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Environmental costs in healthcare system: the case studies of Greece health care

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Abstract
Climate change is considered one of the greatest threats to environmental sustainability, human health and social well-being worldwide. The healthcare sector is one of the main actors with a strong negative environmental footprint, being responsible for about 4% of global emissions, and is also considered one of the costliest sectors, with healthcare spending absorbing about 10% of global economic output. This article examines the environmental costs of the healthcare system in Greece, with a focus on public hospitals. The data analysis methodology was based on linear ordinary regression (OLS) models to calculate environmental costs related to energy consumption, waste management and water consumption. Data was collected through the Ministry of Health's platform (BI Health) and analyzed using Stata software. The main findings suggest that environmental costs are a significant part of total operating costs, particularly in university and specialist hospitals. Factors such as the number of beds, the existence of special units (e.g. ICU) and the use of natural gas have a significant impact on environmental costs. The study offers a mathematical model for predicting environmental costs, which can help hospital administrators to make decisions about sustainable practices. This model could provide an important opportunity for practical application to make targeted decisions such as investing in sustainable technologies, improving energy efficiency and enhancing waste management, leading to cost-effective and environmentally sustainable practices.

Keywords Environmental costs, Healthcare sector, Energy consumption, Waste management, Sustainable healthcare, Green hospitals

Introduction

Climate change, mainly due to human activities, is considered the greatest global health threat of the 21st century [1–5]. In 2023, global temperatures reached their highest levels in decades, putting a strain on already stressed health systems [6–8]. Although efforts are being made to strengthen the resilience of health systems, the health sector's significant contribution to climate change is often overlooked [9–12].

The health sector consumes large amounts of energy and generates significant amounts of medical and health care waste [13–15], accounting for about 4.6% of global greenhouse gas emissions [6, 16, 17]. The environmental

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impact of the sector ranges from 1 to 5% of the global impact, and in some countries may be even higher [18].

The health sector, recognizing its dual role as both a driver of environmental burden and protection, has the potential to lead efforts towards sustainable solutions [19–22]. Transitioning to sustainable, efficient, emission-free health systems could reduce the sector's environmental footprint and enhance global health while integrating environmental, social and governance (ESG) decision making factors [23–28].

This study examines the environmental costs of public hospitals in Greece and their impact on operational efficiency. Specifically, the study answers the following questions:

- How do environmental costs affect the total operating costs of hospitals?
- What characteristics influence environmental costs and to what extent?

The study contributes to the international literature by examining the relationship between environmental costs (energy, water, waste management) and hospital characteristics. The sub-objectives include:

- Identification of the proportion of environmental costs relative to total costs.
- Examination of the characteristics that influence environmental costs.
- Estimating the impact of environmental costs on total operating costs.

The methodology is based on linear regression models with costs and environmental footprint as dependent variables, using logistic transformations to deal with data allocation problems. The data are obtained from the Ministry of Health's platform.

This paper consists of five sections: introduction, theoretical background and literature review, research methodology, results presentation and discussion, conclusions, gaps in the literature and suggestions for future research.

Theoretical background

In recent years we have been facing a serious problem that has been identified by the World Health Organization as the greatest threat to global health in the 21st century: climate change [29–31]. It is estimated that climate change will be responsible for the deaths of 250,000 people a year between 2030 and 2050, due to hardship, malaria, diarrhea and heat stress [32, 33]. The health sector can make a positive contribution to addressing the negative impacts of climate change by safeguarding the health of the population, effectively controlling carbon emissions and implementing an action plan to benefit the environment [34]. The health sector faces significant environmental challenges, with major causes being high energy and water consumption and poor waste management, which are accompanied by significant environmental impacts, such as the generation of millions of tons of waste, increased energy consumption and excessive water use. It is crucial to identify the appropriate data and take the necessary actions and initiatives for the sustainability of the health sector [24].

For the analysis demands, we categorized Greece's public hospitals into five categories (small hospitals, general hospitals, university hospitals, and two types of specialized hospitals). From the 125 hospitals that exist in the country (mainland and the islands), 119 were included in our sample. Two very small hospitals and two specialized hospitals were completely excluded due to the insufficient data they provided, whereas two others were recorded as one with their interconnected hospitals. The distribution of the hospitals according to their type, the area in which they are located, and their number of beds is shown in Table 2.

One factor that should be considered is the generation of hazardous waste in healthcare facilities, which varies from country to country. For example, in Nigeria, it is 26.5%, and in Sub-Saharan African nations, it is 2–10% (Rahmani et al., 2020). In Iran, it is 52.27%, in Bangladesh, it is 36.03% (Rahmani et al., 2020), and in Germany, it is 1–3% (Vogt & Nunes, 2014). According to Janik-Karpinska et al. (2023), the high income countries produce up to almost 11 kg of hazardous waste per hospital bed per day (kg/bed/day), while in low-income countries the production rate ranges up to 6 kg. Another issue that is presented is that in low-income countries, hazardous waste is generated in significantly greater quantities because HCW is typically not segregated into hazardous and non-hazardous waste. Table 1 present is some examples of healthcare waste production rate in several countries around the world.

Studies from Europe and US showed that healthcare sector contributes between 6% to 10% of the entire energy consumption within the healthcare sector [35–37, 38, 39], and the annual average energy costs per patient per bed vary from 2.200€ to 3.900€, represents a varying percentage of the overall yearly operating expenditures in hospitals within the same category, i.e., 2.1% to 10% [40]. In addition, the annual expenditure on energy consumption exceeds 4% and, in certain cases, more than 7% of the annual budgets for the operation of all healthcare units, particularly for Greek public hospitals [41].

