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Hospital waste management before and during COVID-19 pandemic: An analysis of the environmental impact of CO_2 emissions in four Italian facilities

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ABSTRACT
The COVID-19 pandemic caused a surge in hospital waste (HW), posing an urgent public and environmental health challenge. Although a safe HW disposal method, high temperature incineration of fossil-derived materials contributes to air pollution. We analysed the monthly and yearly HW production of four Italian hospitals between 2016 and 2021, including COVID-19-related waste, to quantify the volume of activity related to COVID-19 patients, and estimate the environmental impact of HW through carbon emissions and social cost of carbon (SCC). A Mann-Kendall trend test and an Interrupted Time Series Analysis to detect trends and level changes in HW production after the COVID-19 outbreak were performed. ISMETT had the highest HW production (average annual variation (AAV) 0.89 kg/bed/day) and a positive correlation between HW generated per patient-day and the proportion of COVID-19-related bed-days. IFO (AAV 0.23 kg/bed/day) and IEO (AAV 0.19 kg/bed/day) both showed an overall increasing trend in HW production; CRH behaved similarly, although reporting the lowest HW production. ISMETT and IFO had the highest SCCs; CRH's SCC slightly decreased in the pandemic biennium, IEO's SCC peaked in 2019 and declined in 2020–2021. Optimizing waste management is vital, as disposal emissions pose significant risks to environmental sustainability and human health.

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COVID-19 pandemic; hospital waste; waste management; carbon emissions; trend analyses; environmental sustainability

1. Introduction

The World Health Organization (WHO) defines, as 'healthcare waste' (or medical waste), 'any waste or by-products from hospitals and health care facilities for humans and animals used for diagnosis, treatment, or immunisation, e.g. used syringes, needles, metal sharps, dressings, blood samples, body parts, pharmaceutical, chemical, radioactive materials, and devices' [1]. Particularly, 'hazardous healthcare waste' covers a wide range of categories, including sharps, infectious waste, pathological waste, pharmaceutical and cytotoxic waste, chemical waste, and radioactive waste. Infectious waste is recognized among the groups that poses major health risks [2], defined as any infected or potentially infected material resulting from health care (i.e. waste contaminated by bodily fluids, lab cultures of infectious agents, waste from infected or potentially infected patients) [3] which requires careful handling, management, and disposal. The exposure to such hazardous waste can lead to disease (i.e. cross-contamination, infection, and relative health consequences) or injury (i.e. sharps, used syringes), both for health care professionals, patients, the staff deputed to collection and disposal, and the general public [2]. Therefore, managing healthcare waste produced by hospitals poses many challenges, especially when tackling infectious materials. All staff should be aware and trained to safely dispose infectious waste, through mandatory courses and updates; indeed, lack of qualified human resources, insufficient awareness towards the risks and overall neglect regarding waste disposal issues are further obstacles to overcome [4], especially in developing countries, in which healthcare waste management problems issues are more prominent, due to difficulties in access, inequity and having to invest allocate scarce resources in other, short-term urgencies [5–7]. This demonstrates the wide diffusion of the hitherto-

