedures, which results in the further enhancement of carbon-intensity of water services on hospital grounds (Karliner et al., 2020).

Besides the use of freshwater, hospitals produce huge amounts of wastewater that has organic material, pathogens, pharmaceuticals, disinfectants and chemical residues hospitals (Health Care Without Harm & Arup, 2019). Treatment and disposal of this wastewater consume a lot of energy and exposes the environment and human health to risks in case it is not properly handled. Traditional centralized wastewater treatment units might not be optimization-oriented to the specific effluents of hospitals leading to increased emissions and lowering the chances of reusing water. Considering that the demand on the water resources of urban areas is growing and the energy footprint of wastewater treatment is increasing, sustainable management of water in hospitals has become a highly important topic of research and practice.

As with problems of water, waste management is another significant environmental issue in super specialty hospitals. The streams in hospital wastes are heterogeneous and comprise biomedical waste, sharps, pathological waste, pharmaceutical residues, chemical waste, plastics and packaging materials, food waste and general municipal waste. To avoid infection and contamination, biomedical waste, in particular, should be handled and treated in a specific manner. Incineration, autoclaving or landfilling are common disposal practices that are linked to a large amount of GHG emissions and in others instances, release of dangerous air pollutants. Lack of segregation also leads to more waste being exposed to the energy consuming treatment processes thus increasing the effects on the environment.

The point of convergence between water distribution and waste management systems is an issue and opportunity towards GHG reduction. The use of water affects the generation of waste, and in most cases waste management processes consume a lot of water and energy. As an illustration, ineffective water consumption raises levels of wastewater, thereby increasing the energy requirement to treat and dispose wastewater (Lenzen et al., 2020). . Equally, poor segregation of waste may pollute the wastewater streams, making it more difficult to treat and resulting in more emissions. Nonetheless, even given these interdependences, water and waste management are commonly discussed as distinct operational facilities in hospital management systems, and as a result, a disjointed intervention and less than optimal sustainability results are delivered.

The current sustainability efforts in the health sector have been mainly energy-saving, uptake of renewable energy, and green buildings (WHO & UNICEF, 2020). Though these are crucial steps, they are not comprehensive in the light of the embedded emissions of water distribution systems and the waste management systems. In addition, reactive or compliance-based strategies are adopted in most hospitals and regulatory compliance is prioritized over optimization of environmental performance. The absence of this sparks the necessity of integrated, systems-based frameworks that comprehensively consider the flow of resources, the pathways of emissions, and operational dependencies in the hospital environment.

A unified framework of GHG reduction in water supply and waste management aims at going beyond the narrow technological solutions to a holistic approach covering infrastructure design, optimization of the processes, digital monitoring, behavior change, and institutional governance. The framework identifies hospitals as socio-technical systems that are complex by nature; hence, environmental performance is determined by technology decisions, management, organizational behavior of the staff, and contexts of policies. The identification of emission hotspots along the waterwaste nexus can help provide synergistic benefits, such as decreased energy requirement, decreased operating expenses, increased regulatory compliance, and more effective stewardship of the environment.

The scope, complexity, and innovation potential of the super specialty hospitals makes its provision a particularly relevant environment to develop and test integrated sustainability frameworks. These facilities usually have the technical capacity, financial facilities as well as administrative frameworks required to install new high-technology solutions including smart water metering systems, energy-efficient pumping facilities, on-site wastewater treatment and re-use as well as circular waste management patterns. Meanwhile, the urgency of healthcare provision puts the paramount pressure on the reliability, safety, and quality of the system, so the designed interventions should avoid jeopardizing clinical outcomes.

Hospital water and waste management concept of sustainability is not only in terms of environmental measurements but also in social and economic aspects. Resource use can be more efficient and, therefore, increase the reliability of the service, lessen operational disturbances, and ensure the safety of the occupations of the healthcare workers who are engaged in the waste management and sanitation services. On the economic dimension, a decrease in water, energy, and waste treatment expenses can redirect the funds towards patients and medical research and development. At the social level, the environmentally responsible hospitals may enhance the level of trust among people and prove to be the leaders in solving the climate change and the health risk of the community.

Climate change directly and indirectly affects the healthcare infrastructure, such as water shortage, extreme weather conditions, and waste treatment systems. The hospitals are hence required to integrate adaptive and mitigation-based practices to facilitate resilience in the evolving natural settings. Resilience through integrated frameworks to reduce GHG-reduction helps with this reduction by decreasing the reliance on outside resources, encouraging decentralized treatment options, and improving the system flexibility. Such strategies are especially essential in water-stressed areas and fast urbanizing neighborhoods in order to maintain the quality of healthcare services (Karliner et al., 2020).

Although the importance of sustainability in healthcare is increasing, there are limited empirical investigations on the integrated GHG reduction models with specific reference to water distribution and waste management in super specialty hospitals. A large part of the available literature discusses the individual components individually, e.g., water conservation technologies or biomedical waste treatment techniques, without considering their interactions to produce an effect on emissions and system efficiency. This fragmentation restricts the application of research results to the real-world hospital environment, where the decisions should consider numerous, conflicting goals and restrictions.

This study fills this gap by proposing a comprehensive framework of development of GHG reduction and sustainability in the water distribution and waste management department of a super specialty hospital. The framework is created to methodologically evaluate resource flows, determine inefficiencies, and prioritize an intervention by determining its capacity to reduce emissions and its feasibility to operate. It focuses on combining technological solutions and management, matching the policy with practices, and stakeholder involvement, thus facilitating the comprehensive process of low-carbon operations of the hospital (Eckelman & Sherman, 2016).

The suggested framework can be also linked to the global agenda of sustainability, such as climate reduction policies, sustainable development, and overall tendency to the ecologically friendly systems of healthcare. This study, by drawing attention to two areas of hospital sustainability that are not widely discussed, water and waste, will help to further the body of knowledge on how the hospital infrastructure can be redesigned to promote human health and environmental sustainability. The resulting insights will be applicable to the work of hospital administrators, engineers, policy makers and researchers who want to have a scalable and evidence-based approach to the reduction of environmental footprint of advanced healthcare facilities (Azizi, 2016).