Healthcare waste generation

The health system is a major contributor to environmental problems, producing 1–2% of the world's urban waste

Table 1 Health Care Waste Management generation per country

Countries	the HCW generation per country
Europe	**France** is 2.7– 3.3 (kg/bed/day) [45, 57, 97] **Greece** is 0.3–3.6 (kg/bed/day) [57, 58] **Norway** is 3.9 (kg/bed/day) [46, 97] **Spain** is 3.5–4.4 (kg/bed/day) [45, 46, 97] **Romania** is 1 (kg/bed/day) [63, 98, 99] **Italy** is 4 (kg/bed/day) [59]
Asia	**India** is 0.8–2.3 (kg/bed/day) [60, 97, 103] **Jordan** is 2.5– 6.10 (kg/bed/day) [59, 97] **China** is 0.6–4 (kg/bed/day) [61, 98, 10497] **Kazakhstan** is 5.3 (kg/bed/day) [62, 97] **Taiwan** is 2.41–3.26 (kg/bed/day) [63, 99] **Vietnam** is 1.42–1.57 (kg/bed/day) [98, 99, 105,]
Africa	**Morocco** is 0.4–0.7 (kg/bed/day) [35, 97] **Sudan** is 0.4–0.9 (kg/bed/day) [63, 64, 97] **Egypt** is 0.7–1.7 (kg/bed/day) [65, 97] **Ethiopia** is 1.1–8.2 (kg/bed/day) [66, 67] **Sudan** is 0.6 (kg/bed/day) [63, 99] **Ghana** is 1.2– 2.9 (kg/bed/day) [100] **Mauritius** is 2 (kg/bed/day) [63, 99]
In South America countries,	**Ecuador** is 2.1 (kg/bed/day) [97, 101] **Brazil** is 2.9–3.3 (kg/bed/day) [68, 97] **Argentina** is 2.7–3.0 (kg/bed/day) [97, 103].
In North America	**US** is 4.5– 10.7 (kg/bed/day) [97] **Canada** is 8.2 (kg/bed/day) [65, 106].

[18, 42–44]. In the last thirty years, health sector waste has increased due to population growth and biomedical advances [45–47]. According to WHO guidelines, 85% of healthcare waste is non-hazardous (e.g. paper, packaging, food waste), while 15% is hazardous (e.g. pathological, radioactive, infectious and chemical waste) [48–50]. Hazardous waste poses environmental risks, such as air, water and soil pollution, especially when appropriate management systems are not in place [51–53].

The proportion of hazardous waste varies by region, ranging from 26.5% in Nigeria to 1–3% in Germany [54, 55]. High-income countries produce up to 11 kg of hazardous waste per hospital bed per day, compared to 6 kg in low-income countries. Poor segregation of hazardous and non-hazardous waste exacerbates the problem in low-income countries [56]. Health care waste (HCW) generation varies significantly across countries and regions.

In Europe, HCW generation ranges from 2.7 to 3.3 kg/bed/day in France, 0.3 to 3.6 kg/bed/day in Greece, 3.9 kg/bed/day in Norway, 3.5 to 4.4 kg/bed/day in Spain, 1 kg/bed/day in Romania, and 4 kg/bed/day in Italy [45, 46, 57–59].

In Asia, India's HCW generation ranges from 0.8 to 2.3 kg/bed/day, Jordan from 2.5 to 6.1 kg/bed/day, China from 0.6 to 4 kg/bed/day, Kazakhstan is 5.3 kg/bed/day, Taiwan ranges from 2.41 to 3.26 kg/bed/day, and Vietnam is between 1.42 and 1.57 kg/bed/day [59–63]. In Africa, Morocco generates between 0.4 and 0.7 kg/bed/day, Sudan from 0.4 to 0.9 kg/bed/day, Egypt from 0.7 to 1.7 kg/bed/day, Ethiopia ranges from 1.1 to 8.2 kg/bed/day, Ghana from 1.2 to 2.9 kg/bed/day, and Mauritius is 2 kg/bed/day [35, 64–67]. In South America, Ecuador generates 2.1 kg/bed/day, Brazil ranges from 2.9 to 3.3 kg/bed/day, and Argentina generates between 2.7 and 3.0 kg/bed/day [68]. In North America, the US generates

Table 2 Greek Public hospitals' distribution by category and Health District

Health District	Small Hospitals	General Hospitals	University Hospitals	Specialized type I Hospitals	Specialized type II Hospitals
1st	1	11	0	6	2
2nd	6	9	2	2	2
3rd	0	14	0	1	0
4th	1	10	2	0	1
5th	2	10	1	0	0
6th	6	19	2	1	0
7th	3	4	1	0	0
Total	19	77	8	10	5

