scientific reports

OPEN

Economic evaluation of hazardous healthcare waste treatment systems

Sahar Sharifi[1], Kamyar Yaghmaeian[1,2], Somayeh Golbaz[1], Ramin Nabizadeh[1,2]✉ & Abbas Norouzian Baghani[3]✉

The cost estimation and assessment of healthcare waste treatment systems (HCWTSs) for preventing financial and environmental damage are essential. This work reports economic analyses of treatment of hazardous–infectious waste based on WHO approach in $HCWTS_S$ of 43 hospitals in Tehran, Iran. The waste generation rate for total hospital waste in 43 $HCWTS_S$ was 4.42 ± 2.77 kg/active-bed/day. The mean of chemical, sharps, infectious, and general wastes in 43 $HCWTS_S$ were 13.79 ± 19.71, 30.29 ± 37.46, 336.28 ± 291.31, and 539.6 ± 383.13 kg/day, respectively. Economic analyses proved that general hospitals spent 1.63 times more than specialized hospitals on treating hazardous–infectious waste per year. The annual cost of treating each kilogram of hazardous healthcare waste in studied $HCWTS_S$ was 0.3 dollars. A range of total annual costs in 43 $HCWTS_S$ was limited to 7.9–118 thousand dollars. The results of ANOVA test demonstrated that the age and performance levels of hospitals significantly affect the annual capital and operating costs, respectively. Hence, improving recycling knowledge and increasing source-separated recycling should be considered to control the costs in $HCWTS_S$. The results of this work have implications for the hospital managers in especially developing countries to evaluate previously unknown economic analyses and policies and take action to control wasted costs in $HCWTS_S$.

Keywords Healthcare waste, Chemical treatment, Infectious waste, Waste management, Thermal treatment, Economic analyses

Abbreviations

ACC	The annualized capital cost
ACCs	The annualized capital costs
AOC	Annual operating cost
AOCs	Annual operating costs
ANOVA	Analysis of variance
F2F	Face-to-face
GTAC	Grand total annual cost
$GTAC_{kg}$	Grand total annual cost per kg HHCW that became treatment in 43 $HCWTS_S$ (dollars/kg)
HCF_S	Healthcare facilities
HCW	Healthcare waste
$HCWChTS_S$	Healthcare waste chemical treatment systems
HCWM	Healthcare waste management
HCWTS	Healthcare waste treatment system
$HCWTS_S$	Healthcare waste treatment systems
$HCWThTS_S$	Healthcare waste thermal treatment systems
$HHCW_{year}$	Amount of HHCW produced per year in 43 $HCWTS_S$ (kg/year)
HHCW	Hazardous healthcare wastes
n	Lifespan of the equipment (year)
OACC	Overall annualized capital cost

[1]Department of Environmental Health Engineering, School of Public Health, Tehran University of Medical Sciences, Tehran, Iran. [2]Center for Solid Waste Management (CSWM), Institute for Environmental Research (IER), Tehran University of Medical Sciences, Tehran, Iran. [3]Environmental Health Research Center, Lorestan University of Medical Sciences, Khorramabad, Iran. ✉email: rnabizadeh@gmail.com; rnabizadeh@tums.ac.ir; abbas.jj.norozi@gmail.com

OAOC	Overall annual operating cost
$OAOC_{kg}$	The overall annual operating cost per kilogram of HHCW that becomes treatment in 43 $HCWTS_S$
r	Discount rate (%)
SAF	Standard annualization factor
SI	Supplementary information
SMWHA	The safe management of waste from healthcare activities
TACC	Total annualized capital cost
$TACC_S$	Total annualized capital costs
TAC	Total annual cost
TAOC	Total annual operating cost
WHO	World Health Organization

Healthcare waste (HCW) generation worldwide has increased rapidly throughout recent years due to the prompt population, economic growth and appropriate medical service demand[1,2]. Healthcare facilities (HCF_S) waste is a collection of waste produced by healthcare establishments, research facilities, laboratories related to medical procedures, and home-based healthcare such as dialysis and insulin injection[3,4]. HCW, also called medical waste, can be categorized as nonhazardous (general) wastes and hazardous healthcare wastes (HHCW)[5]. Nonhazardous wastes can be originated mostly from the administrative, kitchen, and housekeeping functions at HCF_S and packaging waste[3,6–8]. Besides, HHCW includes sharps, infectious, chemical, radioactive, and pharmaceutical waste[9].

Infectious waste consists of materials containing pathogens such as bacteria, viruses, parasites, and fungi[10–12]. Adequate quantities of those microorganisms can cause disease in susceptible hosts[11,13,14]. Additionally, HHCW can create potential health and environmental risks for humans and the ecosystem[3,15]. Hence, it is necessary to establish safe and sustainable healthcare waste management (HCWM) to protect the environment from HHCW by the healthcare administrators[16]. It is important to mention that infectious waste treatment and HCWM are complicated processes with a wide variety of economic, environmental and technological factors to minimize social, environmental, and economic impacts on the environment and humans[17]. The management of HCW by applying those complex processes not only creates significant benefits for the environment and humans but also helps to save costs in the management system[18].

To prevail over the issues of HCW, the World Health Organization (WHO) developed the HCWM strategy entitled "the safe management of waste from healthcare activities (SMWHA)," which persuades the legislators to use new incinerators or non-incineration technologies in healthcare waste treatment systems ($HCWTS_S$)[3,19,20]. Besides, the effective $HCWTS_S$ can be selected on the specifications of HCW, the different types of technologies, environmental and safety aspects, and costs[3]. According to past works, several techniques for treating HHCW include autoclave, chemical treatment, hydroclave, and dry-heat[3,21]. Autoclave has applied steam at lower temperatures to destroy the pathogens, while in chemical treatment, organisms have inactivated by using disinfectants[3,21–23]. However, dry-heat technologies using conduction, convection, and thermal radiation apply higher temperatures and longer exposure times than steam-based technologies[3,24,25].

Using these treatment technologies entails spending costs on $HCWTS_S$[3,26]. According to the WHO, the cost of HCWM can be classified as capital costs, operating costs, and overhead costs[3]. The capital costs relate to one-time investments such as the cost of purchasing treatment sterilizers[27]. Those costs can be involved in the equipment costs in HCWTSs with an investment horizon for more than one year, such as plastic bins, wheeled carts, and large waste containers for disposing of waste[3,26]. In addition, the operating costs are recurrent costs incurred in HCWTSs[3]. Furthermore, the main operation and maintenance costs in HCWTSs include human resources (labour), consumable items (e.g., yellow bags), and water and electricity facilities[3,26,28]. Besides, overhead costs are extra costs that may be more difficult to quantify initially[3]. These overhead costs may include training employees and employees benefits such as health insurance and immunization of waste workers[3,27]. WHO reported that managers of HCF_S should consider the estimation and assessment of annual costs in HCWTSs for prevention the issues of financial and environmental damage, and even human death[3].

To date, few studies have focused on the effects of various factors on annual costs in the cost assessment of HCWTSs in developing countries, such as Iran, and scarce information is available regarding capital costs, operating costs, and overhead costs in HCWTSs. For example, Sepetis et al. have performed a study on recognizing and projecting the costs of HCWM in Greek public hospitals[29]. Accordingly, investigated variables in this study included the number of beds, hospital type, the existence of an intensive care unit, the number of internal patients, the days of stay, and the number of employees[29]. The result of the same study indicated that "significant differences were perceived in mean costs per bed, per patient, between the Greek health districts and mean quantities of waste generated in various types of hospitals"[29].

Moreover, it is necessary for the hospital managers, officials at the governmental level, and the Ministry of Health in worldwide especially in the developing countries to be inform of the treatment costs of HHCW in hospitals to sense what requires to be changed and performed to protect the environment, reduce operating costs of hospitals, and implement the necessary policies and action plan[29–31]. Hereinafter, the collection of accurate data and the conduct of relevant analyses are necessary to estimate the capital costs, operating costs, and overhead costs for each HCWTS, which requires the creation of coding for organizing and explanation of the data. Based on previous studies, "coding does not constitute the totality of data analysis, but it is a method to organize the data so that underlying messages portrayed by the data may become clearer to the researcher"[32–34].

Nonetheless, no studies have focused on applying the coding process of data related to cost assessment in HCWTSs. Hence, for the first time, this work has estimated the capital costs, operating costs, and overhead costs in HCWTSs and the effects of independent variables on those costs in HCWTSs by coding method. Therefore, so far, many studies have been conducted about healthcare waste management practices[35,36], evaluation or prioritization of the methods for the disposal and treatment of HCW[37–40], minimization of the treatment costs of HHCW[41–45], and investigation of the effect of the independent variables on the production of HCW and prediction of the management costs using operating costs[29], but this study attempts to regard the costs assessment in HCWTSs and the effects of independent variables (such as the age of the hospital, treatment method and etc.) on those costs in HCWTSs in developing countries such as Iran by coding method.

Hence, the present study aims to (1) fill out the questionnaires related to data collection in 43 HCWTSs of 43 hospitals in Tehran (Iran) and measure its reliability, (2) use the coding process for collecting data related to HCWTSs, (3) study the generation rate and composition of solid waste of 43 HCWTSs in Tehran, (4) compute total annualized capital costs ($TACC_S$), total annual operating costs ($TAOC_S$), total annual costs (TAC_S), overall annualized capital cost (OACC), overall annual operating cost (OAOC), and grand total annual cost (GTAC) in 43 HCWTSs in Tehran, and (5) investigate the effects of qualitative variables (such as infectious waste generation, the number of active beds and etc.) on those costs in 43 HCWTSs in Tehran.

Therefore, this study can inform the hospital managements/managers, officials at the governmental level, and the Ministry of Health in developed and developing countries how to divide the budget allocated for different parts of hospitals regarding waste management systems. Budget separation may lead to cost savings in the long term in providing services for such parts as the collection phase and treatment site in HCWTSs. Generally, the results of this work can be used by researchers and the hospital managers especially in the developing countries to evaluate previously unknown economic analyses and policies and take action to control wasted costs in HCWTSs.