In short, the introduction defines the premise of the integration of GHG reduction strategies in hospital water distribution and waste management systems. It outlines the importance of sustainability of super specialty hospitals to the environment, constraints of fragmented sustainability strategies, and the necessity of overall structures that reflect interdependencies in system operations. Placing the study in the wider framework of climate change, healthcare resilience, and sustainable infrastructure, this research preconditions the creation and analysis of an integrated strategy that could be useful in providing significant environmental and operational advantages at the institutional level.

2. LITERATURE REVIEW

The article by Dolcini et al. (2025) is a deep scoping review of the ways environmental sustainability is being introduced in the performance management system by hospitals as it can be concluded that there is still a gap between the sustainability goals and operational execution of healthcare facilities. The authors also highlight that hospitals are a resource-intense organization, and their energy usage, water, and waste imposes a high presence on the environment. Nevertheless, clinical quality, patient safety, and financial efficiency remain the key performance frameworks in hospitals, and environmental indicators are still peripheral, disjointed, or randomly implemented. Based on the review, the indicators related to sustainability are hardly incorporated in the routine performance assessment practices, which restricts the capacity of hospitals to monitor systematically the greenhouse gas (GHG) emissions and environmental performance.

Dolcini et al. (2025) mention organizational, technical, and institutional obstacles that hinder the successful implementation of environmental sustainability in hospital governance systems. These are lack of standardized indicators, inadequate availability of data, and lack of managerial capability to connect the environmental performance to strategic decision-making. According to the authors, sustainability should be adopted as a performance dimension and not a voluntary or compliance-based activity. They promote systems based performance management strategies that reflect the interconnections among the operating processes like water distribution, wastewater treatment and waste disposal. This view highlights the importance of combined structures that have the potential to coordinate environmental responsibility and operational effectiveness and resilience over time, especially in super specialty hospitals where the magnitude and intricacy of resource utilization considerably enhance GHG emissions.

Dion and Evans (2024) discuss how strategic frameworks can be used to instill sustainability in corporate governance frameworks of healthcare facilities, including the focus on sustainable hospital management that is energy-efficient. The authors believe that successful sustainability transformations in hospitals can only be achieved through alignment of the governance mechanisms, strategic planning, and operational decision making instead of technical Isolated changes. Their research point of view is that energy-consuming systems, including heating, ventilation, air conditioning and key clinical infrastructure are at the centre of the environmental footprints of hospitals, and thus requirement to be dealt with by mainstream governance-based approach. Dion and Evans framework emphasises how leadership commitment, benchmarking of performance, and accountability mechanisms are being utilised in achieving long-term change in energy use and related greenhouse gas emissions across healthcare practice, based on the dual principles of sobriety and resilience.Vallée (2024) critically examines the concept of green hospitals in climate change, presenting sustainability in healthcare as the dual principles of sobriety and resilience. The paper especially highlights that hospitals have to decrease their environmental footprint and at the same time increase their resilience to climate-related risks like extreme weather conditions, water shortage, and energy losses. Vallée refers to the fact that healthcare facilities are the only type of buildings that are exposed to climate change because they have to remain in operation round the clock and rely on important resources, such as water and waste treatment systems. The sobriety concept is introduced as a tactical decrease in resources use in the form of energy, water and materials without affecting the quality of care and thus making a direct impact on the reduction of greenhouse gases (GHG).

Vallée (2024) emphasizes that the resilience-oriented sustainability strategies would make hospitals reconsider the design of infrastructure, resources management and operational governance. The paper highlights that green hospitals need to combine low-carbon technologies with adaptive systems of decentralized water management, waste reduction practices and adaptable energy systems so that services are not disrupted by environmental pressures. Another important point that the paper makes is that sustainability efforts are not just supposed to be technological but a system that would be operationalized by organizational culture and long-term plans. This view is in favour of the necessity of joined-up structures which, at the same time, target GHG mitigation and climate resiliency, especially in the case of super specialty hospitals where the magnitude of water consumption and waste production has a great impact on the environment performance and organizational strength in the wake of climate change.

Azizi (2016) also offers a detailed analysis of the ecological effects of the healthcare sector and outlines a premise framework underpinning green healthcare as an ecologically sustainable approach to methodology. In the doctoral dissertation, it is emphasized that healthcare facilities cause a lot of environmental degradation due to excessive energy consumption, excessive use of water, and production of hazardous and non-hazardous waste. Azizi highlights that the traditional healthcare delivery models have not paid much attention to environmental externalities but paid attention to such issues as clinical outcomes and operational efficiency. The paper establishes green healthcare initiatives, including resource-efficient infrastructure, sustainable procurement, and enhanced waste and water management, as critical measures towards decreasing the footprint of medical services on the environment and maintaining quality and safety levels.

According to Azizi (2016), integrated green programs can help convert medical institutions into systems that are sustainable as opposed to individual green projects. The study claims that the improvement of environmental performance should be meaningful and in this case, it should be holistic in that the design of the facility, practices and policies of the organization should be aligned. Special focus is on the concept of water conservation and waste reduction as among the leverage points of sustainability since they are highly interconnected with energy consumption and greenhouse gas emissions. The study offers a conceptual basis in the study of the integrated approach to GHG reduction in hospital in the present day by promoting system-wide integration of green practices, which gives credence to the role of an integrated approach to water distribution and waste management in the long-term sustainability of the healthcare environment.

The conceptual framework of Ejairu et al. (2024) is the notion of developing advanced eco-friendly wastewater treatment technologies that will mitigate the negative effects of the environment caused by the conventional wastewater treatment systems in industrial and municipal settings. These authors reinforce the point that the conventional wastewater treatment methods tend to be energy-consuming and, to some extent, cause the emission of greenhouse gases, especially during aeration, sludge treatment, and the use of chemicals. The paper points to new sustainable treatment models that focus on energy-saving, resource reuse, and decreased chemical reliance and makes wastewater systems one of the possible components of the circular economy as opposed to strictly end-of-pipe treatment. It is not restricted to healthcare facilities but the presented conceptual framework is very relevant to the hospitals where the wastewater streams are complex and continuous.