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defined problem, that it is a widespread issue, constituting a serious threat to global health [8], and to the environment as well. In fact, the healthcare sector, due to many sophisticated and energy-intensive technological advancements occurred in the last decades, plus a notably increase of medical treatments provided, produces significantly large quantities of infectious waste, which needs to be treated properly to prevent damage from it and disposed through high-energy procedures (e.g. incineration, sanitary landfill, high-temperature steam sterilization, chemical disinfection, microwave sterilization, plasma, pyrolysis, and others) [9,10]. Incineration, in particular, leads to the emission of a variety of pollutants, from particulate matter (PM), to heavy metals (e.g. arsenic, cadmium, copper, nickel, chromium, lead, etc.), to acid gasses (e.g. sulphur, nitrogen, and hydrogen compounds), to organic compounds, to carbon monoxide (CO) and dioxide (CO_2) [1], whose toxicity and detrimental impacts on human health and the environment have been widely studied [11,12]. In particular, a study from 2023 has found that incinerators emit more greenhouse gas emissions per unit of electricity produced (1707g CO_2e/kWh) than any other power source (range: 2.4 – to 991.1 g CO_2e/kWh) [13]. Although the healthcare waste production trend was found to be increasing before the COVID-19 pandemic, mainly due to inappropriate management policies [14,15], it has significantly contributed to the increasing healthcare waste production trend. According to a systematic review from published in 2022 [16], the daily production of healthcare waste (i.e. 'face masks' and 'medical waste') in Asia during year 2020 was of approximately 16,649.48 tonnes [17]; in Wuhan, China, where the pandemic outbreak took place, healthcare waste increased dramatically from 40 and 50 tons/day before the outbreak to about 247 tons on 1 March 2020 [18]. Although the reliability of these calculations largely depends on the accuracy of COVID-19 cases statistics and the availability of data [19], which is further impaired by the differences in waste nomenclatures and coding systems across countries, the sudden surge of demand and usage of personal protective equipment (PPE), plus increased infectious waste, has exacerbated the pre-existing criticalities in healthcare waste management policies [20]. Even though low to middle income countries have been more severely affected by this issue, due to poorer administrations [5,21,22], existing policies and preparedness plans have been heavily challenged worldwide by the increase of COVID-19 patients and the equipment needed to treat them, different quantities and composition of healthcare waste, postponed collection and recycling, the risk of infection spread from the waste, and weak administration control on waste management policy implementation [10,23]. High temperature incineration is traditionally deemed to be the safest disposal technique for infectious waste [24], and response practices have been modified according to the novelty of SARS-CoV-2 virus both for treatment and disposal (e.g. decontamination of infectious waste bags with chlorine-based disinfectants before placing them into containers, appropriate labeling, double-layer packaging, handling limited to specifically-trained staff and with appropriate equipment and vehicles) [25,26]. Nonetheless, emissions and other forms of pollutants from incineration are to be carefully monitored and principles of 'green governance principles' for secondary care facilities [27], for the sake of long-term economic, social, and environmental sustainability, should be followed [28]. In order to strive for waste and emissions reduction, through intelligent and practical developments, more research is needed to assess the impact of COVID-19 on healthcare waste production, and, consequently, society and the environment; to date, few recent studies have been conducted and based on Italian regions [29,30], but not on taking into account hospitals located in different Italian macro areas (i.e. North, Center, South), historically characterized by gaps and inequalities in healthcare access and services [31].

Since 2005, the European Union Emissions Trading System (ETS), a type of carbon pricing meant to compel manufacturers, airlines, and power companies to meet their emission targets by creating a market of supply and demand for emissions units, was launched to make emitters buy permits to cover each ton of CO_2 they emit. Carbon pricing is considered to be a tool to hold accountable industries for their contribution to air pollution and incentivize the internalization of the external costs of greenhouse gasses emission [32]; apart from the ETS, the other main type of taxation on carbon emissions is called Carbon Tax, of which Sweden has the most enduring history in Europe, and also the highest tax rate (118 EUR as of 2022 [33]). In Italy, instead, the Carbon Tax was first introduced by law number 448 of December 23, 1998, but was never made effective.

In light of the considerations made regarding the importance of infectious waste, especially after the pandemic, we collected from four Italian hospitals between 2016 and 2021, henceforth referred to as 'hospital waste' (HW), corresponding to the European Waste Catalogue (EWC) code 18.03.01 that comprises 'waste to be collected and disposed by applying special precautions to avoid infection'. Thus, the aim of this study is to assess the trend in HW production of four Italian hospitals during six years, including the COVID-19 outbreak, and analysing the pandemic impact regarding the amount of HW waste produced, the environmental impact in terms of CO_2 emissions after incineration, and the Social Cost of Carbon (SCC) trend.

2. Materials and methods

2.1 Study setting and data collection

Three Scientific Institutes for Research, Hospitalization and Healthcare (IRCSS), namely the Istituto Mediterraneo per i Trapianti e Terapie ad Alta Specializzazione (ISMETT) [34], the Istituto Europeo di Oncologia (IEO) [35] and the Istituti Fisioterapici Ospitalieri (IFO) [36], and an accredited private hospital facility, Cristo Re Hospital (CRH) [37] were considered. Detailed characteristics of the facilities and a summary of their COVID-19 management policy are available in the Supplementary materials (S1).