Material and methods

This work included several steps: designing a questionnaire (data collection tool), selecting a study area, coding collected data, descriptive analysis, economic analyses, and statistical analysis. A diagram of the eight steps in this study is described in Fig. 1. In addition, the analyses of this work were performed by R software (version 3.3.1), Microsoft Excel® (version 2013), and the SPSS software version 22.0. It should be considered that all experimental protocols were ethically approved by the Research Ethics Committee (REC) of the Tehran University of Medical Sciences in accordance with the national and international ethical standards for biomedical research (with ethics approval ID IR.TUMS.SPH.REC.1395.1958). Informed consent was obtained from all subjects involved in the study.

Designing a questionnaire and measuring its validity

Data used in this work were collected based on WHO policy (SMWHA) [3] using a face-to-face (F2F) questionnaire as shown in Supplementary Table S1 online in Supplementary Information (SI). Informed consent was obtained from all subjects involved in the study. More detailed information in terms of designing a questionnaire and measuring its validity are provided in the supporting information (Section S1).

Selecting a study area and filling out the questionnaires

The treatment costs of HHCW are usually assessed in terms of the type of treatment technology, generated waste types, and treatment equipment capacity[3]. The treatment costs of HHCW are often evaluated based on the treatment technology type, waste types generated, and equipment capacity for treatment. This led to the study of cost estimation in 43 HCWTSs from 43 hospitals across various areas in Tehran (Iran). More detailed information in terms of filling out the questionnaires is provided in the supporting information (Section S2).

Coding of collected variables and data

In this section, each variable in every question of questionnaire was assigned a code to facilitate future analyses (Fig. 1). More detailed information in terms of coding of collected data is provided in the supporting information (Section S3).

Descriptive statistics

Production of different types of hospital wastes

As described in "Coding of collected variables and data" section, categorized codes and subcodes related to this part of questionnaire were applied to measure the waste generation rate of various generated waste in 43 HCWTSs. More detailed information is provided in the supporting information (Section S4).

Economic analyses

The economic analyses of this work included four steps in 43 HCWTSs: (1) computing of the annualized capital costs (ACCs), TACCs, and OACC, (2) doing some calculations of the annual operating costs (AOCs), TAOCs, OAOC, and $OAOC_{kg}$ (overall annual operating cost per kg HHCW which became treatment), (3) doing some analyses of total and overall costs, and (4) drawing a comparison of total costs between different levels (Fig. 1). A calculation diagram of economic analyses for these four steps in this study is described in Fig. 2. Before proceeding with these four steps, all cost-related subcodes in the Excel sheet were converted from Rials to Dollars. The conversion was computed by multiplying the amounts by 9712.5, using the annual average exchange rate from the Central Bank of the Islamic Republic of Iran.

ACC, TACC, and OACC

The first point is calculating annualized capital costs on the capital costs in HCWTSs [3]. According to Supplementary Table S2 online, the capital costs in HCWTSs included the costs in two sections of "onsite waste-treatment

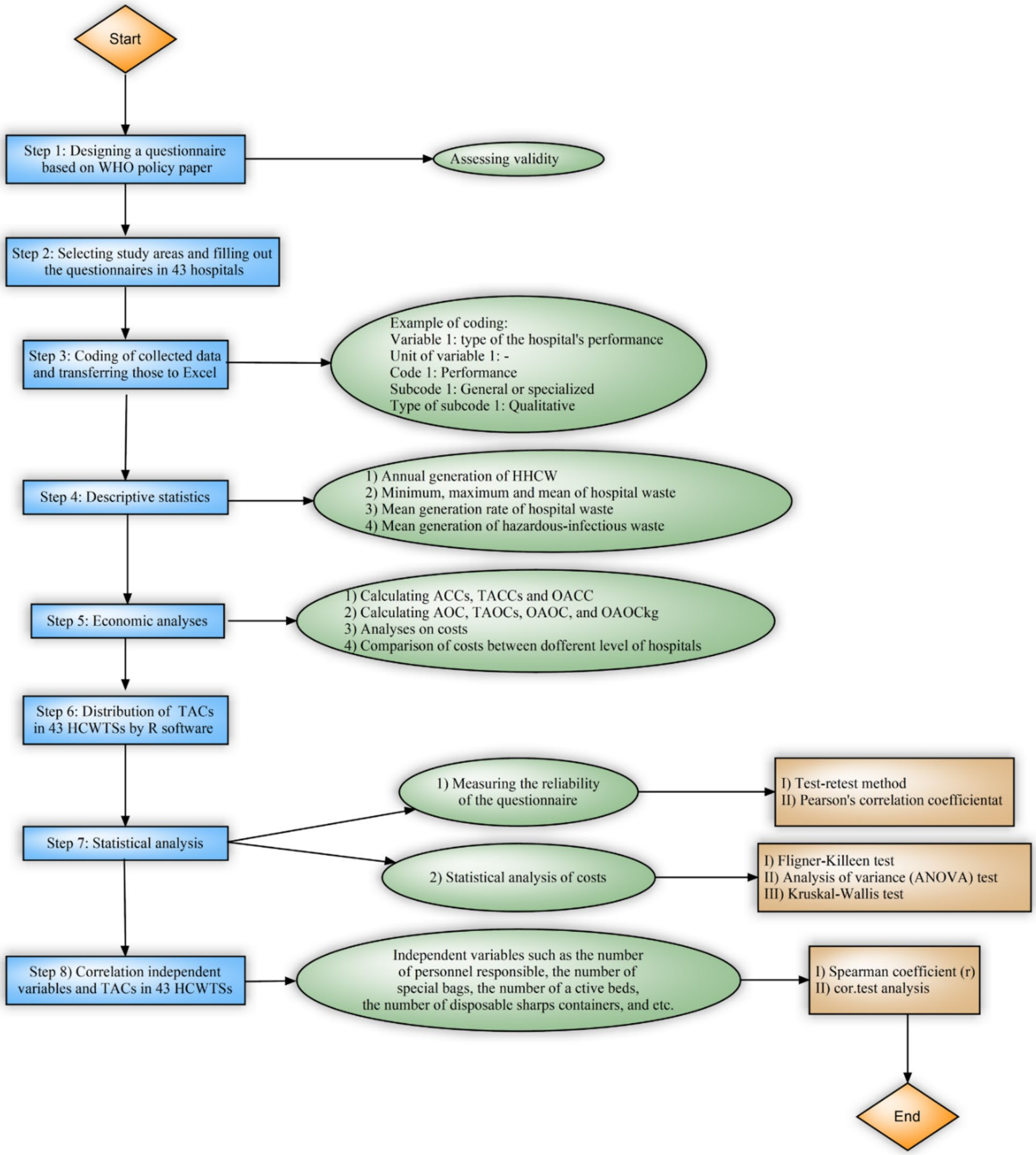

Figure 1. A diagram of eight steps in this study.

technology and related accessories" and "waste-management equipment with a life span of more than a year" with some subsections such as "wheeled carts", "onsite waste-treatment technology", and etc. Categorized codes and subcodes related to capital cost part (dollars), according to Supplementary Table S3 online, were applied for computing ACC (dollars). In this way, a capital cost of each intended subcode (Table S3) could be multiplied into a standard annualization factor (SAF) based on Eq. (1) [3] (Fig. 2):

$$ACC = CC \times SAF \quad (1)$$

SAF for each CC could be computed based on the estimated lifespan of the equipment (n (year)) and discount rate (r (%)) according to a year of purchase of the equipment, as shown in Eq. (2) [3] (Fig. 2):

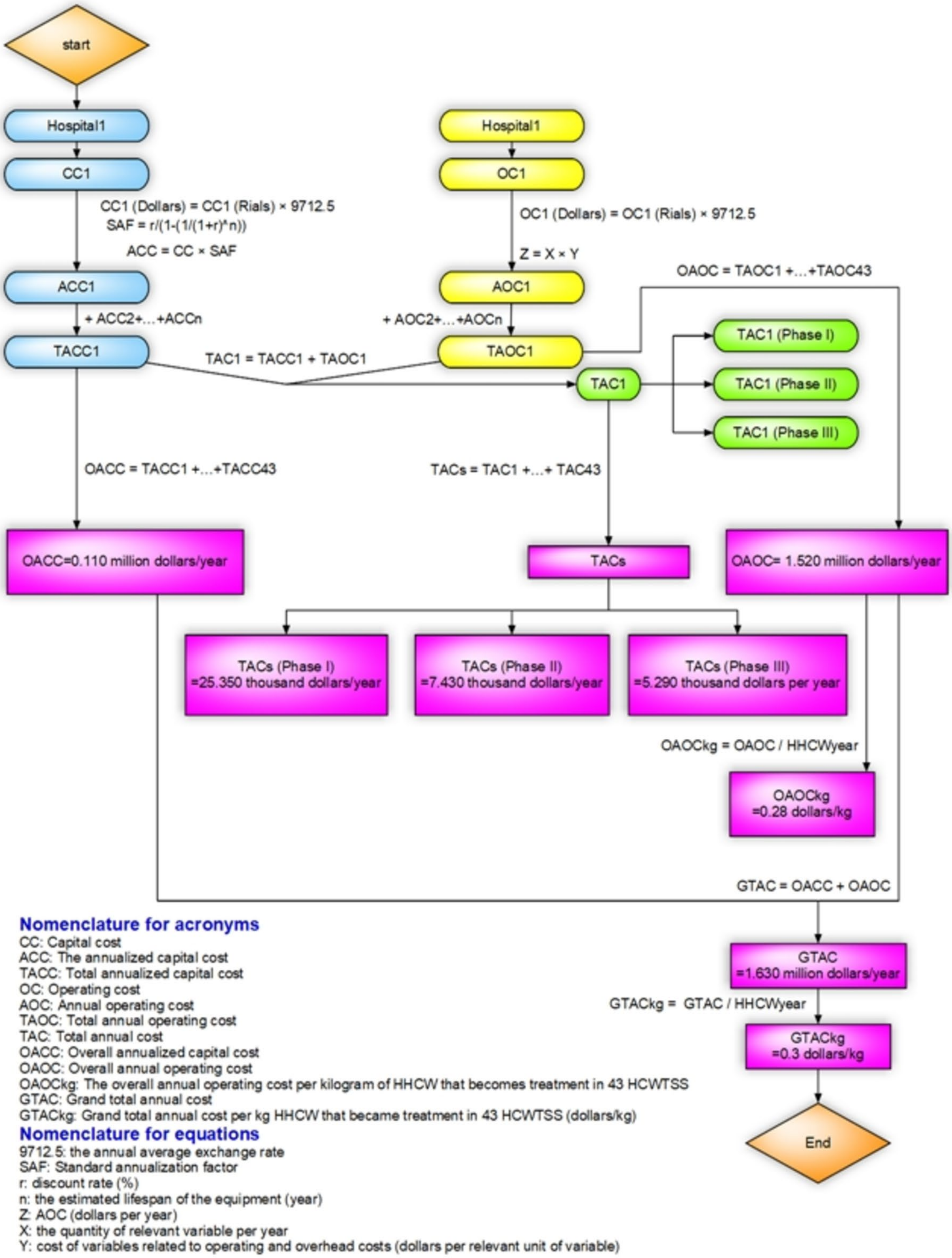

Figure 2. The calculations of economic analyses for four steps in 43 HCWTSs.

$$\text{SAF} = \frac{r}{1 - \left(\frac{1}{(1+r)^n}\right)} \tag{2}$$

According to types of equipment, "n" was obtained from the Direct Tax Law book[46]. More detailed information in terms of "n", "r", annualized capital costs, total annualized capital cost, and overall annualized capital cost for each HCWTS are provided in the supporting information (Section S5) and Fig. 2.