Ejairu et al. (2024) emphasize the fact that wastewater treatment should be considered in the context of wider sustainability goals like reusing that water, extracting energy, and decreasing emissions. The authors believe that sophisticated treatment design -when integrated into planning of institutional infrastructure- can greatly reduce carbon footprints in operation and also improve environmental protection. The given systems-based approach is important to facilitate the creation of unified models in the resource-intensive environment such as super specialty hospitals, where sustainable wastewater treatment could help to decrease the freshwater consumption, limit the pollution levels, and decrease GHG emissions due to water supply and waste treatment. The paper hence offers the theoretical justification of embedding innovative wastewater treatment solutions in the comprehensive sustainability plans of healthcare facilities.

Singhal et al. (2022) discuss the effects of sustainable consumption and production (SCP) programs in the energy and waste management industries in terms of the empirical examples of the Indian context. The paper has emphasized that the selected SCP measures, including resource-efficient technologies, waste reduction strategies, and the enhancement of segregation mechanisms, may considerably lower environmental strains, besides assisting the economic and social sustainability objectives. The authors note that waste management reforms, especially the ones, which aim at decreasing the amount of hazardous waste creation and the improvement of the material recovery, are important in reducing greenhouse gas emissions. They show that comprehensive strategies towards energy and waste management produce greater sustainability results than the sector-specific initiatives.

Although the study is cross-sectoral, Singhal et al. (2022) stress the applicability of SCP frameworks to the resource-intensive industry like a hospital. The study demonstrates how the sustainability programs in India which are policy based and are led by institutions can enhance both efficiency in operations and environmental performance. The study ties consumption trends, waste creation and energy consumption and therefore supports the need of embracing systemic sustainability systems that focus on interdependency. This point of view is especially relevant in super specialty hospitals where the coordinated energy and waste management policy may help achieve considerable GHG emissions at the same time with organizing the institutional practices in accordance with the national sustainability and development priorities.

Dossou et al. (2024) develop the conceptual framework of combining sustainable supply chain management with digital transformation in terms of Industry 5.0, with a focus on human-centric, resilient, and environmentally friendly systems. The authors believe that the sustainability performance can be improved considerably with the introduction of digital technologies, including data analytics, real-time monitoring, and decision-support systems, that will allow organizations to streamline the movement of resources and minimize environmental effects. Although the framework is designed to be used in industrial supply chains, the framework principles can be applied to complex service systems, such as healthcare, in which supply chains support key activities such as water distribution, waste collection, and acquisition of medical consumables.

Moshkal et al. (2024) have done a thorough review of sustainable waste management in Japan, and one of the main points that can be made is that this is a highly systematic and policy-driven process of waste reduction, waste segregation, and waste recovery that takes place in Japan. The authors comment on how efficient waste management in Japan has been achieved due to stringent regulatory systems, sophisticated waste treatment methods and high levels of public involvement which have ensured large volumes of waste management efficiencies and reduced environmental effects. The review notes that the key to curbing the reliance on landfills and minimizing greenhouse gas emissions caused by the waste treatment process has been the focus on integrated waste governance; i.e., the combination of policy enforcement, technology innovation, and institutional accountability.

Ferdan et al. (2018) research the problem of the greenhouse gas emissions related to thermal treatment of non-recyclable municipal waste with reference to such processes as incineration and associated energy recovery systems. The paper gives elaborate information on the emission profiles caused by waste composition, conditions of combustion, and the efficiency of waste treatment and thus it can be noted that even though thermal waste treatment is used to decrease the dependence on landfills, it still emits a significant amount of carbon dioxide and other GHGs. The authors note that although thermal treatment can be used to reduce the volume and generate energy, it presents environmental trade-offs that have to be well managed by optimization of technology and control of emissions. This viewpoint applies specifically to the hospital as the wrong segregation leads to the growth of waste that undergoes the thermal treatment. The paper hence advocates the formulation of combined models in the healthcare institutions that will couple waste reduction and segregation in the hospital with GHG reduction targets, particularly in the super specialty hospitals that produce substantial quantities of compound waste streams.

The review by Velasco Perez et al. (2021) discusses the waste management aspect of absorbent hygiene products and their environmental effects, noting that their proportion in municipal and healthcare waste is increasing. The authors emphasize the fact that, being widespread in hospitals and other long-term care facilities, these types of products produce large amounts of non-recyclable waste that contains high levels of moisture and causes more greenhouse gas emissions in transportation and treatment. The review explains typical disposal routes, such as landfilling and incineration, and also states that both the routes are characterized by considerable environmental load concerning the production of methane, the burning of fossil-based materials, and the use of energy-intensive treatment methods.

Besides, Velasco Perez et al. (2021) highlight the necessity of the design of products, waste sorting, and alternative treatment approaches to reduce negative effects on the environment. The authors opine that the process of waste management planning can be enhanced by incorporating life-cycle assessment to enable healthcare institutions to appreciate and mitigate on emissions related to absorbent hygiene products. Such a view is specifically applicable to super specialty hospitals, whereby patient occupancy is high, which enhances consumption of such materials. The research justifies the implementation of waste management models that will ensure reduction of waste, informed purchasing and optimum treatment pathways as part of the wider GHG reduction and sustainability approaches in healthcare facilities.

