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Systematic Review

Impacts and Regulations of Healthcare Solid Waste Management during the COVID-19 Pandemic: A Systematic Review

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Abstract: In a pandemic context, it is essential to intensify precautions related to healthcare solid waste, known as HCSW, ensuring the continuous search for safer management and handling protocols of these materials. In this sense, the aim of this paper is to conduct a comprehensive review of the literature about the management of healthcare waste during the COVID-19 pandemic. The current investigation was underpinned by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) framework, selected to ensure the comprehensive and transparent presentation of the systematic review. In pursuit of this objective, three distinct keyword combinations were employed, namely, "solid waste management", "medical waste", and "COVID-19 pandemic". Consequently, a total of 76 documents were incorporated into the analysis. The results of this analysis indicate that the amount and treatment of hospital solid waste were significantly affected by the pandemic, bringing impacts on social, economic, and environmental aspects. Recent studies have focused on mitigating these impacts by pursuing "green" solutions, such as implementing sustainable strategies, preserving biodiversity, adopting an eco-conscious lifestyle, improving healthcare infrastructure, raising public awareness, and changing HCSW management policies. In addition, alternative technologies have been explored for the adequate treatment of these wastes, as well as the replacement of harmful materials by safer substances. However, more scientific research on this topic is still needed, especially in the Brazilian context, in order to contribute to the development of strategies that minimize the impacts of the pandemic on both society and the environment.

Keywords: solid waste management; COVID-19 pandemic; healthcare waste

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1. Introduction

In December 2019, the coronavirus, known as SARS-CoV-2, emerged in China and caused respiratory illness in humans [1,2], quickly spreading to most continents and countries, leading the World Health Organization (WHO) to declare a high-transmission pandemic on 11 March 2020. This situation has become a global concern, requiring comprehensive changes in society, especially in the hospital setting.

In addition, the pandemic has raised concerns about overconsumption and environmental issues such as climate change. According to the WHO, the virus had existed in the world for some time, but increasing urbanization and human encroachment allowed it to break its natural cycle and spread to humans [3]. Approximately 60% of the emerging infectious diseases of the last century, including deadly viruses such as HIV, Ebola, influenza, and coronavirus strains such as SARS and MERS, are related to the emergence of zoonotic diseases, that is, when a virus that naturally infects non-human animals starts to infect people [4].

In the context of the COVID-19 pandemic, there is a notable estimation that hospitals, clinics, and healthcare centers have emerged as primary sources generating solid waste [5]. Consequently, the establishment and implementation of adequate hospital waste management is essential to preventing these wastes from becoming carriers of pathogens or potential instigators of accidental hazards throughout treatment processes.

Given this reality, the adoption of rigorous measures for waste management assumes critical importance, particularly within hospital environments closely associated with healthcare delivery. Nations affected by the pandemic have directed substantial efforts toward formulating more robust and secure protocols, targeting the administration and management of solid waste originating from healthcare services. This approach is substantiated by the understanding that one of the potential modes of COVID-19 transmission involves the spread through contaminated solid waste. Furthermore, solid waste from healthcare services, in particular, contains significant traces of infectious agents.

Therefore, the aim of this paper is to conduct a systematic literature review on the management of healthcare waste in the context of the COVID-19 pandemic, from its inception to the present, identifying the impacts on the environment and society, as well as the regulations and/or new protocols implemented by countries to ensure safe management of this waste. Furthermore, the study aims to explore regulations and potential new protocols implemented by various nations to ensure safe and effective management of hospital waste, considering the specificities of this pandemic context.

This article is organized into five sections. The first section presents the introduction, providing contextualization and objectives. Following this is the research methodology, detailing the step-by-step approach taken in the study. It is noteworthy that the study's foundation was the PRISMA method—Preferred Reporting Items for Systematic Reviews and Meta-Analysis. Three keyword combinations were utilized: "solid waste management", "medical waste" or "healthcare solid waste", and "COVID-19 pandemic", resulting in the inclusion of 76 documents. The third subsection presents the study's results, outlining the main findings of the authors. The fourth section engages in discussions and authors' contributions regarding the uncovered results. The conclusion of the study is presented in the fifth section.

It is worth highlighting that this study's primary contributions lie in its comprehension of emerging challenges faced by hospitals and healthcare centers during the COVID-19 pandemic in managing healthcare solid waste. These challenges encompass heightened medical waste generation, including disposable personal protective equipment (PPE), and difficulties in treating such waste. Furthermore, the study offers recommendations to address these challenges, thereby promoting safer, more sustainable, and effective waste management during future health crises.