AOC, TAOC, OAOC, and OAOC$_{kg}$
At first, the calculation of the annual operating costs (AOCs) requires operating costs and overhead costs in HCWTSs [3]. According to Supplementary Table S2 online, the main operating costs in HCWTSs included four sections and subsections.

AOC (i.e., Z (dollars per year)) for each subsection of Supplementary Table S2 online can be computed by the quantity of consumption of variables related to operating and overhead costs indicated in Supplementary Table S4 online (i.e., X (the quantity of relevant variable per year)) and cost of variables related to operating and overhead costs (i.e., Y (dollars per relevant unit of variable)) as shown in Eq. (3) [3] (Fig. 2):

$$Z = X \times Y \tag{3}$$

More detailed information in terms of TAOC for each hospital and OAOC for all 43 hospitals are provided in the supporting information (Section S6) and Fig. 2.

In addition, according to Eq. (4), by dividing overall annual operating cost by the annual generation of HHCW for 43 HCWTS$_S$ (HHCW$_{year}$) (extracted from "Production of different types of hospital wastes" section), OAOC$_{kg}$ for 43 HCWTS$_S$ can be figured[3] (Fig. 2). OAOC$_{kg}$ was known as operating treatment fees for HHCW sent to 43 HCWTS$_S$[3].

$$\text{OAOC}_{\text{kg}} = \frac{OAOC}{HHCW_{year}} \tag{4}$$

where OAOC$_{kg}$ is OAOC per kg HHCW that became treatment in 43 HCWTS$_s$ (dollars/kg), OAOC is an overall annual operating cost in 43 HCWTS$_S$ (dollars/year), and HHCW$_{year}$ is the amount of HHCW produced per year in 43 HCWTS$_S$ (kg/year).

Analyses of total and overall costs in 43 HCWTS$_s$
At first, grand total annual cost was achieved for all 43 HCWTSs by adding OAOC and OACC (Fig. 2). Furthermore, according to Eq. (5), by dividing GTAC by HHCW$_{year}$ (extracted from section "Production of different types of hospital wastes" section), the annual cost per kilogram of HHCW that becomes treatment (GTAC$_{kg}$) in 43 HCWTS$_S$ can be figured[3] (Fig. 2). The GTAC$_{kg}$ was known as treatment fees for HHCW sent to 43 HCWTS$_S$[3].

$$\text{GTACkg} = \frac{GTAC}{HHCW_{year}} \tag{5}$$

where GTAC$_{kg}$ is the grand total annual cost per kg HHCW that became treatment in 43 HCWTS$_S$ (dollars/kg), GTAC is the grand total annual cost in 43 HCWTS$_S$ (dollars/year), and HHCW$_{year}$ is the amount of HHCW produced per year in 43 HCWTS$_S$ (kg/year).

Additionally, total annual cost for each HCWTS can be figured by adding TACC and TAOC from each HCWTS together (Fig. 2). The process was repeated for all 43 HCWTSs, resulting in a total annual cost for each HCWTS. Moreover, the means of TACC$_S$, TAOC$_S$, and total annual costs in general and specialized hospitals were individually acquired and contrasted.

Comparison of total costs between different levels in 43 HCWTSs
According to WHO, "all healthcare facilities need to establish accounting procedures to document the costs they incur in managing wastes"[3]. "Healthcare waste costs should be separate from budget lines in a healthcare facility's financial accounts. This allows costs over different years to be compared"[3]. Hence, we tried to separate total annual cost into 3 levels in HCWTS$_S$ for more cost comparison between different levels of HCWTS to help officials understand more about the budget allocation of waste management in HCWTS (Fig. 2). More detailed information in terms of comparison of total costs between different levels in 43 HCWTS$_S$ are provided in the supporting information (Section S7).

Distribution of total annual costs in 43 HCWTS$_S$
The distribution of TAC$_S$ in 43 HCWTS$_S$ was investigated by R software (version 3.3.1) to show that 95% of those costs (thousand dollars) are which range.

Statistical analysis
Measuring the reliability of the questionnaire
To assess the reliability of the research instrument, the test–retest method and Pearson's correlation coefficient (Pearson coefficient correlation (r)) were used. Data were analyzed using the SPSS software version 22.0 at a significance level of < 0.001. The result of the analysis is reported in the results and discussion part.

Statistical analysis of total costs in 43 HCWTS$_S$
For investigation of the effect of different variables on total costs in 43 HCWTS$_S$, three tests in R software (version 3.3.1) were applied, which included the Fligner-Killeen test, analysis of variance (ANOVA) test, and the Kruskal–Wallis test (Fig. 1). Before using ANOVA, the Fligner-Killeen test for homogeneity of variance was applied. If the *p*-value obtained from the Fligner-Killeen test exceeded 0.05, the ANOVA was performed for further analysis. But, if the *p*-value was less than 0.05, the Kruskal–Wallis test was applied for further analysis. More detailed information in terms of statistical analysis of total costs in 43 HCWTS$_S$ are provided in the supporting information (Section S8).

Correlation of independent variables and TAC_S in 43 $HCWTS_S$

Cor.test analysis in the R software evaluated the association between independent variables and total annual costs. This association was studied in two systems: (i) healthcare waste thermal treatment systems ($HCWThTS_S$) and (ii) healthcare waste chemical treatment systems ($HCWChTS_S$) separately. Those various variables are described in Supplementary Table S9 online. This should be noted that all defined variables were joint parameters for both systems ($HCWThTS_S$ and $HCWChTS_S$), except variable "the amount of disinfectant used in chemical treatment methods", defined only for $HCWChTS_S$. More detailed information in terms of correlation of independent variables and total annual costs in 43 $HCWTS_S$ are provided in the supporting information (Section S9).

Ethical approval

The study design was approved by the Research Ethics Committee (REC) of the Tehran University of Medical Sciences in accordance with the national and international ethical standards for biomedical research (Approval Code: (IR.TUMS.SPH.REC.1395.1958; Approval Date:13.03.2017).

Informed consent

Informed consent was obtained from all subjects involved in the study.

Results and discussion

Validity of questionnaire

The qualitative content validity of this questionnaire was reported as good based on opinions from the group of specialists.

Descriptive statistics

Generation rate and composition of hospital solid waste

The mean (± SD) of different types of generated waste in 43 $HCWTS_S$ in Tehran (Iran), including chemical, sharps, infectious, and general wastes, is shown in Table 1**.** Accordingly, the mean (± SD) of chemical, sharps, infectious, and general wastes were measured at 13.79 (± 19.71 kg/day), 30.29 (± 37.46 kg/day), 336.28 (± 291.31 kg/day), and 539.6 (± 383.13 kg/day), respectively. As shown in the Fig. 3 and according to the mean generation of different types of hospital waste, the total amount of generated waste by 43 $HCWTS_S$ included 58.65% general waste, 36.55% infectious waste, 3.29% sharps waste, and 1.5% chemical waste.

Comparison of the results of hazardous–infectious waste (infectious and sharps wastes) proportions in the current and other related studies is described in Fig. 4. According to Fig. 4, the proportions of hazardous–infectious waste (infectious and sharps wastes) in our work (39.84%) is practically consistent with other studies conducted in Iran and other developing countries[47,48]. For instance, in 837 hospitals in 31 provinces of Iran[48], 16 hospitals in Rasht (Iran)[49], 8 hospitals in Egypt[50], 17 hospitals and clinics in Bangladesh[51], and 5 public healthcare facilities in Adama, Ethiopia[47] found that approximately 37, 38, 39, 36, and 35% of generated waste was potentially hazardous. However, hazardous–infectious waste reported in the USA[52] and France[53] were 15 and 15–20% of HCW, respectively (Fig. 4). The position and value of implementing source-separated waste for HCWTSs are due to the amount and proportion of hazardous–infectious waste in the entire medical waste stream[54,55]. Hence, this high percentage of hazardous waste in cities of developing countries like Tehran (39.84%) may be due to improper segregation or lack of segregation in HCWTSs[47,50].

The mean (± SD) rate of different types of generated wastes in 43 $HCWTS_S$ in Tehran (Iran) is reported in Table 1. The mean total hospital waste generation rate (general, infectious, sharps, and chemical wastes) in this work was 4.42 ± 2.77 kg/active-bed/day, which is consistent with past works in different cities of Iran[48,56] such as in hospitals of Qazvin in 2017 (4.2 kg/active-bed/day)[48], in 15 hospitals of Fars province in 2004 (4.45 kg/active-bed/day)[56], in one hospital in Tehran in 2015 (4.2 kg/active-bed/day)[57], and in 5 hospitals in Tehran in 2018 (4.72 kg/active- bed/day)[58]. According to those results reported, it can be seen that the amount of total hospital waste generation rate in Iran has not changed noticeably[56,58]. It is widely accepted that, the total amount

Descriptive statistics	General	Infectious	Sharps	Chemical
Different types of hospital wastes (kg/day)				
Minimum	15	0.001	0.50	0.02
Maximum	1400	1000	150	100
Mean	539.6	336.28	30.29	13.79
Standard Deviation	383.13	291.31	37.46	19.71
Generation of hospital waste	**General**	**Infectious**	**Sharps**	**Chemical**
Annual generation of hospital waste (Million kg/year)				
Annual generation	8.469	4.909	0.42	0.21
Facilities	**General**	**Infectious**	**Sharps**	**Chemical**
	kg/active-bed/day			
Mean generation rate of various generated hospital wastes				
Total hospitals	2.65 ± 1.51	1.58 ± 1.05	0.13 ± 0.12	0.06 ± 0.09

Table 1. Mean (± SD) of different types of generated wastes in 43 HCWTSs in Tehran (Iran).