Nwakile et al. (2024) focus on ways of minimizing methane and other greenhouse gas emissions in energy infrastructure systems, noting that the reduction of emission is the key to sustainable goals in the long term. The authors emphasize the fact that methane is a significant but frequently overlooked cause of climate change, and especially so in energy-intensive infrastructure systems, as the gas has a high global warming potential. Their conclusions apply to technological, operational and policy-based interventions to curb the emission of methane that will help curb the emission of pollution as well as efficiency of the energy system in the hospital setting that supply water to the hospitals and wastewater to water treatment process as well as processing of waste materials. The paper supports the argument that there must be comprehensive sustainability approaches to super specialty hospitals to deal not only with carbon dioxide but also other powerful GHGs emissions like methane that occur during waste treatment and energy consumption.

Garg and Chaudhary (2025) discuss the progress of zero-waste technologies in the wider context of sustainable development with the transformative aspect of the role of innovation in reducing waste and recovering the resource. The authors claim that the classical model of linear waste management is becoming less and less sustainable because of the growing material use and the greenhouse gas (GHG) emissions. The paper incorporates the zero-waste ideas, including waste avoidance, high-level segregation, recycling, and material recovery, to outline the ways of minimizing environmental loads substantially. The chapter specifically focuses on how emerging technologies, such as artificial intelligence-powered sorting and recycling tools, can streamline the process of waste processing and decrease the reliance on disposal systems that consume a lot of carbon. Despite the fact that the discussion cuts across several industries, the lessons can be very easily applied to healthcare facilities, particularly, super specialty hospitals that produce complex and high volume of waste. The research urges the implementation of complex waste management models that utilize the best available technologies to mitigate the release of GHGs, increase operational efficiencies and harmonize the waste management practices by hospitals with the overarching sustainability and zero-waste objectives.

3. MATERIALS AND METHODS

3.1 Study Site

The research was carried out in a big super-specialty campus hospital in Kochi, Kerala, India. The hospital has a bed exceeding 1,300 and consists of intensive care units, operation theatres, laboratories, residential unit, kitchens, water treatment plants, effluent treatment plants, and waste processing units. The campus representative of high-impact healthcare infrastructure in urban India is the scale and variety of operations.

3.2 System Boundary and Timeframe

The scope of project includes water treatment/reuse facilities, waste management and on premises renewable energy installations within the hospital campus. There is no upstream manufacturing of equipment, as per an attributional LCA that is concerned with operational effects. The GHG reporting timeframe is between April 2022 and March 2025, which is the first half of implementation and monitoring of the integrated framework.

3.3 LCA Approach

The attributional Life Cycle Assessment was carried out focusing on Global Warming Potential, which consisted of tonnes of CO 2 equivalent (tCO 2 e). The metrics of cubic metres of reuse water, tonnes of treated waste, and megawatt-hours of renewable electricity generated were the functional units. The hospital records, monitoring logs, and audited datasets provided the information on the activities.

3.4 GHG Accounting Framework

GHG quantification followed ISO 14064-2:2019, with baseline emissions (BE), project emissions (PE), and emission reductions (ER) calculated for each sub-project using the relationship:

$ER=BE-PE-LE$

where LE represents leakage emissions, assessed as negligible for all sub-projects. Emission factors were sourced from the Central Electricity Authority of India, IPCC guidelines, and recognised international databases.

3.5 Framework of GHG Reduction.

Integrated GHG Reduction Project (IGRP) has five interrelated sub-projects:

- IGRP-A (Water Reuse): Reuse of treated wastewater Toilet flushing and landscaping: This reduces freshwater abstraction and associated energy consumption.
- IGRP-B (Biogas Recovery): Methane obtained during effluent treatment sludge is used, which subsidizes the use of diesel.
- IGRP-C (Plastic Waste Valorisation): It transforms the non-recyclable plastic waste into plastic bricks eliminating the emission of incineration and landfills.
- IGRP-D (Composting of Organic Waste): Food and kitchen waste is composted, which avoids the emission of methane gases in landfills.
- IGRP-E (Solar PV Generation) On-site solar photovoltaics produce renewable electricity, which replaces grid-based electricity.

These sub-projects are to work together synergistically in order to maximise reductions in emissions and increase resources decoupling.

4. RESULTS

The section represents the findings of the attributional Life Cycle Assessment (LCA) and ISO 14064-2-based GHG accounting of the interventions undertaken by the hospital campus between water, waste, and energy. The findings are described in terms of monitored operational data in the interval 20222025 and are systematized to indicate (i) waste-stream interaction, (ii) life-cycle emission implication, and (iii) proven reduction of greenhouse gas emissions as a part of the Integrated GHG Reduction Project (IGRP) report.

4.1 General (Non-Hazardous) Waste Generation Profile

Figure 1 shows the non-hazardous waste generated in the hospital campus in the years 2022-2024. The outcomes show that the waste is going to continuously grow by a medium in the years 2022 to 2023 and slightly decline in 2024. The rise in 2023 is correlated with the broader clinical activity and a greater number of patients in the post-pandemic normalization of the work of hospitals.

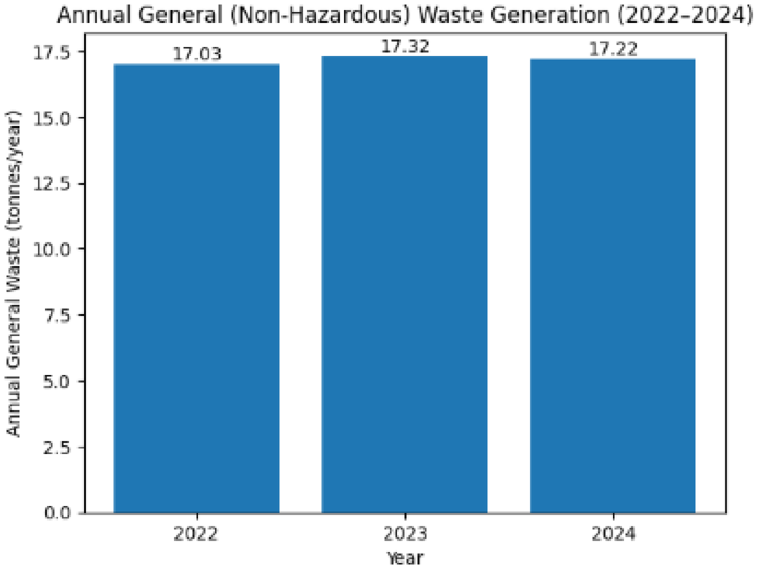

Figure 1: Annual General Waste Generation Trend (2022–2024).