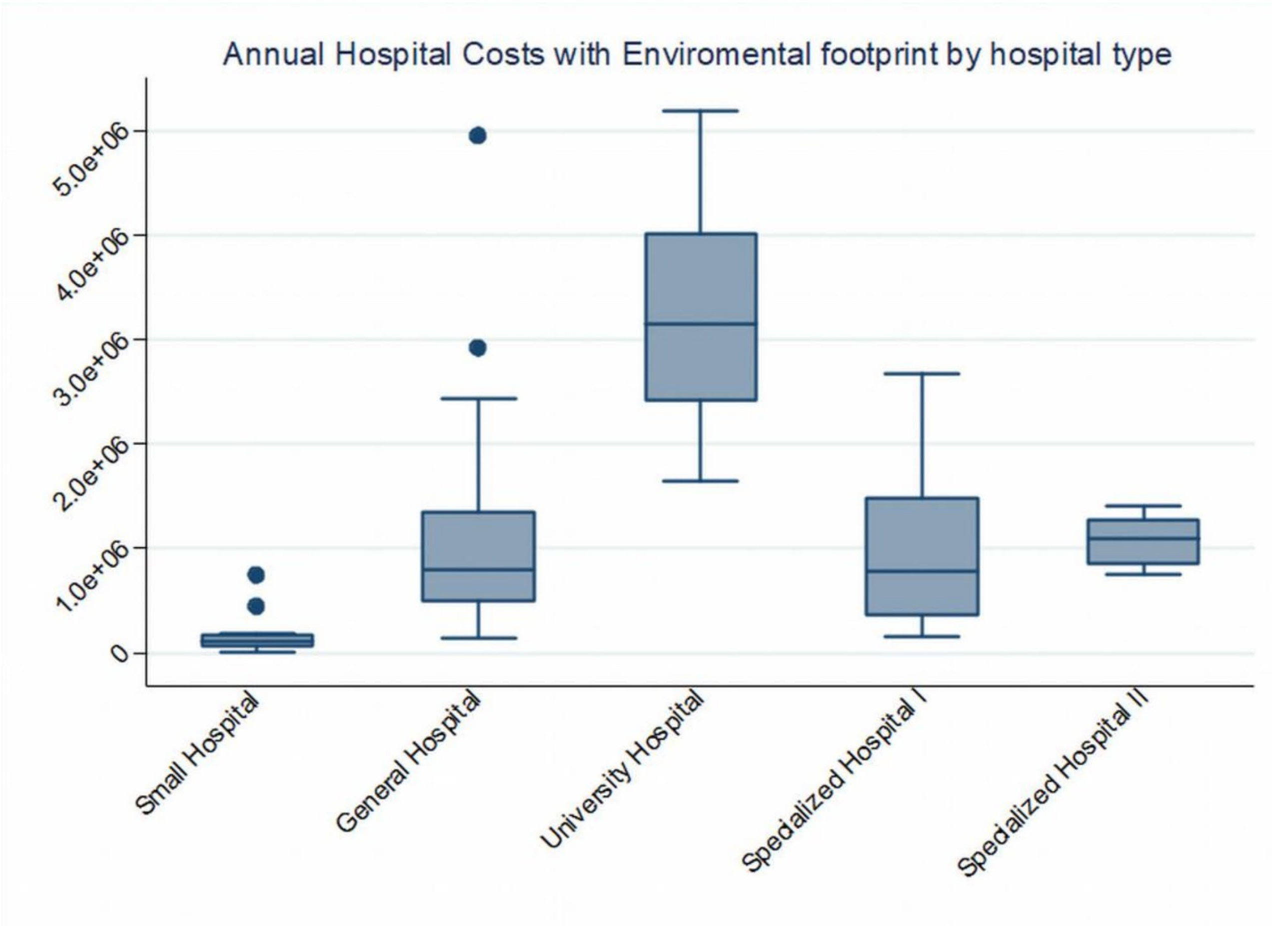

Fig. 1 Annual HCAEF by hospital type

between 4.5 and 10.7 kg/bed/day, while Canada generates 8.2 kg/bed/day [65].

Healthcare providers face challenges in managing medical waste, such as budget constraints, inadequate storage, lack of staff training, lack of equipment, improper decontamination, disposal and poor waste segregation [53]. Only 17% of countries use standardized storage for all medical waste, while 25% separate it at source. Identifying medical waste (HCW) and reducing its volume and cost is critical [69, 70]. Increasing recycling in hospitals can reduce the economic impact. For example, U.S. hospitals saved $100,000 each and $72.4 million in total in 2019 [70].

In Greece, the average waste cost per bed was €571.30, per patient €7.60 and per day €2.30 [71]. University hospitals produce the most waste (0.70 kg/bed/day), followed by military hospitals (0.68 kg/bed/day), while private mental health clinics produce the least (0.043 kg/bed/day) [71, 72]. In 177 health care facilities in Greece, infectious and toxic waste averaged 0.7 kg/bed [73].

Another study in Spain, identify HVAC and medical equipment as major contributors (81.8%), while energy demand varies widely, with operating theatres and ICUs exceeding 1000 kWh/m^2 annually, while most areas use less than 250 kWh/m^2 [74].

Table 3 Average annual HCAEF for each type of hospital

Hospital Type	Number of observations	Mean (€)	Minimum (€)	Maximum (€)
Small Hospitals	19	155.842	16.665	740.155
General Hospitals	77	998.303	149.245	4.944.233
University Hospitals	8	3.250.078	1.647.521	5.192.119
Specialized Hospitals I	10	1.080.136	163.638	2.680.711
Specialized Hospitals II	5	1.075.611	752.684	1.404.772

Table 4 Average percentage of annual hospitals costs related to activities with an environmental footprint on total annual operating costs for each type of hospital

Hospital Type	Number of observations	Mean	Minimum	Maximum
Small Hospital	19	14.6%	5.9%	41.5%
General Hospital	77	11.5%	2.3%	36.3%
University Hospital	8	7.2%	3.8%	14.7%
Specialized Hospital I	10	12.3%	5.8%	23.5%
Specialized Hospital II	5	3.7%	1.6%	5.7%

Healthcare energy consumption

Energy production and consumption, especially electricity, are major contributors to global warming, resource depletion and dependence on fossil fuels [24, 75]. Hospitals, the most resource intensive users in the health sector, consume 50–80% of resources due to the energy required for clinical equipment and continuous heating, ventilation and lighting [36, 74]. Lighting, heating and hot water account for 61–79% of hospital energy consumption [24]. Factors that predict energy consumption include facility size, services offered, number of patients and staff [37, 38].

Healthcare providers should adopt energy management systems, green technologies [40, 41, 76], optimized buildings [77–79], staff training [79, 80], energy audits and high-tech lighting systems [81]. The healthcare sector is responsible for 6–10% of energy consumption in Europe and the US, with annual costs per bed ranging from €2,200 to €3,900, representing 2.1–10% of hospital operating costs [80, 82–84].

In public hospitals in Greece, energy costs represent 4–7% of annual budgets, with the total amount amounting to €93.4 million in 2018 and €101.3 million in 2019, i.e. about 4.5% of healthcare budgets. Costs vary