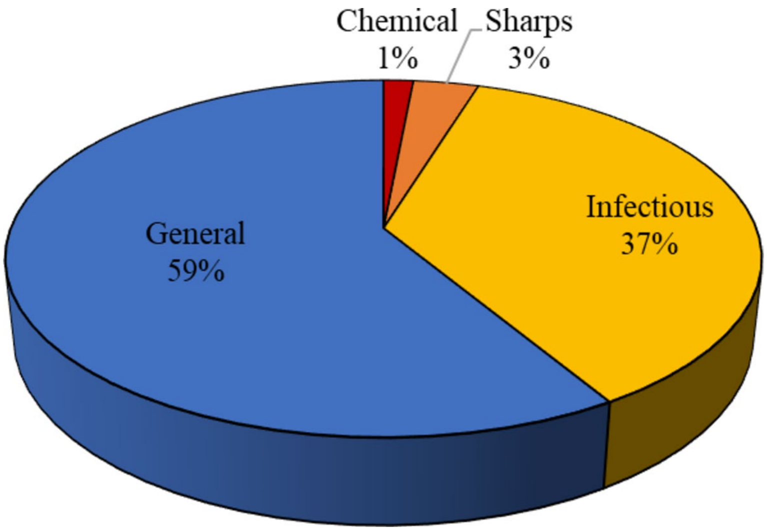

Figure 3. The composition of the medical waste in 43 HCWTSs in Tehran, Iran.

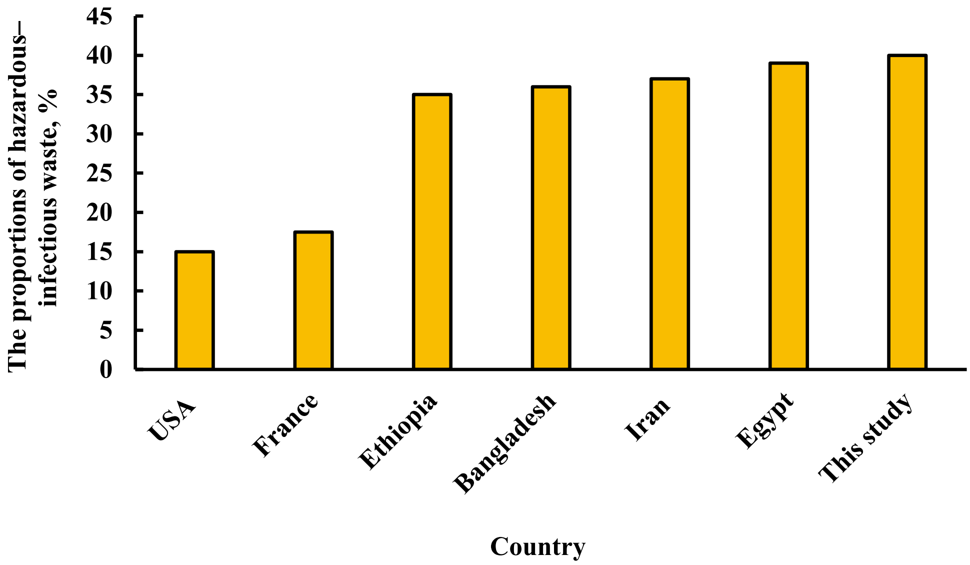

Figure 4. The proportions of hazardous–infectious waste (infectious and sharps wastes) in 43 HCWTSs in Tehran, Iran in comparison with the other studies.

of generated waste in hospitals is related to the choice of waste management strategies, the adoption of consistent plans for the segregation of medical waste, the existence of a plan to minimize HCW in the hospitals, and the cultural status of persons (employees and patients)[48,56,59]. Hence, it can be said that in the last few years, the government managers in developing countries such as Iran not only have been surprisingly unable to adopt and implement a policy to achieve less hospital waste production[56,58,60] but they have been affected by increases in the quantity of the generation of hospital waste[61]. This is probably due to a lack of knowledge and carelessness by hospital workers and patient's companions[62]. Additionally, considering the very low generation rate of chemical waste (0.06 kg/active-bed/day) and total infectious and sharps wastes (1.71 kg/active-bed/day) compared to total hospital waste generation rate (4.42 kg/active-bed/day), it can be said that this difference was probably due to the improper segregation of infectious waste[48]. In addition, based on results of this work, the average generation of hazardous–infectious waste (infectious and sharps waste) in general hospitals (1.72 kg/act-bed/day) were higher than in specialized hospitals (1.54 kg/act-bed/day). More detailed information in terms of medical waste generation rate is provided in the supporting information (Section S10).

Analyses on costs in HCWTS$_S$: TACC$_S$, TAOC$_S$, TAC$_S$, OACC, OAOC, and GTAC

Analysis of overall annualized capital cost, overall annual operating cost, and grand total annual cost in 43 HCWTSs in Tehran is shown in Table 2. As shown in Table 2, OAOC and GTAC were assessed at to be about 1.52

Performance of hospitals	Descriptive statistics	TACCS	TAOCS	TACS
Analyses on costs (thousand dollars/year) in 43 HCWTSS in different performance levels of hospitals				
General hospitals	Average	2.89	39.79	42.68
Specialized hospitals	Average	1.89	24.30	26.20
Facilities	**Descriptive statistics**	**OACC**	**OAOC**	**GTAC**
Analyses on costs (million dollars/year) in 43 HCWTSS in Tehran				
43 HCWTSS	Sum	0.11	1.52	1.63
Descriptive statistics	**Phase I: Collection of HHCW from various wards and transport to the treatment site**	**Phase II: Treatment site**	**Phase III: Sterilizer**	
Comparison of total annual costs (thousand dollars/year) for various phases in 43 HCWTSS in Tehran				
Minimum	3.71	1.29	0.97	
Maximum	83.01	38.93	14.61	
Mean	25.35	7.43	5.29	

Table 2. Analyses on costs in 43 $HCWTS_S$, in the general and specialized hospitals, and comparison of total annual costs for various phases in 43 $HCWTS_S$ in Tehran.

and 1.63 million dollars per year in 43 hospitals, respectively. It is clear that OAOC accounts for 93.2% of GTAC (1.52 million dollars per year vs. 1.63 million dollars per year). Similarly, in the study of Brayal Carry D'Souza et al. at three hospitals in India, it was found that about 80% of the expenses were spent on operating costs[63].

Furthermore, the average of total annualized capital costs, total annual operating costs, and total annual costs in general and specialized hospitals is shown in Table 2. According to Table 2, the average of total annual costs with a value of 42.68 thousand dollars per year in general hospitals was more when compared to specialized hospitals with a value of 26.20 thousand dollars per year. The average total annual costs for managing HHCW treatment is 1.63 times lower in specialized hospitals than in general hospitals. Since the existence of a significant difference in the generation of infectious waste for these two types of hospitals was confirmed by Eslami et al. in 2017, perhaps this difference in annual costs between different types of hospitals can be attributed to the difference in the generation of infectious waste in specialized hospitals compared to general hospitals[48]. Because probably specialized hospitals with less infectious waste generation have less need for bags and safety boxes to collect the produced waste and transfer those to the treatment site. In addition, in the treatment site, the sterilizer is used less during the day and has less depreciation. As a result, the cost spent on repairing sterilizers is less. Hence, the less generation of infectious waste in specialized hospitals can probably cause lower operating costs in HCWTSs by affecting other parameters. In addition, operating costs cover 93.2% of the total costs; hence, total annual costs can be decreased in a specialized hospital by reducing TAOCs.

As shown in Table 2, GTAC for 43 HCWTSs was 1.63 million dollars per year. Besides, according to Table 1, the amount of annual generation of HHCW (i.e., infectious (4.909 million kg per year) and sharps waste (0.42 million kg per year)) was 5.329 million kg per year in 43 HCWTSs. According to Eq. (5), by dividing GTAC by the amount of annual HHCW, the treatment fee for HHCW was sent to 43 $HCWTS_S$ was copmuted, and it was 0.3 dollars per kg HHCW. Various studies conducted during different years are presented in Supplementary Table S10 online. For comparison, $GTAC_{kg}$ based on dollars per kg in high-temperature facilities was about 0.73 dollars per kg HHCW in England[64]. This quantity is approximately 2.5 times higher than the results obtained by this study (0.3 dollars per kg HHCW that became treatment). Besides, $GTAC_{kg}$ in the incineration-microwaving treatment method was 1.72 dollars per kg HHCW for hospitals in Massachussets, USA[65]. A 1.7 dollars per kg HHCW is 5.7 times higher than the results obtained by this study (0.3 dollars per kg HHCW that became treatment). The treatment process in the two mentioned studies was the waste incineration[64,65]. In contrast, steam treatment technologies (i.e., autoclave and hydroclave), dry-heat, and chemical technologies were researched in the present work. The literature study showed that the cost of treatment per unit weight of infectious waste in incinerators is higher than alternative technologies (i.e., autoclave, hydroclave, or chemical)[66,67]. Hence, these differences in results are probably related to the researched treatment methods.