The marginal decrease in 2024 indicates the initial success of the operational improvement, such as improved waste separation, resource-use optimisation, and internal awareness measures introduced within the framework of the integrated sustainability. Notably, there is no sharp decline, so in the large tertiary-care hospitals the general waste generation is still closely associated with the service demand and intensity of infrastructure. The general waste leads to indirect contribution of greenhouse gases by the collection, transportation, and downstream treatment processes. Consequently, by avoiding further expansion of this waste stream, the cumulative emissions throughout life cycles would be minimized and the gains in emission reduction through tailored actions in manual organic waste management and renewable energy application will be facilitated.

4.2 Organic (Food) Waste Generation Dynamics

The findings show that the food waste amounts have continuously increased in a monotonic manner with a level of 888 tonnes in 2022 and a period of 961 tonnes in 2023 and an additional increase of 1,076 tonnes in 2024. Such a consistent positive trend compares with the stabilisation in overall (non-hazardous) waste streams and is a characteristic of the food waste generation in large tertiary-care hospitals that is service-sensitive in nature. Figure 2 shows that the waste produced by the hospital campus food and kitchen in the years 2022 through 2024 is as shown below; the annual production is 10,000 lbs.

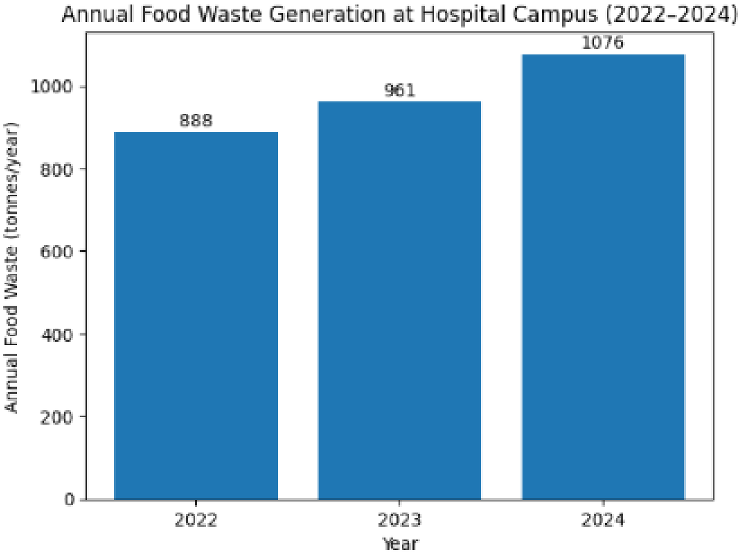

Figure 2: Annual Food Waste Generation Trend (2022–2024).

The rise in food waste is also strongly associated with the rise in bed occupancy rates, expansion of clinical and support services, as well as increased dietary provisioning of the patients, attendants, and healthcare staff. Food waste production cannot be reduced by the same methods as packaging or general waste, as it does not directly influence the quality of patient care, nutrition needs, or infection control measures. Consequently, the quantity of food wastes is likely to increase in direct proportion to the intensity of healthcare services.

Considering the life-cycle assessment, the apparent increase of organic waste is one of the most crucial environmental pressure points in the conditions of the baseline management. With no treatment intervention, food waste deposited in landfills would yield large amounts of methane, which is a greenhouse gas with a force of global warming that is much higher than that of carbon dioxide during a 100-year time span. It, therefore, follows that even small changes in the mass of food waste can lead to a disproportionate rise in the life-cycle GHG emissions.

The findings thus highlight the strategic significance of treatment-based mitigation interventions especially IGRP-D (organic waste composting) in the integrated sustainability. Even though the absolute amounts of food waste doubled over the course of the study, the fact that the stream of waste is no longer directed to the landfill routes has the effect of decoupling the generation of waste and the GHG emissions caused by waste. Composting transforms bio degradable waste material into a stabilised product and it significantly reduces the development of methane hence countering life-cycle emission despite the increasing demand of services. The findings show that the growth of waste levels does not always correlate with the greater impact on the environment, as long as proper life-cycle interventions are established. The performance of the composting system to take in increased loads of organic wastes without corresponding increment in emissions underscores the strength and expandability of the interconnected structure. This observation has special importance to the rapidly growing healthcare institutions, where the absolute decreases in food waste might be operationally impractical.

4.3 Statistical Normalization and Intensity-Based Results

In order to allow effective comparison of the mitigation measures as well as benchmarking against other healthcare facilities, the results of emission reduction were normalised by percentage contribution and GHG reduction intensity per bed-day. Normalisation enables the interpretation of performance regardless of the size of the hospital and the volume of service.

To compute the intensity, the hospital capacity was taken to be 1,350 beds and the average occupancy rate was 80 as per the norms of operation by the tertiary care. This translates to around 1.18 million bed-days of the three-year reporting period.

4.3.1 Relative Contribution of Integrated Sub-Projects to GHG Reduction

Table 1 summarises the relative contribution of each Integrated GHG Reduction Project (IGRP) sub-project to the cumulative emission reduction of **5,228 tCO_2e** achieved during the 2022–2025 reporting period. Figure 4 visually represents the proportional distribution of these reductions across intervention categories.

Table 1: Contribution of Sub-Projects to Total GHG Reduction (2022–2025).