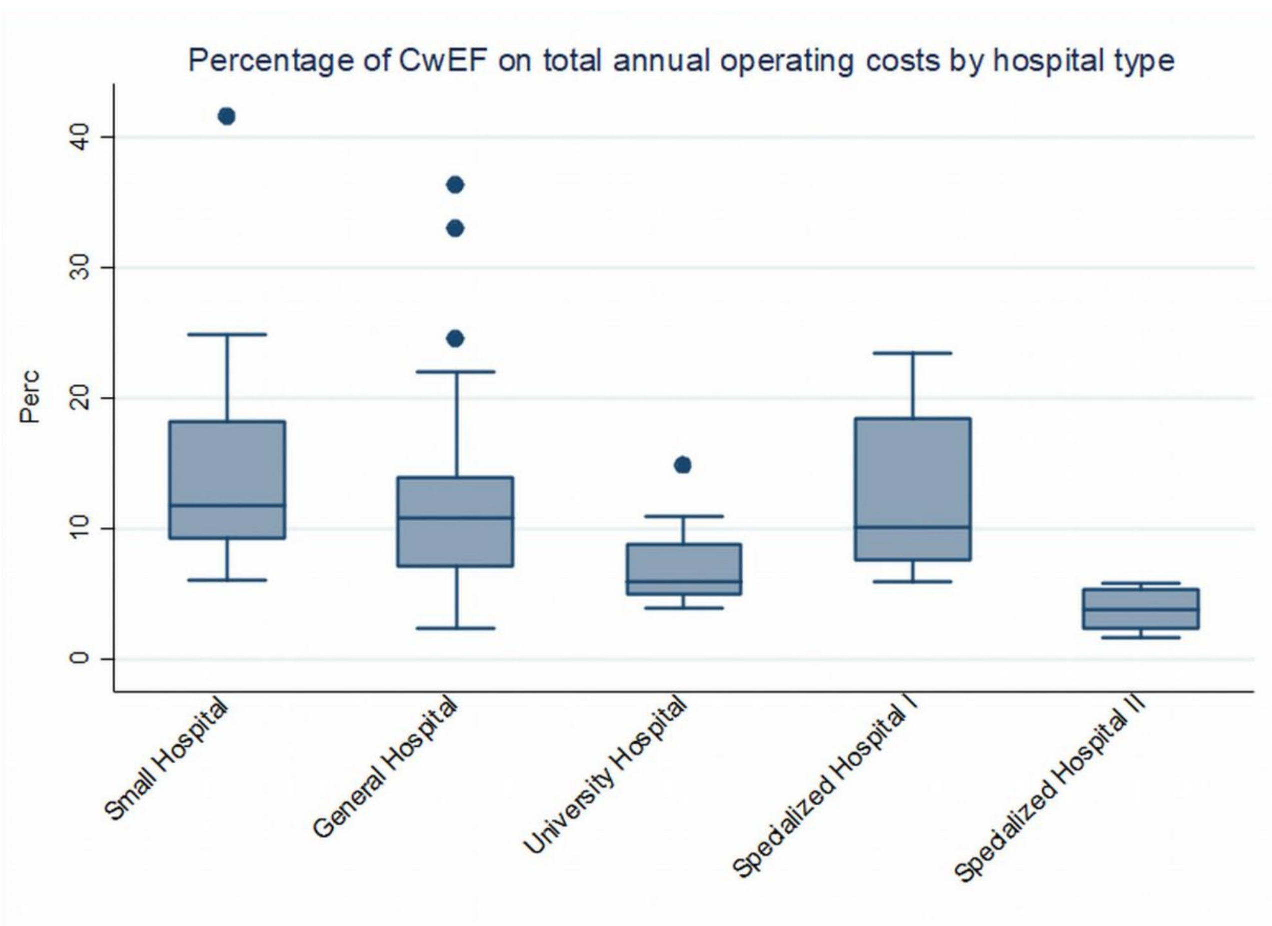

Fig. 2 Boxplot with average percentage of annual hospitals costs related to activities with an environmental footprint on total annual operating costs for each type of hospital

Table 5 Correlations between the individual costs with an environmental footprint

	Cost of water consumption	Coste of waste management	Cost of energy resources
Cost of water consumption	1.0000		
Coste of waste management	0.4292	1.0000	
Cost of energy resources	0.6761	0.6559	1.0000

considerably due to differences in management, hospital size, staffing and energy sources such as gas. Additional factors include the number of inpatients, surgeries and imaging tests [85, 86].

Healthcare water consumption

Hospitals consume significant amounts of water in various services such as laundry, cleaning, kitchens and medical services, producing waste containing hazardous chemicals, pathogens and radioactive materials, endangering human health and the environment [87–89]. Waste from hospitals is among the most hazardous, threatening both humans and ecosystems [24]. Water consumption in hospitals ranges from 400 to 1,200 L per bed per day [90], with waste generation ranging from 198 to 2,258 L per patient per day in the EU [91] and 100–150 L per patient per day in the USA [90]. Water management systems are essential as 4–15% of water use is for medical procedures, with the remaining 85–96% used for cleaning, washing and cooking [92]. Monitoring the quantity and quality of waste is critical for implementing preventive measures to protect ecosystems and public health [93].

Necessity of taking actions

Sustainable and green finance plays a key role in energy transitions, adopting low-emission strategies, reducing emissions, attracting innovative green capital [94], improving environmental performance [95] and promoting sustainable development goals [96]. Efforts to minimize waste, optimize energy use and enhance water management support environmental conservation and align with the goal of decarbonizing the healthcare sector by involving decision-makers [97–101].

This research highlights the urgent need for a holistic approach to hospitals' environmental footprint-related expenditures (HCAEF), including energy, water and waste management costs. It examines the financial burden on healthcare infrastructure, identifies the different profiles of hospitals and analyses which factors have the greatest impact on environmental costs. This approach bridges environmental and economic parameters, providing useful information on the characteristics that significantly affect a hospital's environmental costs.

Materials and methods

The survey methodology is based on the analysis of data from the Ministry of Health's BI Health platform, where public hospitals enter monthly data. Data were collected upon request and cross-checked with the official websites of the hospitals and the Transparency Program [102]. The hypothesis of the study was the above:

Hypothesis: Hospital characteristics (type, size, geographical location, etc.) influence their environmental footprint (HCAEF) (Tables 1 and 2).

The analysis was performed through multiple linear regression, using logarithms to manage the normality of the data [107, 108]. Tools such as Stata and the Huber/White estimator were used to assess the variability and independence of observations [109–111]. The reason for building this model was to quantify the relationship between hospital characteristics and environmental costs (energy, water, waste), providing a practical tool for

Table 6 Correlations between the quantitative independent variables

	Beds	Inpatients	Days of stay	Outpatients	Hemodialysis	Surgeries	Laboratory Tests	Employees	Medical Imaging Tests
Beds	1.0000								
Inpatients	0.8199	1.0000							
Days of stay	0.9295	0.8969	1.0000						
Outpatients	0.7548	0.8694	0.7957	1.0000					
Hemodialysis	0.3035	0.3884	0.3100	0.5070	1.0000				
Surgeries	0.7062	0.8155	0.7458	0.8670	0.4276	1.0000			
Laboratory Tests	0.7958	0.8855	0.8837	0.8397	0.3576	0.7717	1.0000		
Employees	0.9211	0.8940	0.9350	0.8567	0.3536	0.8041	0.9241	1.0000	
Medical Imaging Tests	0.6264	0.7209	0.6851	0.7887	0.3791	0.7699	0.7216	0.7403	1.0000

*All the above correlation coefficients where statistically significant (p-value < 0.05)

Table 7 Correlations between the qualitative independent variables

	Hospital Type	Location	ICU	INCCU	AKU	GAS
Hospital Type	1.0000					
Location	−0.3199*	1.0000				
ICU	0.2977*	−0.1989*	1.0000			
INCCU	0.0824	−0.0083	0.0886	1.0000		
AKU	−0.1377	0.0115	0.3233*	0.0549	1.0000	
GAS	0.4286*	−0.4210*	0.3681*	0.1196	−0.1718	1.0000

*Correlation coefficients statistically significant (*p*-value < 0.05).

strategic decision making and efficient resource allocation to reduce the environmental footprint of hospitals.

The confirmation or rejection of the hypothesis will be based on the results of the model, defining practical applications and strategies to reduce the environmental footprint in the healthcare sector.

Results

Greece is organized into seven health districts under the Ministry of Health's administration, with 125 public hospitals of various sizes and specialties distributed across the mainland and islands. In some cases, 2–3 hospitals with shared administration and consolidated financial records on the BI Health platform were treated as a single entity for this research.