The $GTAC_{kg}$ in microwave treatment method was 0.16 dollars per kg HCW for hospitals in Massachussets, USA[65]. A 0.16 dollars per kg HCW is about 1.87 times less than our study (0.3 dollars per kg HHCW that became treatment). For comparison, the treatment cost per unit weight of infectious waste in the microwave is lower than in autoclave and chemical technologies[68,69]. For example, the annual operating costs for autoclave, chemical technology, and microwave was 0.23, 0.32, and 0.13 dollars per kg HHCW[68]. In addition, previous work such as Soares et al. has taken a systematic approach to analyze the costs (the periodic payment, the cost of operations, and the cost of HCW transport and landfilling) for three disinfection techniques (i.e., microwave, autoclave, and lime) for HHCW treatment in hospitals[69]. Accordingly, the cost analyses for the waste treated with microwaves and autoclaves were 0.12 dollars per kg HCW and 1.10 dollars per kg HCW, respectively[69]. These differences in results are probably related to the difference in the studied treatment methods[65,69].

Nevertheless, $GTAC_{kg}$ obtained from past works in treatment sites with the shredder (0.4 dollars per kg biomedical waste)[27] and from several treatment processes of special HCW in different countries such as Denmark (0.27 dollars per kg HCW)[70], United Kingdom (0.35 dollars per kg HCW)[70] and France (0.32 dollars per kg HCW)[70] is approximately consistent with the results of present study having $GTAC_{kg}$ 0.3 dollars per kg HHCW. The former study reported that the $GTAC_{kg}$ for alternative treatments in England was 0.394 dollars per kg HCW, which is consistent with the results of this study (0.3 dollars per kg HHCW)[64].

As shown in Table 2, overall annual operating cost for 43 hospitals was 1.52 million dollars per year. Besides, according to Table 1, the amount of annual generation of HHCW (i.e., infectious (4.909 million kg per year) and sharps waste (0.42 million kg per year)) was 5.329 million kg per year in 43 HCWTSs. According to Eq. (4), by dividing OAOC by the amount of annual HCW, $OAOC_{kg}$ was assessed, and it was 0.28 dollars per kg HHCW. For comparison, $OAOC_{kg}$ in waste-treatment facilities with 6 to 210 tonnes capacities for biomedical waste in Maine (U.S. state) was about 0.1 dollars per kg HCW[27]. However, the operating cost for our work is 0.28 dollars per kg HCW, which is 2.8 times more than waste-treatment facilities in Maine (U.S. state)[27].

In addition, the mean, maximum and minimum total annual costs for three phases in 43 HCWTSs are described in Table 2. Accordingly, the mean of total annual costs, in 43 HCWTSs, in phase I (collection), phase II (treatment site), and phase III (sterilizer) were 25.35, 7.43, and 5.29 thousand dollars per year, respectively. Thus, the highest and the lowest total annual costs were related to phase I (collection) and phase III (sterilizer) with a percentage of 66.5% (25.35 thousand dollars per year vs. 38.07 thousand dollars per year (phase I + II + III)) and 13.9% (5.29 thousand dollars per year vs. 38.07 thousand dollars per year (phase I + II + III)), respectively. Therefore, phase I was the most effective phase in cost generation, with a share of about 70% of total annual costs in 43 $HCWTS_S$.

It can be noted that the main route for controlling the annual costs for each of the three phases is the cost-generating variables. Therefore, the cost-generating variables in phase I (due to the higher portion) can be considered to control the cost in 43 HCWTSs. As mentioned before, Supplementary Table S7 online shows the cost-generating variables in various phases. By investigating the variables defined in different phases, it can be concluded that the variables of phases II and III were used a limited number of times or did not change in price during the year. In other words, maybe the hospital only spent money once or twice a year to buy them. In addition, despite being used monthly, maybe these variables only faced an increase in price once a year (with a certain percentage). Among these variables, it can mention the wage and benefit paid to the sterilizer's operator, the cost of repairs, and the efficacy tests of the sterilizer.

Besides, variables of phase I were mostly purchased monthly or even weekly. It should be noted that, sometimes, the cost of purchasing variables of phase I were changed monthly due to Iran's economic situation and the inflation rate. Among these variables, it can mention infectious plastic bags, sharps containers, and PPE for personnel. Hence, may be attributed the effectiveness of phase I in producing the annual cost to the existence of variables that must be supplied in the near time intervals. It can be stated that the only solution to control and reduce those costs in the short term is to buy bulk consumables in large quantities for several months instead of monthly purchases in smaller quantities. The main reason for this proposal is that the inflation rate and economic conditions in developing countries like Iran are constantly changing.

In addition, with bulk purchasing, the possibility of bargaining and getting more discounts from the seller increases[63]. Finally, there is a possibility that this action will lead to cost reduction in HCWTSs.

Distribution of total annual costs in 43 $HCWTS_S$

The distribution of total annual costs for 43 $HCWTS_S$ in Tehran is shown in Fig. 5. Accordingly, 95% of total annual costs in 43 $HCWTS_S$ was limited to 7.9–118 thousand dollars. As shown in Fig. 5, total annual costs followed the exponential distribution. total annual costs include all the operating and capital expenses spent on treating hazardous–infectious waste in those $HCWTS_S$ so that the efforts of managers and those involved in hospital waste management can lead to safe infectious waste from the sterilizer. Hence, about total annual costs, the efforts of managers and those involved in hospital waste management can lead to safe infectious waste from the sterilizer.

Statistical analysis

Reliability of the questionnaire

Pearson coefficient correlation (r) between test and re-test was 0.70 (p-value < 0.001). According to the category provided in the study of Konjengbam et al., if r (Pearson coefficient correlation) is between 0.7 and 0.8, reliability is acceptable[71]. Hence, based on this work's results, our questionnaire's reliability was acceptable.

Statistical analysis of $TACC_S$, $TAOC_S$, and TAC_S in 43 hospitals

Statistical analysis of $TACC_S$ in 43 hospitals with various age. The output of the Fligner-Killeen test was that the p-value for total annualized capital costs for different ages of hospitals (Table S8) exceeded 0.05. This shows that the difference between hospital age variances was insignificant ($p > 0.05$). Hence, a parametric ANOVA test was applied to study the differences between $TACC_S$ for different ages of hospitals. The results of the ANOVA test in Supplementary Table S11 online revealed that the p-value for $TACC_S$ was less than 0.05, demonstrating a significant difference in the amount of $TACC_S$ between hospitals of various ages.

In addition, the boxplot of the distribution of $TACC_S$ (thousand dollars) in 43 hospitals with different ages in Tehran (Iran) is shown in Fig. 6a. According to Fig. 3a, the distribution of $TACC_S$ in hospitals with code 4 (30–40 years old) was different from other hospitals with various codes. In addition, the mean $TACC_S$ in hospitals with code 4 (8.2 thousand dollars) was higher than the mean $TACC_S$ for other hospitals (i.e., codes 3, 6, 7, and 9 (about 1–2 thousand dollars) and hospitals with codes 1, 2, 5, and 8 (2–3 thousand dollars)). Hence, based on the results of this work and field observation, the hospitals with code 4 compared to other hospitals (i.e., codes 1, 2, 3, 5, 6, 7, 8, and 9) used no-Iranian sterilizers. Consequently, the hospitals with code 4 spent more money purchasing sterilizers because non-Iranian sterilizers were much more expensive than Iranian sterilizers. In addition, the hospitals with code 4 used to cool the air, eliminating odor and controlling the temperature. Hence, using those devices in hospitals with code 4 can be extensively affected $TACC_S$ compared with other hospitals.

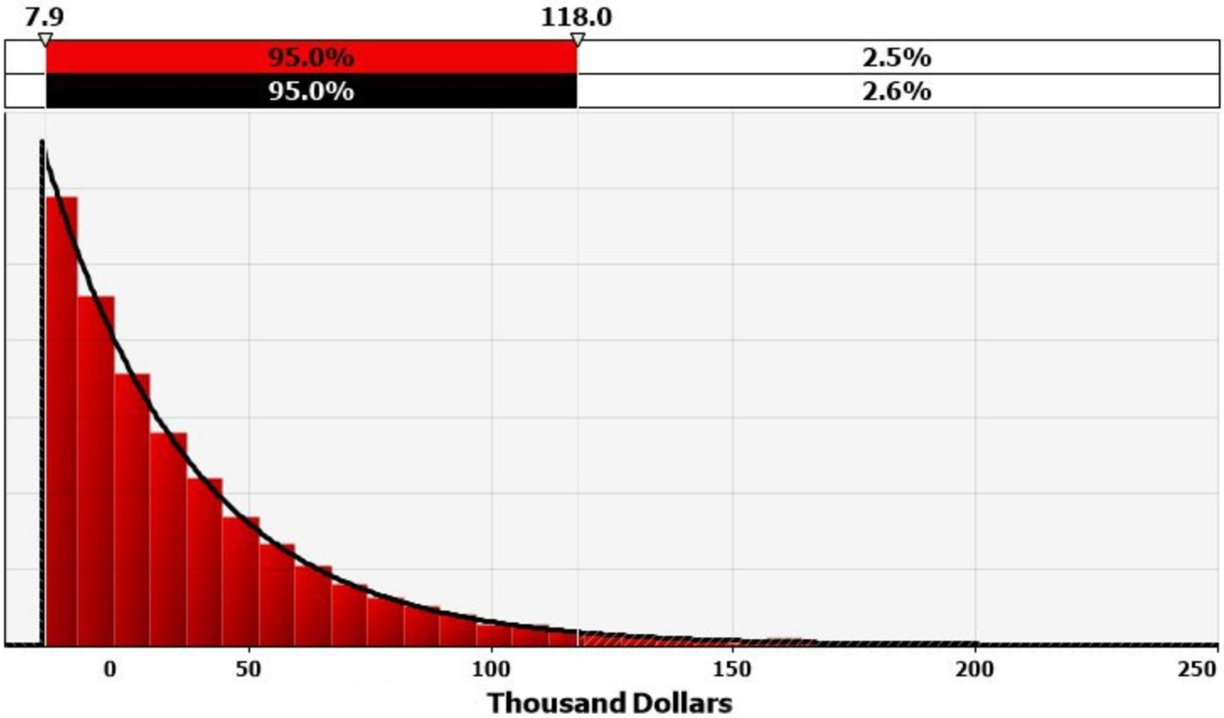

Figure 5. The distribution pattern of total annual costs in 43 $HCWTS_S$ in Tehran (Iran).

Generally, using no-Iranian sterilizers and many cooling appliances for eliminating odor and controlling the temperature can increase hospitals' $TACC_s$.