The data retrieval on HW generation was performed retrospectively by the Clinical Management Staff (CMS) and to their respective Facility Management. Monthly data were collected between January 2016 and December 2021 in three hospitals (ISMETT, IEO, IFO), whereas in CRH only annual data were available for the same period. To classify the HW collected, we assessed both the classification and sources proposed by the WHO [3] and theEWC, the list of classification codes that, according to Directive 75/442/EEC, reflect the production process at its origin, and allows the identification of the most appropriate ways to transport, treat and dispose waste pertaining to each category. The HW code taken into account was the 'hazardous waste' EWC 18.01.03, defined as 'waste to be collected and disposed by applying special precautions to avoid infection' [38], as it comprised COVID-19 related waste and for its ease of collection by the four facilities involved.

Pooled data concerned the net weight of HW generated by the whole facility, including every ward and department. The total number of hospitalization days were extracted by the Accounting and Management Department of the facilities. The length of stay related to the activation of COVID-19 beds during the pandemic emergency, requested by the Italian National Health System (NHS), was acquired as well. All data were collected anonymously, in conformity with the European regulatory framework for data protection and privacy (Regulation EC/2016/679).

2.2 Outcomes

The primary outcomes identified for the analyses were the amounts of HW generated each month by the hospital and their relative amount per patient-day. The volume of activity related to the hospitalization of COVID-19 patients was quantified through the percentage of hospitalization days due to positive patients out of the total. The environmental impact of the HW generated before and during the COVID-19 pandemic was estimated in terms of CO_2 emissions per kilogram of HW incinerated.

2.3 Statistical analysis

The average daily weight of HW per occupied bed and its average yearly variation were calculated. A Mann-Kendall trend test to detect yearly monotonic trends was adopted to analyse CRH data. Correlation between the amounts of HW generated (in relation to occupied bed-days) and the fraction of bed-days that could be ascribed to COVID-19 was tested through Pearson's correlation coefficient. An Interrupted Time Series Analysis (ITSA) was performed to detect trends and level changes in monthly HW production after the COVID-19 outbreak. The standard ITSA regression model assumes the following equation (Equation 1):

$$Y_t = \beta_0 + \beta_1 T_t + \beta_2 X_t + \beta_3 X_t T_t + \varepsilon_t. \qquad (1)$$

[39–42]. As for the terms, Y_t is the aggregated outcome variable measured at each equally spaced time point t, T_t is the time since the start of the study, X_t is a dummy (indicator) variable representing the intervention/event which may have caused the change in the trend of the outcome, and X_tT_t is an interaction term. Here, β_0 represents the intercept or starting level of the outcome variable. β_1 is the slope or trajectory of the outcome variable until the introduction of the intervention. β_2 represents the change in the level of the outcome that occurs in the period immediately following the introduction of the intervention (compared with the counterfactual). β_3 represents the difference between pre-COVID-19 and post-COVID-19 slopes of the outcome. Thus, we look for significant *p*-values in β_2 to indicate an immediate treatment effect, or in β_3 to indicate a treatment effect over time [40].

Different ITSA methods are available in the scientific literature [43]: we adopted ordinary least squares regression (OLS) with Newey-West standard errors (NW), which yield OLS estimates of the model regression parameters, but with standard errors that are adjusted for autocorrelation [44]. For this purpose, we made use of the ITSA function available with the Stata 14 software [45]. The significance level was set at $\alpha = 0.05$.

To calculate the CO_2 emissions generated by each facility before and during the pandemic, the annual tons of HW produced per hospital were converted into CO_2 equivalent ('CO_2-eq'), generated by incineration with high-temperature disposal (1074 kg CO_2-eq per tonne of waste [46]), the most frequently used disposal method in Italy.

The SCC is a quantitative measure that represents the cost of producing additional quantity (known as 'marginal cost'), at any point in time, of one CO_2-eq ton. This includes impacts on human health, in terms of amount of damage done, the cost to remedy it, and the environment's well-being [47], i.e. keeping the global average surface temperature below the 1.5 °

C limit [48]. The CO_2-eq is a measurement used to evaluate the emissions of different greenhouse gasses based on their impact on global warming, by converting them into the equivalent amount of CO_2 with the same global warming potential (GWP) factor [49]. The reason why CO_2 is used as the reference is that it has a GWP of 1. Thus, the GWP factor is a number that represents the relative warming effect of a unit of that gas compared to a unit of CO_2 over a specific timespan (usually 20 or 100 years).