2. Materials and Methods

To conduct this study, we used the PRISMA method—Preferred Reporting Items for Systematic Reviews and Meta-Analysis; this method is employed for the execution and documentation of systematic reviews and meta-analyses, consisting of a set of guidelines that assist researchers in adhering to a standard protocol encompassing all aspects of the review, from the data search strategy to the analysis and presentation of results [6] (Supplementary File). These guidelines establish how the research was conducted, thus ensuring the production of high-quality, transparent, evidence-based research with standardized structure, minimizing bias in the selection and inclusion of studies in the review, as well as reproducible methodology, in order to ensure a more complete and transparent systematic review article. Thus, first, a quantitative search of the scientific papers found in the databases Periódicos Capes and PubMed was carried out, in order to select the relevant publications for the development of this study.

The choice of these two platforms was due to the fact that the CAPES Periodicals Portal includes a wide variety of databases covering various fields of knowledge. Some examples of databases available on the portal include Scopus, Web of Science, ScienceDirect, Scopus, and SciELO. Additionally, considering the topic being investigated, it was deemed important to include a more specific health-related database, which, in this case, was PubMed.

For this, three combinations of keywords were used: "solid waste management", "medical waste", and "COVID-19 pandemic", to be located in any field of papers published between 2019 and 2022. Initially, these keywords were used in English due to the predominance of the English language on scientific platforms. Consequently, the first stage of the search was carried out in three phases, as shown in Table 1 below.

Table 1. Quantification of searches with keywords in English.

Phases		Keywords in English	Logical Operator Used	Quantity Found (Any Field)	Search Period
I	1	"COVID-19 pandemic"	AND	Periódicos Capes: 46	10 February 2022
	2	"Solid waste management"		PubMed: 38	to 18 August 2022
II	3	"COVID-19 pandemic"	AND	Periódicos Capes: 190	10 February 2022
	2	"Medical waste" or "healthcare solid waste"		PubMed: 107	to 18 August 2022
III	1	"Medical waste" or "healthcare solid waste"	AND	Periódicos Capes: 16	10 February 2022
	2	"Solid waste management"		PubMed: 11	to 18 August 2022
	3	"COVID-19 pandemic"			

Source: Authors (2022).

As shown in Table 1, a search was initially conducted for articles that related the words "COVID-19 pandemic" and "solid waste management" using the logical operator "and" in the two databases mentioned. In the Periódicos Capes database, 46 articles were found, while in PubMed, 38 were found. Then, in the second stage of the search, the words "COVID-19 pandemic" and "medical waste" or "healthcare solid waste" were connected, resulting in 190 articles in the Periódicos Capes database and 107 in PubMed. Finally, in the third stage of this first phase, the combination of the three keywords was sought, that is, "COVID-19 pandemic", "solid waste management", and "medical waste" or "healthcare solid waste", resulting in 16 articles in the Periódicos Capes database and 11 in PubMed. It is important to highlight that when performing the search with keywords in Portuguese, all results were zeroed, evidencing the lack of Brazilian studies on the subject.

It is worth noting that we considered it important to specify the start and end dates of the search for documents due to the constant updating of databases. The number of scientific publications in a given portal may vary over time as new studies are published. Given that this systematic review addresses a current and constantly evolving topic, the specification of search dates becomes even more essential.

Starting the second stage, a table was created with all the main data (title, authors, abstracts, and full references) of the 408 articles found in the two databases, in order to aid the search for repeated documents. A total of 147 repeated articles were found, of which 111 were in the PubMed database and 36 in the Periódicos Capes database. After removing the duplicate articles, primary exclusion criteria were established to select the articles. These criteria included the exclusion of articles that were not freely available and scientific articles from journals that did not go through the peer review process, thus ensuring the quality of the articles, especially on the Periódico Capes platform. In addition, a sifting was performed by reading the titles and abstracts of all publications, resulting in the exclusion of 75 articles.

In the eligibility stage, the final papers were selected based on the theme of medical/hospital solid waste management during the COVID-19 pandemic. Three main eligibility criteria were established, as presented in Table 2. As a result, 57 more articles were excluded as they did not meet these eligibility criteria.

Table 2. Scientific papers' eligibility criteria.

Eligibility Criteria	
1.	Quantitative assessment of healthcare solid waste during the COVID-19 pandemic
2.	Impacts and mitigation measures for healthcare solid waste contaminated by SARS-CoV-2
3.	Information on changes in policies and/or executive and/or operational strategies in solid waste management during the COVID-19 pandemic

Source: Authors (2022).

Figure 1 depicts a flowchart of the steps described, following the recommendations proposed by the PRISMA method—Preferred Reporting Items for Systematic Reviews and Meta-Analysis [6]. Therefore, we included 76 documents from both databases (see Figure 1), which will be discussed in the following section.