Statistical analysis of $TAOC_S$ in 43 hospitals with different performances. The Fligner-Killeen test output showed that the *p*-value for total annual operating costs in different performance levels of 43 hospitals (general and specialized) exceeded 0.05. This indicated that the variances in different performances of 43 hospitals were insignificant (p-value > 0.05). Hence, a parametric ANOVA test was applied to study the differences between $TAOC_S$ in different performances of 43 hospitals. The results of the ANOVA test in Supplementary Table S11 online revealed that the *p*-value for $TAOC_S$ was less than 0.05, demonstrating a significant difference in the amount of $TAOC_S$ in different performance levels of 43 hospitals.

In addition, the boxplot of the distribution of $TAOC_S$ (thousand dollars) in 43 hospitals with different performance levels (general and specialized) in Tehran (Iran) is shown in Fig. 6b. According to Fig. 6b, the mean $TAOC_S$ for general hospitals was about 30 dollars in thousands. In contrast, $TAOC_S$ for specialized hospitals was about 12 thousand dollars. Besides, the mean $TAOC_S$ for general hospitals was 2.5 times higher than the mean $TAOC_S$ for specialized hospitals. The main reason for this difference in $TAOC_S$ in various performance levels in hospitals (general and specialized) may be attributed to a significant difference in generating infectious waste, which aligns with the findings of past work[48]. In addition, based on the results of this work, the average generation of hazardous–infectious waste (infectious and sharps waste) in general hospitals (1.72 kg/act-bed/day) was higher than in specialized hospitals (1.54 kg/act-bed/day). Generally, it can be concluded that more HHCW production in general hospitals led to increasing operating costs of HCWTSs for treating infectious waste. Thus, governments and hospital managers can control the operating costs of HCWTSs via HHCW generation and management in hospitals, especially in general hospitals, which aligns with the results of the former works[48].

Statistical analysis of total annual costs in 43 hospitals with different performances. The Fligner-Killeen test output indicated that the *p*-value for total annual costs in different performances of 43 hospitals (general and specialized) exceeded 0.05. This showed that the variances in different performances of 43 hospitals were insignificant (p-value > 0.05). Hence, a parametric ANOVA test was applied to study the differences between total annual costs in different performance levels of 43 hospitals. The results of the ANOVA test in Supplementary Table S11 online revealed that the *p*-value for total annual costs was less than 0.05, demonstrating a significant difference in the amount of total annual costs in different performance levels of 43 hospitals.

In addition, a boxplot of the distribution of total annual costs (thousand dollars) in 43 hospitals with different performances (general and specialized) is provided in Fig. 6c. According to Fig. 6c, the mean total annual costs for general hospitals was about 32 thousand dollars. In contrast, total annual costs for specialized hospitals was about 12 thousand dollars. Besides, the mean total annual costs for general hospitals was 2.6 times higher than that for specialized hospitals to manage HHCW treatment. The main reason for this difference in total annual costs in various performances of hospitals (general and specialized) may be attributed to a significant difference in generating infectious waste, which aligns with the findings of past work[48]. Furthermore, the mean total annual

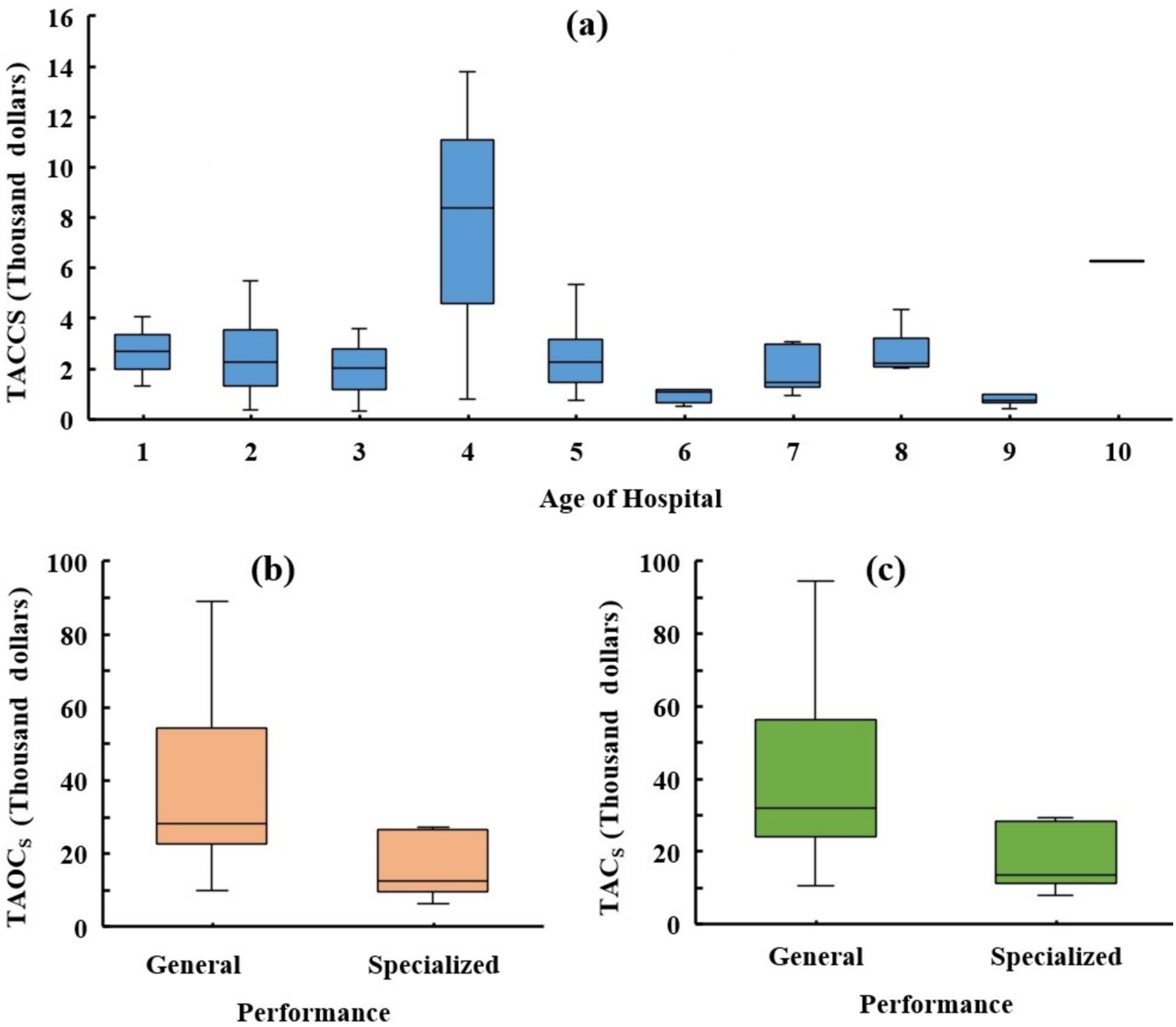

Figure 6. Boxplots of $TACC_S$ distribution in 43 hospitals with different ages (**a**), $TAOC_S$ for 43 hospitals with different performances (**b**), and TAC_S for 43 hospitals with different performances (**c**) in Tehran (Iran).

costs for managing HHCW treatment is 2.6 times higher than in general hospitals compared with specialized hospitals. Generally, it can be concluded that more HHCW production in general hospitals led to increasing operating costs in HCWTSs for treating HHCW.

Statistical analysis of the cost of energy consumption per bed in 43 hospitals. The Fligner-Killeen test output indicated that the *p*-value for the annual energy consumption cost for different types of thermal technologies (i.e., autoclave, hydroclave, and dry-heat) exceeded 0.05. This showed that the difference between the variances in different the cost of annual energy consumption for different types of thermal technologies (i.e., autoclave, hydroclave, and dry-heat) were not significant (p-value > 0.05). Hence, a parametric ANOVA test was used for further analysis (Supplementary Table S11 online). The results of the ANOVA test in Supplementary Table S11 online revealed that the *p*-value for the cost of annual energy consumption of thermal sterilizers per active bed in different types of thermal technologies was less than 0.05, which demonstrates a significant difference in the cost of annual energy consumption for different types of thermal technologies in hospitals that use these technologies for HHCW treatment.

In addition, based on Supplementary Fig. S1 online, the annual energy consumption cost for autoclave, hydroclave, and dry-heat technologies were about 0.2, 0.6, and 2.5 dollars per active bed, respectively. As shown in Supplementary Fig. S1 online, the lowest cost of those technologies is related to autoclaves. The use of steam at lower temperatures in autoclave and hydroclave and steam recycling technology in hydroclave can decrease energy consumption per active bed compared to dry-heat technologies[3,22,23]. However, dry-heat technologies apply higher temperatures and longer exposure times than steam-based technologies[3,24,25]. Dry-heat technologies are not usually applied in large-scale facilities and generally treat only small volumes [3]. Hence, dry-heat processes can increase the energy consumption cost per active bed compared with autoclave and hydroclave technologies[3].

Relationships between independent variables and total annual costs in 43 HCWTSs

The relationship between total annual costs and various independent variables in healthcare waste thermal treatment systems ($HCWThTS_S$) of hospitals in Tehran (Iran) is shown in Supplementary Table S12 online. Accordingly, cor.test analysis showed between total annual costs and the number of personnel responsible (p-value < 0.05, r = 0.7), total annual costs and the number of personnel (p-value < 0.05, r = 0.6), total annual costs and infectious waste generation (p-value < 0.05, r = 0.6), total annual costs and the number of the sterilizer's cycles per year (p-value < 0.05, r = 0.6) in $HCWThTS_S$. A significantly positive correlation was perceived between total annual costs and the number of personnel (p-value < 0.05, r = 0.6) and total annual costs and the infectious waste generation (p-value < 0.05, r = 0.6). It can be concluded that increasing infectious waste generation increased the number of personnel. In addition, increasing the infectious waste generation can increase the number of sterilizer cycles per year. Consequently, the increasing infectious waste generation and the number of personnel can subsequently impact total annual costs.