According to the latest SCC, which amounts to 185 $ per tonne of CO_2-eq [50], the kilograms of CO_2 were converted in dollars for each year of the period considered and in every facility studied; SSC was estimated accordingly by multiplying the yearly tonnes of CO_2-eq and the discounted and converted SCC value for the relative time period. The inflation rate and exchange rates for each year, used to respectively discount and convert the SCC (previously expressed in US dollars), were retrieved from the World Bank [51] and European Central Bank [52].

3. Results

Figure 1 shows the graph representation of how different the increase of HW in the facilities was. In the annual output, the greatest increase was detected for ISMETT, which in 2020 and 2021 had the highest number of beds/day dedicated to COVID-19 patients. Peculiar is the increase of IFO in HW production without a direct correlation to the hospitalization of COVID-19 patients, in pandemic emergencies.

Table 1 shows annual data indicating the total amount of HW generated annually for each facility and the average daily weight of HW per occupied bed. All hospitals showed a positive increase in the daily weight of HW per occupied bed over the study period. With an average annual variation (AAV) of 0.89 kg/bed/day, ISMETT is the facility with the highest increase. A lower increase of AAV is observed in the other facilities that have a smaller number of beds/days COVID-19 dedicated, respectively 0.19 kg/bed/day for CRH and AAV 0.15 kg/bed/day for IEO. The IFO presents an increase of 0.23 AAV in kg/bed/day, notwithstanding bed/day for COVID-19 patients was used.

In the following paragraphs, we reported the analysis of the HW production by each single facility.

3.1 IEO

The average amount of waste production was 257.6 tons per year. During the study period, an overall

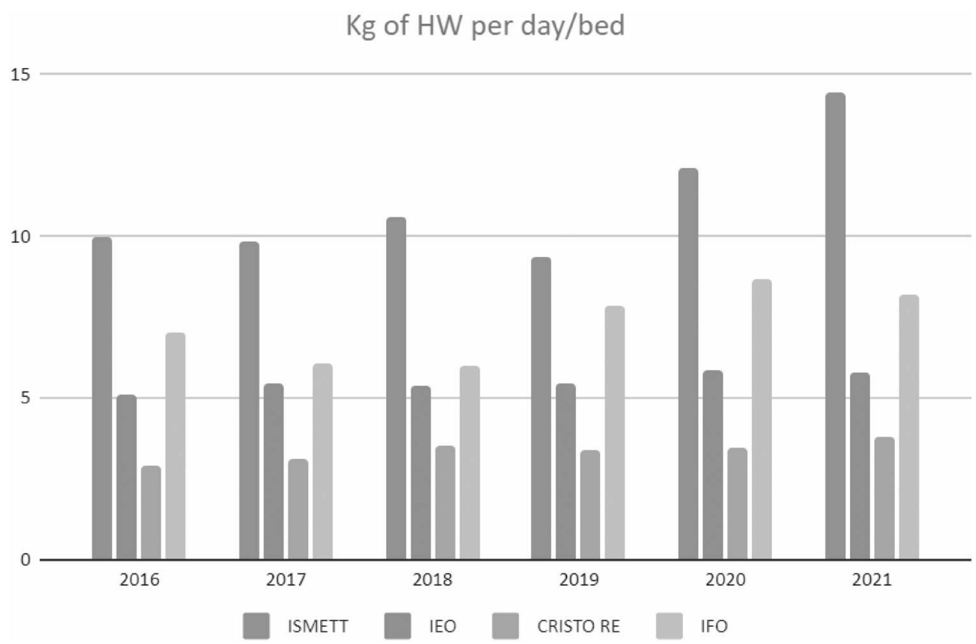

Figure 1. Graph of annual HW per day/bed, per each facility.

Table 1. Yearly total amount of HW for each facility and the average daily weight of HW per occupied bed.

Year / Facility	2016		2017		2018		2019		2020		2021		%Δ
ISMETT	261.5	9.98	261.5	9.86	288.2	10.56	287.5	9.34	337.1	12.12	453.0	14.44	+0.89
IEO	237.4	5.06	249.5	5.44	262.4	5.40	266.7	5.41	259.8	5.88	269.9	5.79	+0.15
CRH	128.7	2.89	136.8	3.13	157.2	3.51	151.1	3.35	131.8	3.45	142.3	3.82	+0.19
IFO	353.0	7.05	294.2	6.06	290.0	5.97	348.6	7.86	358.1	8.65	357.6	8.22	+0.23

Note: For each year, the first column refers to tons and the second one refers to kgs/bed/day.

increasing trend was detected for the generation of HW per bed-days, with an average increase of 3%, corresponding to an amount of HW of 6.8 tons per year.