For analysis, Greece's public hospitals were categorized into five groups: small hospitals, general hospitals, university hospitals, and two types of specialized hospitals. From the 125 hospitals, 119 were included in the sample. Two very small hospitals and two specialized hospitals were excluded due to insufficient data, while two others were merged with their interconnected hospitals. The distribution of public hospitals in Greece by category and health region is as follows:

– In the 1st Health Region, there is 1 small hospital, 11 general hospitals, 6 specialized type I hospitals and 2 specialized type II hospitals.
– In the 2nd Health Region, there are 6 small hospitals, 9 general hospitals, 2 university hospitals, 2 specialized type I hospitals and 2 specialized type II hospitals.
– In Health Region 3, there are 14 general hospitals, 1 type I specialised hospital and no small, university or type II specialized hospitals.
– In Health Region 4, there is 1 small hospital, 10 general hospitals, 2 university hospitals and 1 type II specialised hospital.
– In Health Region 5, there are 2 small hospitals, 10 general hospitals, 1 university hospital and no specialised hospitals.
– In the 6th Health Region, there are 6 small hospitals, 19 general hospitals, 2 university hospitals, 1 type I specialised hospital and no type II specialised hospitals.
– Finally, in the 7th Health Region, there are 3 small hospitals, 4 general hospitals, 1 university hospital and no specialised hospitals. In total, there are 19 small hospitals, 77 general hospitals, 8 university hospitals, 10 type I specialized hospitals and 5 type II specialized hospitals.

Table 8 Analytical results of the Simple Linear regression model for the HCAEF

Simple Linear Regression Model		$R^2 = 0.8935$
		Number of obs = 119
		Coef. (Std.Err.)
Constant	**b0**	9.832815 (10.62123)
Number of Beds	**b1**	0.247811 (0.0040874)
Hospital Type		
General Hospital	**b2**	1.632896 (2.555173)
University Hospital		2.117931 (5.625709)
Specialized Hospital Type I		1.179553 (2.444872)
Specialized Hospital Type II		1.546217 (4.428734)
Hospital Type # Beds		
General Hospital	**b3**	−0.0317488 (−0.0156318)
University Hospital		−0.0348637 (−0.0179372)
Specialized Hospital Type I		−0.030826 (−0.0145603)
Specialized Hospital Type II		−0.0347517 (−0.0163719)
Artificial Kidney Unit	**b4**	0.0239404 (0.4435528)
Intensive Care Unit	**b5**	0.0834428 (0.5703742)
Gas	**b6**	−0.1390652 (0.5505465)
Gas # Beds	**b7**	−0.0020715 (−0.0000904)
Employees	**b8**	0.0003701 (0.0014592)

Hospitals in Greece are divided into five categories: Small hospitals (20–80 beds, basic services in remote areas), General hospitals (61–945 beds, multiple medical specialties), University hospitals (368–863 beds, specialized services), Type I Specialized hospitals (e.g. psychiatric, gynecological, pediatric), and Type II Specialized hospitals (cancer, 107–380 beds). Our analysis revealed many differences in the HCAEF between different types of hospitals as shown in Fig. 1 and Table 3.

Expenditure on environmental costs is much higher in university and specialized hospitals, and lower in general and small hospitals. Despite the differences, environmental costs remain significant in all hospitals, as they

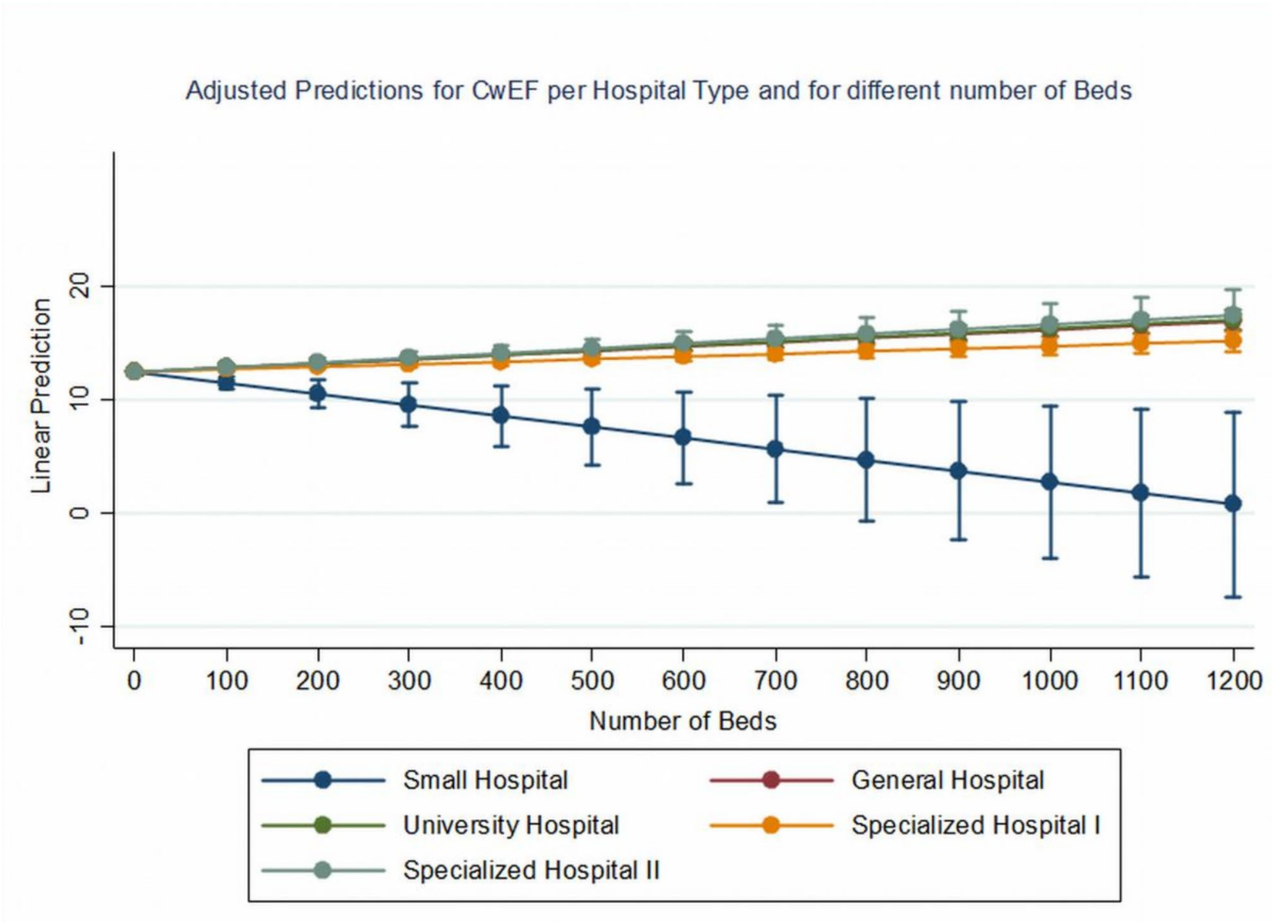

Fig. 3 The impact of extra beds on total hospital costs for each type of hospital