Besides, the relationship between total annual costs and various independent variables in (HCWChTSs) of hospitals in Tehran (Iran) is shown in Supplementary Table S12 online. Accordingly, Supplementary Table S12 online depicted that a significant correlation was acquired between total annual costs and the number of special bags (p-value < 0.05, r = 0.8968), total annual costs and the number of active beds (p-value < 0.05, r = 0.8851), total annual costs and the number of disposable sharps containers (p-value < 0.05, r = 0.8232), total annual costs and the number of the sterilizer's cycles per year (p-value < 0.05, r = 0.8085), total annual costs and infectious waste generation (p-value < 0.05, r = 0.7834), total annual costs and the number of personnel responsible (p-value < 0.05, r = 0.7661), total annual costs and the amount of water consumed from the sterilizer and cooling appliance (p-value < 0.05, r = 0.7115), total annual costs and the number of personnel (p-value < 0.05, r = 0.6894), and total annual costs and the number of reusable hard plastic or metal bins (p-value < 0.05, r = 0.6655) in healthcare waste chemical treatment systems ($HCWChTS_S$). According to Supplementary Table S12 online, it can be concluded that increasing the number of active beds increased the amount of HHCW. Consequently, increasing the amount of HHCW required a greater number of special bags for treatment of HHCW in the sterilizers as well as the number of personnel. Hence, the number of active beds and special bags can extensively affect the total annual costs in hospitals' $HCWChTS_S$ in Tehran, Iran.

Conclusion

For the first time, this work reports an estimation of economic analyses of 43 HCWTSs of 43 hospitals, in Tehran, Iran, including (1) doing some calculations of ACC, TACC, and OACC, (2) the computing of AOC, TAOC, OAOC, and $OAOC_{kg}$, (3) doing some analyses of total and overall costs in 43 HCWTSs, and (4) drawing a of total costs between different levels in 43 HCWTSs. The procedure of this study was performed according to WHO approach in 2022. The results indicate that the average (± SD) of chemical, sharps, infectious, and general wastes in 43 HCWTSs were 13.79 (± 19.71 kg/day), 30.29 (± 37.46 kg/day), 336.28 (± 291.31 kg/day), and 539.6 (± 383.13 kg/day), respectively. The waste generation rate for total hospital wastes in 43 hospitals was 4.42 ± 2.77 kg/active-bed/day, which includes 2.65 kg/active-bed/day for general waste and 1.71 kg/active-bed/day for hazardous–infectious waste (infectious and sharps wastes). In addition, economic analyses showed that general hospitals spent 1.63 times more than specialized hospitals on treating HHCW per year. OAOC) and GTAC were about 1.52 and 1.63 million dollars per year in 43 HCWTSs, respectively. It is clear that OAOC accounts for 93.2% of GTAC (1.52 million dollars per year vs. 1.63 million dollars per year). Furthermore, less production of HHCW in hospitals, especially specialized hospitals, may probably create lower operating costs in HCWTSs by affecting other parameters. Based on the results, operating costs spent 93.2% of the total costs of healthcare waste management; hence, total annual costs can be decreased in a specialized hospital by reducing TAOCs. The average total annual costs in collection, treatment, and sterilizer phases in 43 hospitals were 25.35, 7.43, and 5.29 thousand dollars per year, respectively. Based on the results, the collection phase was the most effective in cost generation, with a share of about 70% (66.5%) of total annual costs in 43 HCWTSs of 43 hospitals. Based on the cor-test analysis, a significant correlation was observed between total annual costs and quantitative variables such as the number of personnel responsible, number of personnel, infectious waste generation, and number of the sterilizer's cycles per year in both $HCWThTS_S$ and $HCWChTS_S$ (p-value < 0.05). The results of the ANOVA test demonstrated that the age and performance levels of hospitals significantly affect the annual capital and operating costs, respectively. Economic analyses showed that general hospitals consume 1.63 times more than specialized hospitals for the treatment of HHCW annually. Hence, it can be concluded that more HHCW production in general hospitals led to increasing operating costs in HCWTSs of those hospitals for the treatment of HHCW. Thus, governments and hospital managers can control the operating costs of HCWTSs via HHCW generation and management in hospitals, especially in general hospitals. Finally, using local sterilizers and a low number of cooling appliances to eliminate odor and control the temperature can decrease hospitals' $TACC_S$.

The results of this work have implications for the hospital managers to evaluate previously unknown economic analyses and policies and take action to control wasted costs in HCWTSs of hospitals. In addition, the results of this work can motivate researchers to perform further studies in the field of various modeling to improve and reduce hospital waste management costs. This study highlights the importance of alleviating the cost of treatment in healthcare waste management.

Data availability

The data generated and/or analyzed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Received: 21 March 2024; Accepted: 12 August 2024
Published online: 18 September 2024

References

1. Kenny, C. & Priyadarshini, A. *Healthcare.* 284 (MDPI).
2. Dihan, M. R. *et al.* Healthcare waste in Bangladesh: Current status, the impact of Covid-19 and sustainable management with life cycle and circular economy framework. *Sci. Total Environ.* **871**, 162083. https://doi.org/10.1016/j.scitotenv.2023.162083 (2023).
3. Chartier, Y. *Safe management of wastes from health-care activities*. (World Health Organization, 2014).
4. Rafiee, A. *et al.* Assessment and selection of the best treatment alternative for infectious waste by modified sustainability assessment of technologies methodology. *J. Environ. Health Sci. Eng.* **14**, 1–14 (2016).
5. Derso, S. *et al.* Biomedical waste disposal systems of health facilities in Ethiopia. *Environ. Health Eng. Manag. J.* **5**, 29–37 (2018).
6. Patil, A. D. & Shekdar, A. V. Health-care waste management in India. *J. Environ. Manag.* **63**, 211–220 (2001).
7. Norouzian Baghani, A. *et al.* Economic aspects of dry solid waste recycling in Shiraz, Iran. *J. Mazandaran Univ. Med. Sci.* **25**, 330–334 (2016).
8. Norouzian Baghani, A., Dehghani, S., Farzadkia, M., Delikhoon, M. & Emamjomeh, M. Comparative study of municipal solid waste generation and composition in Shiraz city. *J. Inflamm. Dis.* **21**, 65–57 (2017).
9. WHO, WHO Safe management of wastes from health-care activities: A summary. (World Health Organization, 2017).
10. Acharya, A., Gokhale, V. A. & Joshi, D. Impact of biomedical waste on city environment: Case study of Pune, India. *J. Appl. Chem.* **6**, 21–27 (2014).
11. Chandra, V. *et al.* Environmental Biotechnology for Medical Waste Management: A Review of Current Practices and Future Directions. (2023).
12. Delikhoon, M., Guzman, M. I., Nabizadeh, R. & Norouzian Baghani, A. Modes of transmission of severe acute respiratory syndrome-coronavirus-2 (SARS-CoV-2) and factors influencing on the airborne transmission: A review. *Int. J. Environ. Res. Public Health* **18**, 395 (2021).
13. Baghani, A. N. *et al.* Pollution characteristics and noncarcinogenic risk assessment of fungal bioaerosol in different processing units of waste paper and cardboard recycling factory. *Toxin Rev.* **40**, 752–763 (2021).
14. Baghani, A. N. *et al.* Characteristics and assessing biological risks of airborne bacteria in waste sorting plant. *Ecotoxicol. Environ. Saf.* **232**, 113272. https://doi.org/10.1016/j.ecoenv.2022.113272 (2022).
15. Ghali, H. *et al.* Health and environmental impact of hospital wastes: Systematic review. *Dubai Med. J.* **6**, 67–80 (2023).
16. Puška, A., Stević, Ž & Pamučar, D. Evaluation and selection of healthcare waste incinerators using extended sustainability criteria and multi-criteria analysis methods. *Environ. Dev. Sustain.* **24**, 11195–11225 (2022).
17. Chen, X., Lin, J., Li, X. & Ma, Z. A novel framework for selecting sustainable healthcare waste treatment technologies under Z-number environment. *J. Oper. Res. Soc.* **72**, 2032–2045 (2021).
18. Alharbi, N. S., Alhaji, J. H. & Qattan, M. Y. Toward sustainable environmental management of healthcare waste: A holistic perspective. *Sustainability* **13**, 5280 (2021).
19. Makan, A. & Fadili, A. Sustainability assessment of healthcare waste treatment systems using surrogate weights and PROMETHEE method. *Waste Manag. Res.* **39**, 73–82 (2021).
20. Tilahun, D., Donacho, D. O., Zewdie, A., Kera, A. M. & Haile, G. Healthcare waste management practice and its predictors among health workers in private health facilities in Ilu Aba Bor Zone, Oromia region, South West Ethiopia: A community-based cross-sectional study. *BMJ Open* **13**, e067752 (2023).
21. Geetha, S., Narayanamoorthy, S., Kang, D. & Kureethara, J. V. A novel assessment of healthcare waste disposal methods: Intuitionistic hesitant fuzzy MULTIMOORA decision making approach. *IEEE Access* **7**, 130283–130299 (2019).
22. Zhao, W., van der Voet, E., Huppes, G. & Zhang, Y. Comparative life cycle assessments of incineration and non-incineration treatments for medical waste. *Int. J. Life Cycle Assess.* **14**, 114–121 (2009).
23. Lan, X. *et al.* Autoclave foaming and steam-chest molding of polypropylene/polybutene-1 blend bead foams and their crystallization and mechanical properties. *J. Cell. Plast.* **59**, 29. https://doi.org/10.1177/0021955X221150863 (2023).
24. Vidhyalakshmi, R. & Meera, M. Dry heat and ultrasonication treatment of pearl millet flour: effect on thermal, structural, and in-vitro digestibility properties of starch. *J. Food Meas. Charact.* **17**, 1–11 (2023).
25. Bento, C. S., Gaspar, M. C., Coimbra, P., de Sousa, H. C. & Braga, M. E. A review of conventional and emerging technologies for hydrogels sterilization. *Int. J. Pharm.* **634**, 122671 (2023).
26. Rashidian, A., Alinia, C. & Majdzadeh, R. Cost-effectiveness analysis of health care waste treatment facilities in Iran hospitals; a provider perspective. *Iran. J. Public Health* **44**, 352 (2015).
27. Files, A. C., Allen, T. G. & Criner, G. K. TB184: Least-Cost Options for the Collection, Treatment, and Disposal of Biomedical Waste in Maine. (2002).
28. Ökten, H. E., Corum, A. & Demir, H. H. A. comparative economic analysis for medical waste treatment options. *Environ. Prot. Eng.* https://doi.org/10.37190/epe150310 (2015).
29. Sepetis, A., Zaza, P. N., Rizos, F. & Bagos, P. G. Identifying and predicting healthcare waste management costs for an optimal sustainable management system: Evidence from the Greek Public Sector. *Int. J. Environ. Res. Public Health* **19**, 9821 (2022).
30. Authority, I. H. P. (Independent Hospital Pricing Authority (IHPA), 2014).
31. Newbrander, W. & Lewis, E. Hospital costing model manual. *Management Sciences for Health. USAID: Health Reform and Financing and Sustainability Project* (1999).
32. Charmaz, K. *Constructing grounded theory: A practical guide through qualitative analysis* (Sage Publications, 2006).
33. Theron, P. M. Coding and data analysis during qualitative empirical research in Practical Theology. *In die Skriflig* **49**, 1–9 (2015).
34. Karen, S. & Joanne, D. Qualitative data analysis. In *Practical researcher and evaluation: A start-to finish guide for practitioners* (eds Dahlberg, L. & McCaig, C.) (Sage Publications, 2010).
35. Ferreira, V. & Teixeira, M. R. Healthcare waste management practices and risk perceptions: Findings from hospitals in the Algarve region, Portugal. *Waste Manag.* **30**, 2657–2663 (2010).
36. Wassie, B., Gintamo, B., Mekuria, Z. N. & Gizaw, Z. Healthcare waste management practices and associated factors in private clinics in Addis Ababa, Ethiopia. *Environ. Health Insights* **16**, 11786302211073384 (2022).
37. Dursun, M., Karsak, E. E. & Karadayi, M. A. Assessment of health-care waste treatment alternatives using fuzzy multi-criteria decision making approaches. *Resour. Conserv. Recycl.* **57**, 98–107 (2011).
38. Dursun, M., Karsak, E. E. & Karadayi, M. A. A fuzzy multi-criteria group decision making framework for evaluating health-care waste disposal alternatives. *Expert Syst. Appl.* **38**, 11453–11462 (2011).
39. Mishra, A. R., Mardani, A., Rani, P. & Zavadskas, E. K. A novel EDAS approach on intuitionistic fuzzy set for assessment of healthcare waste disposal technology using new parametric divergence measures. *J. Clean. Prod.* **272**, 122807 (2020).
40. Liu, P., Rani, P. & Mishra, A. R. A novel Pythagorean fuzzy combined compromise solution framework for the assessment of medical waste treatment technology. *J. Clean. Prod.* **292**, 126047 (2021).
41. Kargar, S., Pourmehdi, M. & Paydar, M. M. Reverse logistics network design for medical waste management in the epidemic outbreak of the novel coronavirus (COVID-19). *Sci. Total Environ.* **746**, 141183 (2020).