3.1.1 Trend analysis of monthly data

The starting level of waste was estimated by the model at 19.7 tons (per month), and waste appeared to increase significantly, every month prior to February 2020 by 60.29 kgs ($P = 0.003$, CI = [21.28, 99.91]). In the first month of COVID-19, a decrease in waste production of 968.89 kgs ($P = 0.294$, CI = [−2797.91, 860.13]) has shown, followed by a decrease in the monthly trend of production (relative to the pre-COVID-19 trend) of 20.88 kgs per month ($P = 0.703$, CI = [−129.81, 88.05]). Moreover, during the COVID-19 period waste production increased monthly at a rate of 39.71 kgs.

3.2 IFO

The average amount of waste production was 333.6 tons per year. During the study period, an overall increasing trend was detected for the generation of HW per bed-days, with an average increase of 4%, corresponding to an amount of HW of 10.8 tons per year.

3.2.1 Trend analysis of monthly data

The starting level of HW was estimated by the model at 27.0 tons (per month), after that decreased, even though not significantly, every month until February 2020 by 8.11 kgs ($P = 0.87$, CI = [−108.17, 91.96]). During the first month of the pandemic, a significant increase in HW production of 3526.09 kgs ($P = 0.071$, CI = [−316.42, 7368.61]), followed by a significant decrease in the monthly trend of production (relative to the pre-pandemic trend) of 13.54 kgs per month ($P = 0.898$, CI = [−223.61, 196.52]). It is also noticeable that, during the pandemic period, HW production decreased monthly at a rate of 21.65 kgs.

3.3 Ismett

The average amount of waste production was 314.8 tons per year. Considering the whole period, an overall increasing trend was detected for the generation of HW per bed-days, with an average increase of 9%, corresponding to an amount of HW of 25.2 tons per year.

The proportion of COVID-19-related bed-days varied according to the epidemic waves, ranging around 0.1% in lower-incidence months (from June to July 2021) to 25% – 32% in acute phases (from November 2020 to April 2021). The amount of HW generated per patient-day was positively correlated with the proportion of hospital load referable to COVID-19 disease (Pearson's r = 0.797, $p = 0.0004$).

3.3.1 Trend analysis of monthly data

The occurrence of the COVID-19 outbreak caused a level change in total HW production, with an increase of 3.09 tons/month compared to the baseline level ($p = 0.291$), with the slope of the rising trend modified by the pandemic ($p = 0.072$, Figure 2). In the post COVID-19 period, an increase in the monthly trend of waste production was observed, relative to the pre-COVID-19 trend, of 467.27 kgs per month. Additionally, we observed that, during the COVID-19 period, waste production increased monthly at a rate of 523.39 kgs.

For IEO, IFO and ISMETT, Figure 2 shows the trend analysis of monthly data, reporting both predicted and observed results from each facility, whereas Table 2 depicts the estimates for the ITSA analysis.