Sub-Project	GHG Reduction (tCO_2e)	Contribution (%)
Water reuse (IGRP-A)	67	1.28
Biogas from ETP sludge (IGRP-B)	469	8.97
Plastic waste valorisation (IGRP-C)	534	10.21
Organic waste composting (IGRP-D)	986	18.86
Solar PV generation (IGRP-E)	3,172	60.67
Total	**5,228**	**100.00**

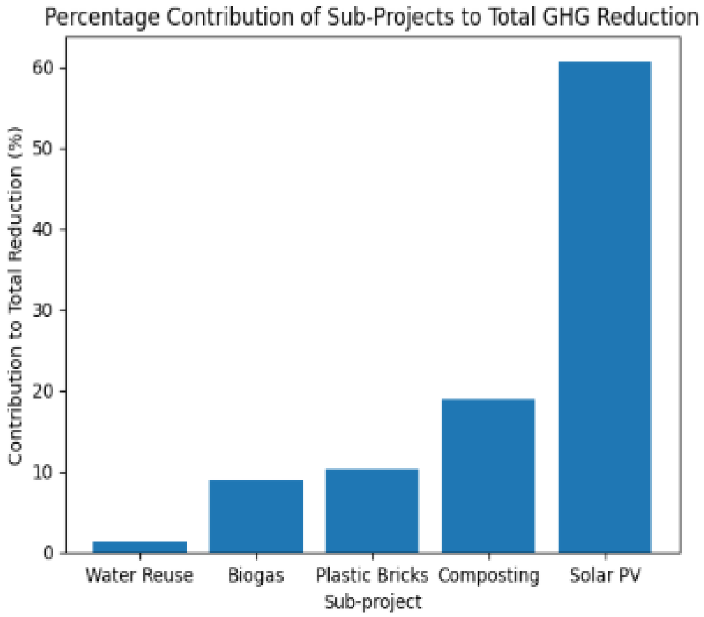

Figure 4: Percentage contribution of sub-projects to total GHG reduction.

The findings show a high differentiation pattern in contribution, and IGRP-E (solar photovoltaic generation) became the leading way of mitigation. The solar PV contributes 60.67 percent of all the avoided emissions, which reflects the carbon intensity of the replaced grid electricity and the round the clock operation of the installed systems. This observation is not new, as, according to life-cycle evaluations of medical organizations, electricity usage continues to be one of the key contributors to the operational emissions. The share of waste- and water-related interventions (IGRP-A to IGRP-D) is significant (39.33), even though there is a large dominance of renewable energy. The most significant non-energy contributor among them is organic waste composting (IGRP-D) which delivers 18.86 percent of the total reductions. This points to the high life-cycle avoidance prospect of biodegradable waste streams (which include methane) in institutional (especially high-volume) places, like hospitals.

IGRP-C and IGRP-B give 10.21 percent and 8.97 percent contributions respectively to plastic waste valorisation and biogas recovery respectively. These interventions are smaller in absolute magnitude than solar PV but cover the emissions pathways that are otherwise ignored in traditional approaches to hospital sustainability, such as fossil fuel replacement and prevention of uncontrolled waste decomposition. Their presence makes the entire mitigation portfolio stronger in terms of diversifying sources of emission reduction. However, by comparison, water reuse (IGRP-A) does not bring about such a significant contribution to total reductions: 1.28%. This decrease is anticipated, as reusing water provides indirect mitigation advantages as it will cause a decrease in the energy and chemical requirements used to treat water and supply it. However, its strategic value is crucial in reducing the dependency on the resources and contributing to the system-wide efficiency in the integrated framework.

4.3.2 GHG Reduction Intensity Normalised per Bed-Day

Normalisation of greenhouse gas emission reductions per bed-day was used to compare mitigation effectiveness to healthcare service delivery to make comparisons across intervention types regardless of the size of the hospital or throughput of patients. Figure 5 depicts the results of the same using a graph, whereas Table 2 is a summary of the resulting intensity indicators.

Table 2: GHG Reduction Intensity Normalised per Bed-Day.

Sub-Project	GHG Reduction (tCO_2e)	Intensity (kg CO_2e per bed-day)
Water reuse (IGRP-A)	67	0.057
Biogas from ETP sludge (IGRP-B)	469	0.397
Plastic waste valorisation (IGRP-C)	534	0.452
Organic waste composting (IGRP-D)	986	0.834
Solar PV generation (IGRP-E)	3,172	2.68

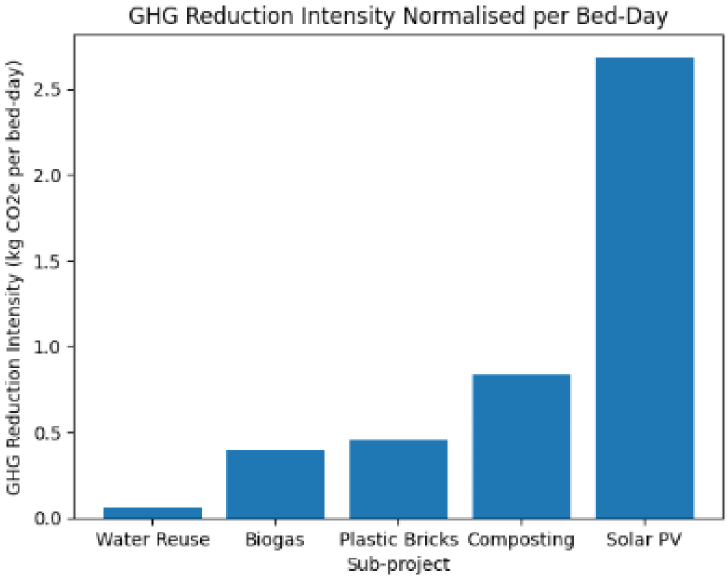

Figure 5: GHG reduction intensity normalized per bed-day.

The normalised outputs reveal that there is a strong hierarchy between the mitigation effectiveness of sub-projects. The reduction intensity of solar photovoltaic generation (IGRP-E) is the highest with a calculation of about 2.68 kg CO 2e per bed-day. This is an expression of the ongoing replacement of grid electricity whose emission factor is relatively high, and a stable operation profile of a solar installation. Regarding the life-cycle, this outcome validates electricity usage as the focal point of hotspot operation emissions in large campuses of hospitals.