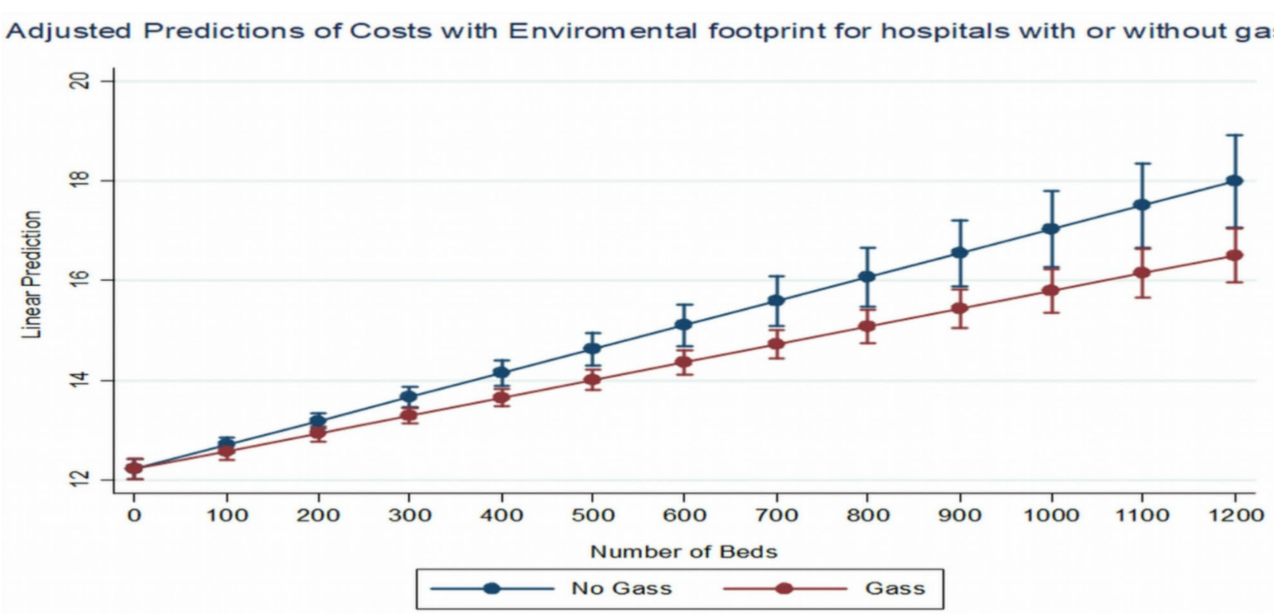

Fig. 4 The impact of gas supply existence on total hospital costs with environmental footprints for different number of beds

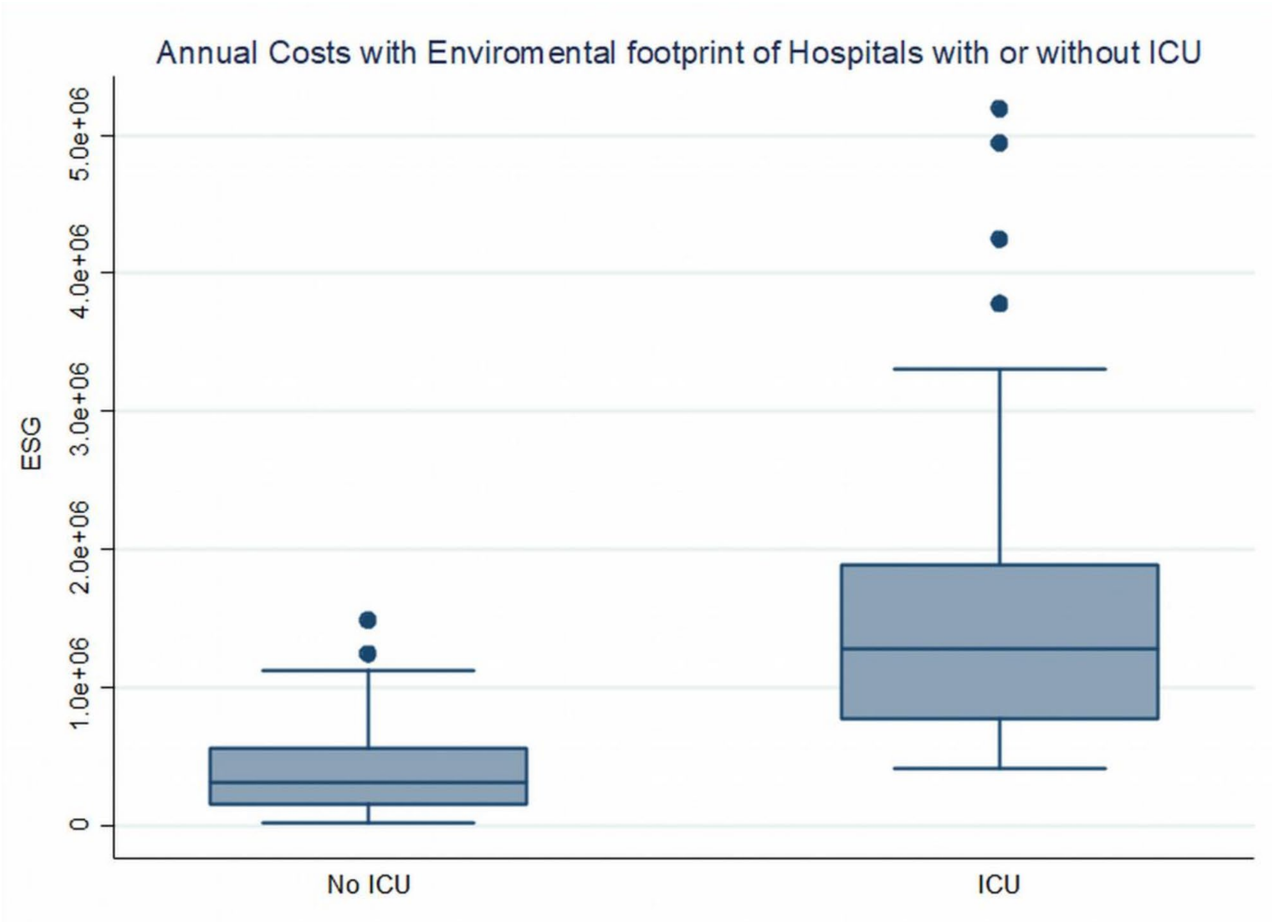

Fig. 5 The impact of ICU existence on total HCAEF

constitute a large proportion of total operating costs, reinforcing the need for further analysis of the factors that influence them (Table 4).