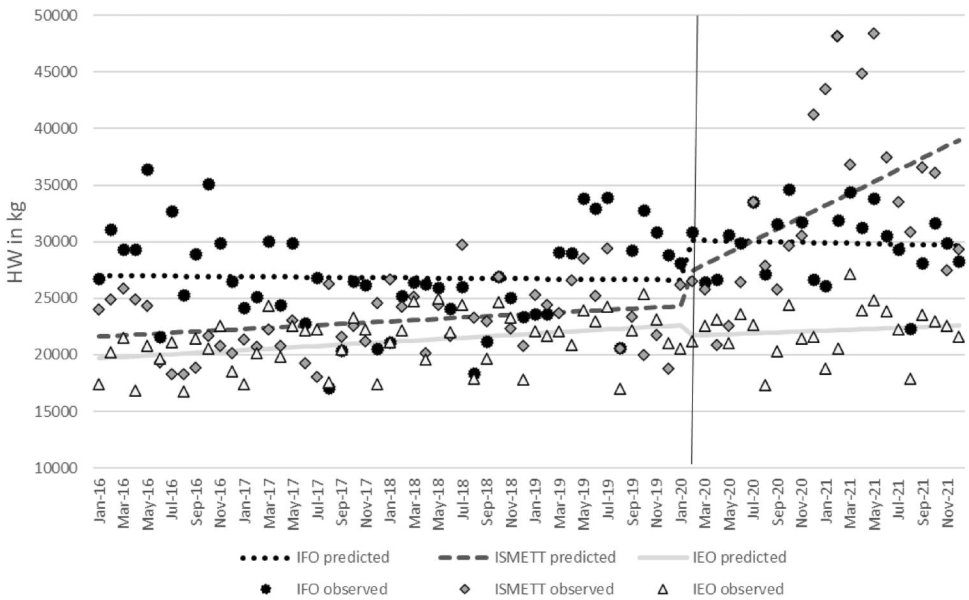

Figure 2. Trend analysis of monthly data of IFO, ISMETT, IEO.

Table 2. Parameters of the ITSA models.

Facility Models' parameters	IEO		IFO		ISMETT	
β0: intercept	19700.43	0.00	27006.44	0.00	21611	0.00
β1: slope prior to pandemic	60.59	0.00	−8.11	0.87	56.11	0.15
β2: change in level in the period immediately following pandemic's start (compared with pre-pandemic period)	−968.89	0.29	3526.09	0.07	3093.03	0.29
β3: difference between pre-COVID-19 and post-COVID-19 slopes	−20.88	0.70	−13.54	0.90	467.27	0.07
β4: slope post pandemic	39.71		−21.65		523.39	

Note: For IEO, IFO and ISMETT the first column refers to the ITSA parameter, the second one shows the *p* value.

CRH was not included in the analysis due to discrepancy in the data format (yearly versus monthly).

3.4 Cristo re hospital

The average amount of HW production was 141.3 tons per year. During the study period an overall increasing trend was detected for the generation of HW per bed-days, with an average increase of 6%, corresponding to an amount of HW of 7.8 tons per year. The time trend of HW production in the study period was marginally statistically significant ($p = 0.07$). The average daily weight of HW per occupied bed in the post-COVID-19 period increased by 12.8% compared to the pre-COVID-19 period. The total number of hospital days related to COVID-19 was 804 in 2020, corresponding to 2.1% of utilized bed-days, whereas an 3% increase in the average daily weight of HW per occupied bed was observed compared to the previous year. In 2021, there was an increase of 14% in the average daily weight of HW per occupied bed was observed, compared to 2019.

3.5 CO_2 production from HW

The weight amount of HW (EWC 18.01.03) was collected in Table 3, per facilities and per year of production, and expressed in kilograms (kgs).

In Table 4 the CO_2 produced by each facility through high temperature incineration is reported: ISMETT showed a steadily increasing trend as well as did IEO, with a minor decrease in 2020 for the latter. CRH experienced a rather fluctuating trend in CO_2 production over the timespan considered, peaking in 2018 and 2019. Additionally, after a substantial decrease in 2017 and 2018, IFO documented an important increase during the first 2 years of pandemic (2020-2021).

3.6 SCC of HW

Table 5 shows the estimated SCCs for each facility in the considered period. Accordingly with the CO_2 emission trends discussed above, ISMETT peaked in 2021 with the largest SCC, followed by IFO. The SCC for CRH showed a slight decrease between the

Table 3. EWC 18.01.03 weight records per facilities, in kilograms.

Year Facility	2016	2017	2018	2019	2020	2021
ISMETT	261538,9	261540,5	288152	287476	337100	452974
IEO	237357,74	249537	262446,4557	266709	259785	269902
CRH	128693	136822,6	157199	151108	131844	142300,25
IFO	352952,1	294159,5	290008,4	348554,15	358100,9	357628,36

Table 4. Yearly tonnes of CO_2-eq produced by each facility.

Year Facility	2016	2017	2018	2019	2020	2021
ISMETT	280,892	280,894	309,475	308,749	362,045	486,494
IEO	254,922	268,002	281,867	286,445	279,009	289,874
CRH	138,216	146,947	168,831	162,289	141,600	152,830
IFO	379,070	315,927	311,469	374,347	384,600	384,092

Table 5. Estimated SCCs for each facility in the considered period.