Out of non-energy interventions, the reduction intensity of organic waste composting (IGRP-D) is the greatest (0.834 kg CO 2e per bed-day) highlighting the high climate advantage of avoiding methane in biodegradable waste streams. Considering the quantity and biodegradability of the hospital food waste, composting provides disproportionately large life-cycle emission reductions compared to its size of operation. The plastic waste valorisation (IGRP-C) and biogas recovery of effluent treatment plant sludge (IGRP-B) have a similar intensity of 0.452 kg CO 2 e and 0.397 kg CO 2 e per bed-day, respectively. These findings underscore the usefulness of the specific waste-to-resource initiatives in the control of emission pathways that are not traditionally considered in the standard hospital level energy-efficient strategies, including the unregulated waste decomposition and the replacement of fossil fuels.

Water reuse (IGRP-A) on the other hand has the lowest intensity, which is 0.057 kg CO 2e per bed-day. This is unsurprising because the main benefits of water reuse are indirect mitigation given by the freshwater reduction and treatment, energy and chemical consumption. Although it has a small direct role in mitigating emissions, water reuse is also a vital enabling factor as it reduces the total system demands in the resource and enables the combined effectiveness of other mitigation strategies.

4.3.3 Integrated Life-Cycle Interpretation

The results based on the intensity provide that the benefits of life-cycle mitigation are shared among various subsystems. Energy interventions result in high per-bed-day reductions whereas waste and water interventions offer the much needed complementary benefits that stabilise the emissions with increase in service demand. Importantly, the percentage contribution and intensity metrics prove that the decarbonisation of hospitals cannot be based only on renewable electricity. Waste and water systems represent one of the major hotspots of life-cycle emission that needs to be better handled so as to accomplish long lasting and sustained reductions.

4.4 Life-Cycle Emission Reduction Performance by Sub-Project

The cumulative greenhouse gas (GHG) emission reductions of every Integrated GHG Reduction Project (IGRP) sub-project during the 20222025 reporting period are compared in figure 6. These findings indicate that the mitigation profile is highly differentiated in types of interventions, which are varied, as the life-cycle pathways of avoiding emissions are varied.

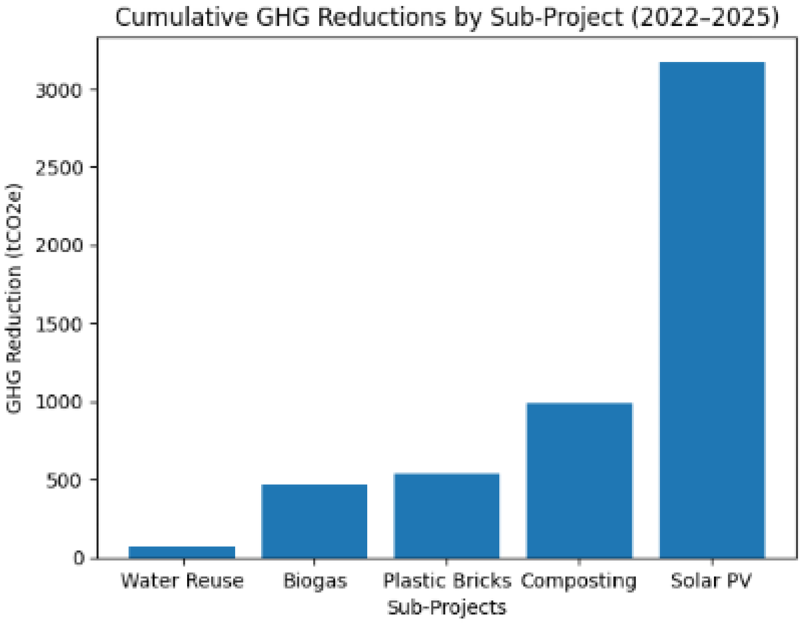

Figure 6: Cumulative GHG Reductions by Sub-Project (2022–2025).

The IGRP-E (solar photovoltaic generation) is the most significant contributor (more than half of the avoided emissions). This is largely due to the fact that the replacement of grid electricity which is mostly characterised by the property of a comparatively high carbon emission factor is coupled with the sustained and foreseeable performance of the on-site solar installations. Electricity substitution is a high leverage and direct mitigation channel in the life-cycle perspective especially in the hospital setting, which is energy-intensive and whose power needs are not seasonal.

The second contribution is made by IGRP-D (organic waste composting) which highlights the life-cycle importance of the methane avoidance of biodegradable waste streams. Organic waste that is produced in hospital food services and kitchen is one of the key hotspots of emission in the baseline conditions of landfill disposal. The project significantly interrupts methane pathways by redirecting this waste to controlled composting resulting in significant emission savings even though their volume of waste keeps growing throughout the period of the study. The resultant effect of this finding is an emphasis on treatment based interventions to handle the unavoidable organic waste in health care facilities.

IGRP-C (plastic waste valorisation) and IGRP-B (biogas recovery of effluent treatment plant sludge) make moderate but significant contribution towards cumulative emission reduction. Plastic waste valorisation saves or minimises emissions through avoiding the incineration or landfill of non-recyclable plastics and replacing traditional building materials, whereas biogas recovery compensates the use of fossil fuels by means of controlled use of methane. Though not as large as renewable electricity generation, these interventions fill in gaps in the pathways of emission reduction, which are commonly omitted by traditional hospital sustainability plans, to augment the overall sustainability and thoroughness of the mitigation portfolio.

IGRP-A (water reuse) on the other hand gives relatively less absolute reductions in emissions. This is not surprising since the major impacts of water reuse are some indirect mitigation factors in terms of freshwater abstraction, pumping, treatment, and other related chemical use. However, its input has still a strategic value in the combined system, since it leads to the decrease in the life-cycle energy requirement and allows the efficiency increase in other sub-projects, which facilitates the successful functioning of the whole system.