This reinforces the need to assess the factors affecting them, as both the direct costs of consuming and managing goods with an environmental footprint, and the indirect costs of their environmental impacts, are very high. (Fig. 2).

The research focused on actual costs and the factors that influence them. While previous studies analyzed HCAEF costs individually, this one looks at the categories (energy, waste management, water consumption) separately, considering their interactions due to correlations (Table 5). Regression methods (OLS with Huber/White estimator and seemingly unrelated regression models) [110], were used to analyze the data, with annual costs as dependent variables and hospital activities and characteristics as independent variables (Tables 6 and 7).

A regression analysis was performed for the combined HCAEF index of outputs, with the model achieving an R^2 of 89.35%, indicating a significant contribution of the variables (Table 8). To reduce multicollinearity, principal component analysis was used [111]. Although some continuous variables had significant interactions with qualitative variables, all were included in the analysis. Variables with high VIF coefficients were excluded via stepwise regression for a robust model.

The analysis shows that hospital services do not have a significant impact on environmental costs. However, factors such as number of beds, type of hospital, ICU availability, gas supply and number of employees significantly affect HCAEF, confirming the hypothesis. In particular, the number of beds increases costs, while in small hospitals there may be economies of scale. We propose a mathematical model to predict HCAEF (Fig. 3).

$$\begin{aligned}\mathbf{Log\,HCAEF} = &\mathbf{10.22 + 0.025 * Beds + b_2 * HospitalType} \\ &\mathbf{- b_3 * HospType\#Beds + b_4 * AKU} \\ &\mathbf{+ b_5 * ICU + b_6 * Gass} - 0.01 * \mathbf{Gass\#Beds} \\ &\mathbf{+ 0.001 * Employees}\end{aligned}$$

The availability of a gas supply for heating the facilities is clearly associated with lower costs in proportion to the size of the hospital which the larger hospital (more beds), the greater the savings from the use of gas, Fig. 4.

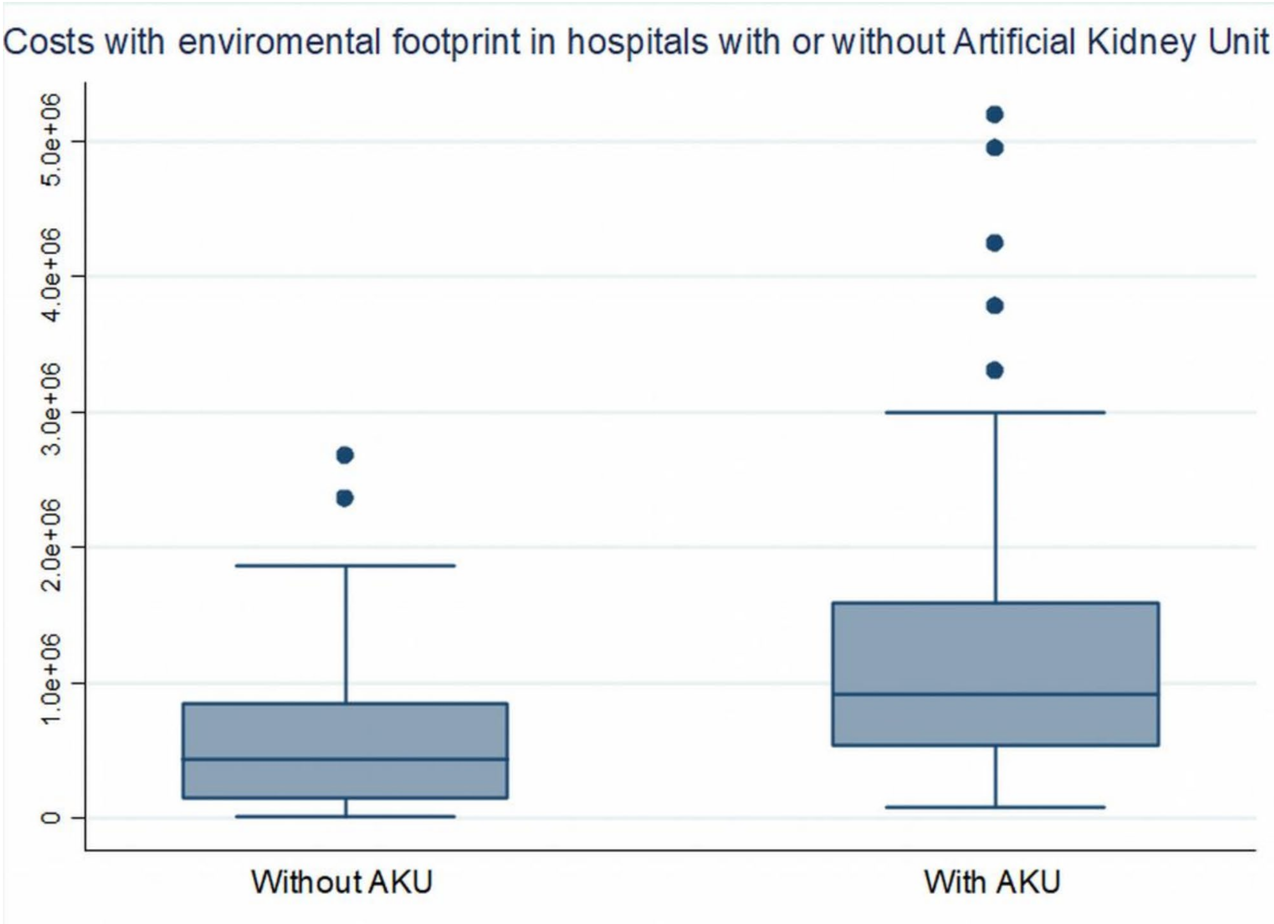

Fig. 6 The impact of an artificial kidney unit on the HCAEFs

Another characteristic that seems to have a significant upward impact on HCAEF is the existence of an intensive care unit, Fig. 5.