Year Facility	2016	2017	2018	2019	2020	2021
ISMETT	€ 47.254	€ 43.425	€ 46.450	€ 50.122	€ 58.891	€ 74.721
IEO	€ 42.885	€ 41.432	€ 42.306	€ 46.501	€ 45.384	€ 44.522
CRH	€ 23.252	€ 22.717	€ 25.340	€ 26.346	€ 23.033	€ 23.473
IFO	€ 63.770	€ 48.840	€ 46.749	€ 60.771	€ 62.560	€ 58.993

pandemic biennium (2020–2021), whereas in the years before the trend was almost constantly rising. IEO, on the other hand, maintained a certain SCC consistency until 2018, then peaked in 2019, and progressively declined through 2020-2021.

4. Discussion

Hospital waste increasing production trend and management policies are one of the most underestimated challenges and currently a particularly debated topic in healthcare; in fact, the COVID-19 pandemic has dramatically exacerbated the failure of safe disposal services [16].

To date, some countries have analysed the increase in medical waste correlated to COVID-19 on a national scale, such as in Bangladesh [53], Lebanon [54], and Taiwan [55]. The findings show an increase related to the pandemic, but also that infectious and non-infectious waste generation and management are issues related to the socioeconomic conditions of the country of reference. Several primary studies have tackled the impact of COVID-19 related waste, for example describing their composition to aid disposal planning [56], and the potential harm for the environment without strict regulations [17]. A 2023 study from Turkey performed an analysis on three hospitals of different legal nature (a private, a public and a university hospital), similar to what we have advocated in our study; their findings detected an increase in medical waste during the pandemic as well, and suggest stronger management policies to handle this growth [57].

In this paper, we analysed the HW production trend from four Italian healthcare facilities before and during the pandemic period, focusing on hazardous waste (i.e. EWC 18.01.03), which was found to be increasing for all the facilities considered, albeit at different rates. The CO_2 emissions deriving from the incineration and the SCC related were also considered, to enable broader reflection on its environmental and economic burden. An overall increase in HW production over the study period was observed. The impact of COVID-19 was clear in two hospitals (ISMETT, IFO), where HW increased with the start of the pandemic. After the initial impact, the trend decreased in IFO, while it continued to increase in ISMETT. On the other hand, ISMETT had a relevant percentage of occupation of day/bed attributable to COVID-19 cases with a correlated increased amount of HW generated. Even though a limited number of beds per day had to be set aside for patients who tested positive during hospitalization, IEO and IFO did not hospitalize patients during the epidemic. Therefore, a decrease in the monthly trend is shown, while an increase was noticed during 2020. The CRH, like ISMETT, provided support to the Italian NHS during the pandemic with dedicated beds and services, and an increase in the annual waste produced by the facility was observed, like the other facilities considered in our analysis. Our study findings are in line with those by Garlasco et al., who has highlighted the increasing trend in HW generation before and during COVID-19 outbreak in a tertiary hospital in Alessandria (Piedmont, northern Italy). The Authors points out that, apparently, the pandemic has worsened this increase but cannot be recognized as the solely responsible for it, and consequently new management and control measures should take into account the complexity of the overall picture, instead of focusing exclusively on the pandemic impact [30].

Additionally, other international recent studies have focused on the general increase in HW due to the pandemic and have underlined the lack in the disposal system, [58], policies and regulations gap for containing and appropriately manage COVID-19 related waste, especially in developing countries [54], and addressing effective temporary measures that should encourage hospitals to increase their baseline capacity for HW and build preparedness for emergencies [59]. Most of the scientific production on this topic has focused on the management and disposal methods implemented in the countries of reference and relatively less studies have assessed the environmental impact, especially in conjunction with an economic viewpoint [60]. In fact, there is a growing emphasis on 'green hospitals' within the scientific community, as these institutions offer potential solutions to the healthcare sector's significant contribution to the ongoing climate change crisis [61]. Our research, which sheds light on hospital waste production and its associated greenhouse gas emissions resulting from disposal, contributes to the collective knowledge in this area. By doing so, we aim to accelerate the transition towards more sustainable alternatives, aligning the healthcare sector with broader efforts to combat climate change. Moreover, in an effort to interpret the increasing HW waste production trend in Italy, we hypothesize three main drivers: the catchment areas determined by highly specialized tertiary care facilities (e.g. ISMETT is a very well-known center that performes liver and kidney transplants from a living donor), the technological development in diagnosis and treatment of various conditions that has occurred in the last decades, augmenting the expected lifespan, and resulting in a better understanding of many diseases, and the consequent increased, more diversified health needs of the population; each one of these drivers lead to an increased number of procedures, which produce HW.