Combined, these findings indicate that the total of non-energy interventions is a significant portion of the total amounts of emissions reduced, even with the prevalence of renewable power generation. This observation demonstrates that successful hospital decarbonisation cannot be based only on energy-sector solutions. Rather it needs a systems based mitigation program that incorporates energy, waste and water management to deal with several sources of life-cycle emissions at the same time. This distinction of performance in the sub-projects supports the main assumption in this paper that multi-sectoral interventions are stronger and more sustainable than single-technology interventions in terms of GHG reductions.

4.5 Summary of Quantitative Results

The integrated sustainability framework has recorded a total confirmed greenhouse gas reduction of 5,228 tCO 2 e over the three years of reporting between the year 2022 and 2025 and this shows that mitigation efforts were coordinated in the energy, waste and water systems in the hospital campus. The overall mitigation intensity of the interventions was around 4.4 kg CO 2e/bed-day when normalised to the delivery of healthcare services and showed significant decarbonisation advantages compared to patient throughput and scale of operation. Although on-site solar-powered photovoltaic systems that generated renewable power gave the greatest contribution to overall reduction of emission, which was more than half of the total reduction, the joint action of waste and water management interventions continued to play an important role and was close to 40 percent of the total reduction. This even distribution underscores the role of non-energy indicators in dealing with life-cycle emission sources which are frequently not included in hospital decarbonisation plans. Moreover, the application of bed-day normalisation proofs the strength and scalability of the findings and proves that the level of the performance of the emission-reduction is not affected by the variations in the number of patients and the level of demand on the services. On the whole, the quantitative results support the principles of an integrated and systems-wide strategy on the way to sustainable and robust mitigation of greenhouse gases in big healthcare institutions.

5. DISCUSSION

This paper shows that a life-cycle-based and integrated approach to environmental management can provide significant and measurable greenhouse gas (GHG) reductions in a large super-specialty hospital environment. The findings indicate the constraints of the siloed approach to sustainability intervention and support the importance of systems-based mitigation strategies in healthcare infrastructure by integrating energy generation, waste management, and water reuse into the single analytical and functional approach. Instead of depending on one dominant intervention, the cumulative emission reductions that are witnessed in this study are an extension of the interaction of several subsystems that work at various stages of the life-cycle.

Conceptually, the results support the theoreticalisation on hospitals as complex socio-technical systems marked with interdependent flows of energy, materials, water and waste. Traditional analyses of hospital sustainability often focus on one aspect of the problem in isolation (e.g. use of renewable energy or treatment of biomedical waste) which might obscure the interactions across the system and result in problem shifting. Conversely, the attributional Life Cycle Assessment (LCA) has been used in this study, whereby there are operational emission hotspots that are spread in terms of electricity consumption, organic waste decomposition, and auxiliary fossil fuel use. The combination of LCA and ISO 14064-2 project-based accounting of GHG enhances methodology rigor through a direct connection between the life-cycle impact assessment and quantifiable and verifiable effect of reduction of emissions. By combining both methods, this will be able to fill a major research methodological gap of healthcare sustainability studies and offer an analytical model that can be repeated in future investigations.

The standardization of the emission abatements per bed-day also increases the interpretable and comparable nature of the results because it matches the environmental performance measurement with healthcare service provision. The intensity-based analysis shows that the effectiveness of mitigation can be sustained despite variation in patient throughput and service demand which help to prove the theoretical view that the environmental impact can be partially disconnected with the institutional growth by designing an integrated system. The conclusion is especially applicable to tertiary-care hospitals, where the growth is usually necessitated by demand.

Policy wise, the findings indicate that decarbonisation efforts by the healthcare services should not be strictly limited to a limited scope of implementing renewable energy. Although solar photovoltaic generation contributed the greatest percentage of the reduction of emissions in this study, waste and water interventions made nearly 40 percent of the total avoided emissions, which indicate the importance of climate of non-energy pathways. The existing regulatory and incentives frameworks tend to consider energy, water, and waste management as different areas of policy, which may be restrictive to the success of sustainability efforts. This integrated framework has shown that there is a need to have more policy coherence in these areas to ensure meaningful and sustainable GHG mitigation in healthcare facilities. Besides, the successful implementation of ISO 14064-2 in a hospital setting highlights the opportunities of harmonizing healthcare sustainability efforts with new carbon markets, institutional climate reporting policies, and national climate commitments.

6. CONCLUSION

The paper shows that a life-cycle-based sustainability model is the key to achieving significant and measurable greenhouse gas (GHG) reductions in a large super-specialty hospital environment. The study offers a solid methodological framework to measure and explain the results of emission-reduction in interdependent water, waste and energy systems by integrating attributional Life Cycle Assessment (LCA) and the establishment of project-based GHG accounting under ISO 14064-2:2019. The empirical evidence provided by the application of this framework to a real-life hospital campus in a three-year monitoring period is that organized interventions could result in significant decarbonisation of operations without fundamental effects on healthcare service provision. The findings indicate that the integrated framework had a total GHG reduction of 5,228 tCO 2 e of which renewable electricity generation contributed the highest amount and interventions based on waste and water contributed approximately 40 percent to the overall avoided emissions. The sustained effectiveness of mitigation through normalisation of results per bed-day proves that effectiveness does not reduce with changes in patient volumes and operational demand, which underlines the versatility and resilience of the methodology. Notably, the results demonstrate that decarbonisation in hospitals can not be based only on solutions in the energy sector since large life-cycle emission cuts can also be achieved through organic waste composting, plastic valorisation, biogas recovery, and water reuse. In addition to quantitative results, the paper contributes to conceptual knowledge by placing the hospitals in the role of holistic socio-technical systems where environmental performance is being a result of interactions in various areas of operations. LCA combined with ISO-compliant GHG accounting has the potential to address a significant gap between the evaluation of the environment and the practice of climate mitigation that can be verified and thus provide an example that can be replicated by other healthcare facilities that are interested in providing transparent and credible sustainability reporting. Practically, the framework gives administers of hospitals and policymakers practical insights into the importance of prioritising interventions on the basis of their impact on life-cycle and not individual efficiency improvements.

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