42. Mantzaras, G. & Voudrias, E. A. An optimization model for collection, haul, transfer, treatment and disposal of infectious medical waste: Application to a Greek region. *Waste Manag.* **69**, 518–534 (2017).
43. Hu, T.-L., Sheu, J.-B. & Huang, K.-H. A reverse logistics cost minimization model for the treatment of hazardous wastes. *Transp. Res. Part E Logist. Transp. Rev.* **38**, 457–473 (2002).
44. Mei, X., Hao, H., Sun, Y., Wang, X. & Zhou, Y. Optimization of medical waste recycling network considering disposal capacity bottlenecks under a novel coronavirus pneumonia outbreak. *Environ. Sci. Pollut. Res.* **29**, 1–19 (2021).
45. Torkayesh, A. E., Vandchali, H. R. & Tirkolaee, E. B. Multi-objective optimization for healthcare waste management network design with sustainability perspective. *Sustainability* **13**, 8279 (2021).
46. Mansour, J. *Direct Tax Law*. (Visit Publication, 2008).
47. Hayleeyesus, S. F. & Cherinete, W. Healthcare waste generation and management in public healthcare facilities in Adama, Ethiopia. *J. Health Pollut.* **6**, 64–73 (2016).
48. Eslami, A., Nowrouz, P. & Sheikholeslami, S. Status and challenges of medical waste management in hospitals of Iran. *Civ. Eng. J.* **3**, 741–748 (2017).
49. Shakiba, M. & Mohagheghian, A. Hospital waste generation and management status in Rasht, north of Iran. *Casp. J. Health Res.* **3**, 20–23 (2018).
50. Abd El-Salam, M. M. Hospital waste management in El-Beheira governorate, Egypt. *J. Environ. Manag.* **91**, 618–629 (2010).
51. Sarkar, S., Haque, M. A. & Khan, T. A. Hospital waste management in Sylhet city. *ARPN J. Eng. Appl. Sci.* **1**, 32–40 (2006).
52. Asante, B., Yanful, E. & Yaokumah, B. Healthcare waste management; its impact: A case study of the Greater Accra Region, Ghana. *Int. J. Sci. Technol. Res.* https://doi.org/10.2139/ssrn.2410909 (2014).
53. Mbarki, A., Kabbachi, B., Ezaidi, A. & Benssaou, M. Medical waste management: A case study of the souss-massa-draa region, Morocco. (2013).
54. Taghipour, H. & Mosaferi, M. Characterization of medical waste from hospitals in Tabriz, Iran. *Sci. Total Environ.* **407**, 1527–1535 (2009).
55. Farzadkia, M. *et al.* Municipal solid waste recycling: Impacts on energy savings and air pollution. *J. Air Waste Manag. Assoc.* **71**, 737–753 (2021).
56. Askarian, M., Vakili, M. & Kabir, G. Results of a hospital waste survey in private hospitals in Fars province, Iran. *Waste Manag.* **24**, 347–352 (2004).
57. Bayat, N. *et al.* A Survey on the status of hospital waste management using Individualized rapid assessment tool unique (I-RAT). *J. Res. Environ. Health* **1**, 217–227 (2015).
58. Farzadkia, M., Akbari, H., Gholami, H. & Darabi, A. Management of hospital waste: A case study in Tehran, Iran. *Health Scope* https://doi.org/10.5812/jhealthscope.61412 (2018).
59. Sanida, G. *et al.* Assessing generated quantities of infectious medical wastes: A case study for a health region administration in Central Macedonia, Greece. *Waste Manag.* **30**, 532–538 (2010).
60. Bayat, N. *et al.* A Survey on the status of hospital waste management using rapid assessment tool unique (I-RAT). *J. Res. Environ. Health* **1**, 217–227 (2015).
61. Eleyan, D., Al-Khatib, I. A. & Garfield, J. System dynamics model for hospital waste characterization and generation in developing countries. *Waste Manag. Res.* **31**, 986–995 (2013).
62. Hatam, N., Askarian, M. & Mohammadi, M. Survey of the results of solid waste management quality gradation template in hospital of Shahid Faghihi in Shiraz during 2005. *J. Health Manag. Res.* **26**, 26–31 (2006).
63. D'Souza, B. C., Seetharam, A. M., Chandrasekaran, V. & Kamath, R. Comparative analysis of cost of biomedical waste management across varying bed strengths in rural India. *Int. J. Healthc. Manag.* **11**, 38–43 (2018).
64. Tudor, T. L., Townend, W. K., Cheeseman, C. R. & Edgar, J. E. An overview of arisings and large-scale treatment technologies for healthcare waste in the United Kingdom. *Waste Manag. Res.* **27**, 374–383 (2009).
65. Lee, B.-K., Ellenbecker, M. J. & Moure-Ersaso, R. Alternatives for treatment and disposal cost reduction of regulated medical wastes. *Waste Manag.* **24**, 143–151 (2004).
66. Karagiannidis, A., Papageorgiou, A., Perkoulidis, G., Sanida, G. & Samaras, P. A multi-criteria assessment of scenarios on thermal processing of infectious hospital wastes: A case study for Central Macedonia. *Waste Manag.* **30**, 251–262 (2010).
67. Diaz, L. & Savage, G. Risks and costs associated with the management of infectious wastes. *WHO/WPRO, Manila, Philippines*, 1–69 (2003).
68. Emmanuel, J. Compendium of technologies for treatment/destruction of healthcare waste. *Osaka, UNEP DTIE* **225** (2012).
69. Soares, S. R., Finotti, A. R., da Silva, V. P. & Alvarenga, R. A. Applications of life cycle assessment and cost analysis in health care waste management. *Waste Manag.* **33**, 175–183 (2013).
70. Johannessen, L. *et al. Healthcare waste management guidance note*. (World Bank, Health Population and Nutrition Team, 2000).
71. Konjengbam, H., Kapoor, A. K. & Meitei, S. Y. Test and Retest in Anthropological Research. (2022).

Acknowledgements
Acknowledgments The present study was adapted from the master's thesis of Sahar Sharifi at Tehran University of Medical Sciences. All experimental protocols were ethically approved by the Research Ethics Committee (REC) of the Tehran University of Medical Sciences in accordance with the national and international ethical standards for biomedical research (with ethics approval ID IR.TUMS.SPH.REC.1395.1958). The authors gratefully acknowledge the support given by all relevant personnel of all 43 hospitals in Tehran for dedicating time to filling out the questionnaires and authorities of the Tehran University of Medical Sciences. Informed consent was obtained from all subjects involved in the study. Data availability The data generated and/or analyzed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request. Ethical approval The study design was approved by the Research Ethics Committee (REC) of the Tehran University of Medical Sciences in accordance with the national and international ethical standards for biomedical research (Approval Code: (IR.TUMS.SPH.REC.1395.1958; Approval Date:13.03.2017). Informed consent Informed consent was obtained from all subjects involved in the study.

Author contributions
Conceptualization, R.N., K.Y., and S. Sh.; methodology, R.N., K.Y., and S. Sh.; Writing—Original Draft Preparation, S. Sh. A.N.B., and R.N.; Writing—Review and Editing, S. Sh., A.N.B., R.N., and S.G. Visualization, S. Sh.; Software, R.N., A.N.B., S. Sh., and S.G.; Supervision, R.N.; Project Administration, R.N.; Formal analysis R.N., S. Sh., K.Y., and S.G. All authors have read and agreed to the published version of the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-024-69940-0.

Correspondence and requests for materials should be addressed to R.N. or A.N.B.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.