Likewise, the existence of an artificial kidney unit also weighs on the costs under consideration, Fig. 6.

The number of employees in each hospital shows a small but statistically significant positive correlation with the costs under consideration as we observe a positive regression coefficient for the variable Employees.

Figure 7 shows the annual cost of expenditure with an environmental footprint per bed for each type of hospital separately. The graph shows that university hospitals have the highest costs of expenditure with an environmental footprint per bed, followed by general and type II special hospitals.

Discussion

This study analyses hospital costs associated with activities with an environmental footprint, highlighting the need for sustainability in the health sector. An important contribution is the development of a predictive model for the Healthcare Sector Environmental Footprint (HCAEF), incorporating factors such as energy consumption, waste management and water use. This model provides a tool for managers to reduce their environmental footprint and improve efficiency.

The findings show that environmental costs are influenced by characteristics of hospitals, such as their type (e.g. university and specialized hospitals have higher costs), number of beds, the existence of intensive care, the use of gas for heating and the number of staff, confirming the hypothesis of this study, and showing similarities with results of previous studies [21–24, 84, 92].

The study also highlights challenges in waste management, with problems such as inaccurate categorization and overuse of ‘contaminated waste’ bags. Variations in water and energy expenditure in Greek hospitals show the influence of parameters such as size and access to renewable energy sources.

Limitations of the study are limited data availability and the time period of analysis (2018–2019), with potential for improvement if more recent data after the COVID-19 pandemic are incorporated.

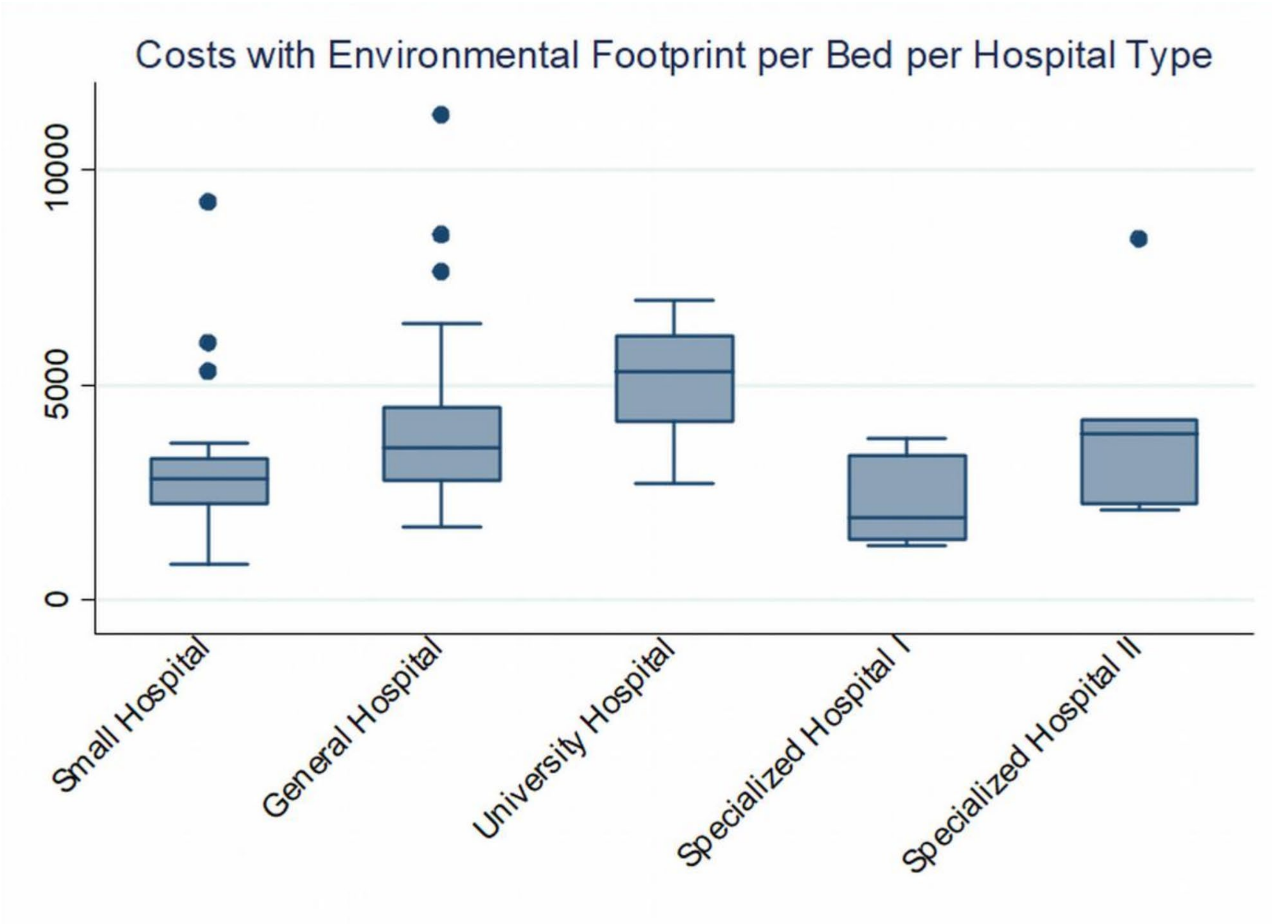

Fig. 7 Annual environmental costs (€) per bed and hospital type

Conclusion

This research contributes to the healthcare sustainability literature by filling the gap in understanding and reducing the environmental costs of hospitals. The HCAEF predictive model is a tool for hospital managers, as well as all those involved in decision-making and policy-making for healthcare providers, to be able to identify cost drivers and reduce their environmental footprint.

The findings show that environmental costs are affected by characteristics such as the size, type and complexity of hospitals, while highlighting the need for better waste management and recycling.

The use of advanced technologies and innovative practices offers possibilities for future research and applications. The practical application focuses on applying the HCAEF model to reduce the environmental footprint and improve operational costs, with actions such as reducing energy and water consumption and integrating renewable energy sources.

The research paves the way to explore the impact of digitization and smart technologies on energy efficiency and circular economy management in the health sector, while also looking at the impact of public policies and green infrastructure financing.

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Authors' contributions
All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by AS and PZ. The first draft of the manuscript was written by AS, RF, NZ and PZ. All authors reviewed and edited previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
All participants accepted the study protocol and signed a written informed consent document before participating in the study.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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