The joint reading of study findings allows for some conceptual and practical premises.

In our study, we undertook a comprehensive analysis with dual objectives. First, we examined the production trends of hospital waste across four distinct units, differing significantly in geographical location, institutional type, management, and ownership. This approach allowed us to delineate variations within the Italian NHS, both pre and post the COVID-19 pandemic. Additionally, we sought to identify potential causal factors responsible for the observed increase in waste generation. To ensure the broad applicability of our findings within the Italian NHS, we deliberately selected these four units, recognizing the inherent challenges in collecting such specific data from numerous facilities.

Firstly, the organizational aspects of hospital assistance should undergo a massive rearrangement and to be resilient towards the new health care needs associated with the COVID-19 emergency [62]. In line with this, CRH and ISMETT have reallocated ICU and subacute ICU care unit beds, along with dedicated pavilions, while IEO and IFO have been reorganized to minimize the pandemic impact on their ordinary activities. These changes have led to an increase in extraordinary activity in the facilities and PPE devices and procedures, resulting in a rising amount of waste produced in the pandemic period, as highlighted in our analysis. Our research findings bear significant relevance in the realm of health planning, particularly in the context of hospital waste management. These findings hold relevance on three distinct policy-making levels. On the macro level, given the substantial decentralization within the Italian NHS, it is the Central Government's prerogative to formulate and promote customized hospital waste management policies, emphasizing appropriateness in waste disposal [63]. These policies, at the meso level, pertain to Local Health Units [64], where their timely adoption, endorsement, and vigilant implementation by healthcare facilities become crucial, representing the micro level [65]. Thus, decision-makers should aim for implementing health policies that consider emissions from HW disposal as a threat for human health, as it is currently made with different sources of air pollution [66].

This study has several limitations. Firstly, the facilities analysed showed several heterogeneous structural characteristics, such as bed capacity, COVID-19 patients' triage, and different geographical localization which is also linked to a different epidemiological spread of the virus during the pandemic waves. However, to date there is no evidence comparing hospitals from different Italian regions, neither adopting a similar methodology, nor assessing comprehensively the environmental impact of HW disposal. Secondly, to determine CO_2 production, we employed a conversion rate from the literature that considered all types of clinical waste generated in a hospital, including EWC 18.01.03. Notwithstanding the availability of other conversion rates, they were not inherent to the Italian disposal systems. Nonetheless, currently there is no study suggesting an estimate of carbon emissions specifically related to EWC 18.01.03, therefore we utilized the approximation deemed the most accurate. Another caveat was the impossibility of calculating the precise chemical composition, especially the proportion of carbon compounds, in the HW analysed. One hospital could provide only year-based data, preventing us from using the ITSA method to study the trend and evaluate the impact of COVID-19. Additionally, the data were only available in an aggregate form, which hindered the analysis of HW production by each hospital ward. Furthermore, the adopted value of the SCC was retrieved from a US study, showing the economic impact on the US socio-economic context. Further research is needed to develop indices to assess the environmental impact of CO_2 emissions in the European area, following the SCC model, as well as to address the disparities in terms of laws and regulations regarding the ETS application across European countries.

Additional studies are required to bridge the literature gap about chemical composition of HW and to emphasize the proportion of waste whose carbon compounds are believed to be from fossil sources, as this is crucial in determining the CO_2 emissions from waste incineration that are relevant to climate change and aid the implementation of policies regarding their containment. Furthermore, this research could be expanded to encompass additional units, to strengthen the credibility and robustness of our results, providing further support for our conclusions. Lastly, a thorough investigation of HW life cycle associated with current policies could lead to understanding hitherto unknown or neglected causal factors of the rising trend for HW, observed even before the COVID-19 pandemic began.

5. Conclusion

Our study aimed to evaluate the environmental and economic impact of HW management in Italian healthcare facilities before and during the COVID-19 pandemic. According to our findings, the increasing trend in HW production, regarding hazardous waste, has continued throughout the first 2 years of the pandemic and has brought an estimated parallel increase in CO_2 emissions and economic consequences. This study also emphasized the need for more accurate and comprehensive data on HW, particularly on EWC 18.01.03. Despite some limitations, it provides significant insights into the HW management system and its environmental impact in different Italian regions, and the findings underline the importance of implementing sustainable waste management practices in the healthcare sector to reduce environmental impacts and promote economic sustainability.

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