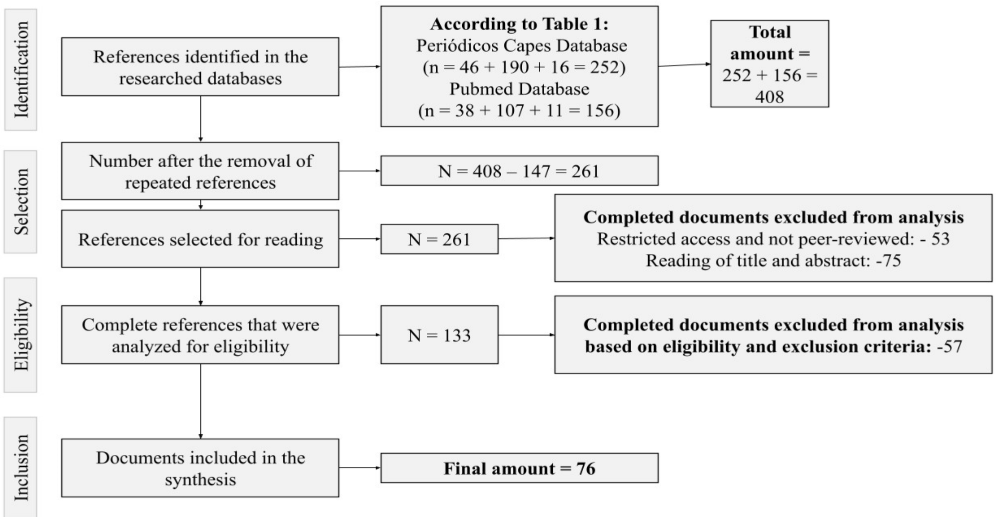

Figure 1. Flowchart of the selection of papers with the recommendations of the PRISMA method. Source: Authors (2022).

The first stage involved identification, where all articles with the defined keywords were sought in the two proposed databases. The second stage was the selection of these articles, involving the removal of duplicates, articles with restricted access, and articles that did not fit the theme after title and abstract screening. In the third stage, articles that did not meet the eligibility criteria were removed, leading to the final stage with the included articles for analysis and full reading, to be presented and discussed in the results and discussion sections of this article.

3. Results

This section will present the outcomes of this article and is structured into subsections in accordance with the eligibility criteria outlined in Table 2. Information regarding the quantity and composition of healthcare solid waste during the COVID-19 pandemic is detailed in Section 3.1. The impacts and mitigation measures pertaining to healthcare waste contaminated by SARS-CoV-2 are addressed in Sections 3.2 and 3.3. Finally, insights concerning alterations in policies and/or executive and operational strategies related to solid waste management during the COVID-19 pandemic are expounded upon in Section 3.4.

3.1. COVID-19 Pandemic and Healthcare Solid Waste

A significant increase in the volume of healthcare solid waste (HCSW) has been observed worldwide due to the COVID-19 pandemic, and this waste originates from the disposal of materials used in hospitals, clinics, and other healthcare facilities, such as gloves, masks, aprons, caps, and foot protectors, which creates an additional challenge in the proper management of this healthcare waste [7]. Thus, to ensure the safety of healthcare workers and patients, greater attention needs to be paid to routine protocols, including regular changes of personal protective equipment (PPE) and hand washing [8].

Despite the large discrepancies in the increase in volume of solid waste from health services in the countries affected by COVID-19 (ranging from 18% to 425% increase), there was a significant increase in all countries, highlighting the urgency of understanding the impacts of this waste on the environment and, consequently, on society [9]. There has been a considerable increase in the amount of personal protective equipment used and widespread distribution of infectious waste from hospitals, healthcare facilities, and quarantined households, as well as an increase in the disposal of plastic materials used for food [10]. These factors have overwhelmed waste treatment facilities, prompting the need for rapid treatment and disposal to enhance processing capacity [10].

In Brazil, it is estimated that a hospitalized patient generates, on average, 1.4 kg of waste per day [11]. However, during the pandemic, this number increased on average by 10 to 20 times, according to the Brazilian Association of Public Cleaning and Special Waste Companies. This increase was also observed in many other parts of the world. In Jordan, for example, there was a 10-fold increase in waste production associated with 95 patients diagnosed with COVID-19 at a university hospital, while in Spain the increase was 350% [12]. In Iran, this expansion has also been quantified, with significant rates of increase in the production of personal protective equipment such as face masks (55 times), face shields (1000 times), and gowns (860 times) [13].

Studies conducted in five hospitals in Iran also revealed an increase in waste generation from 0.95 to 3.51 kg/bed/day, with an average increase of 102.2% in both public and private hospitals [13], while in Bangladesh, there was a more than 24-fold increase in the volume of COVID-19 waste from 658.08 tons in March 2020 to 16,164.74 tons in April 2021 [14].

Considering the above, the need for fundamental changes in solid waste management during the COVID-19 pandemic becomes evident in order to cope with the variations in the composition and quantity of this waste [15]. The daily use of masks and gloves to reduce the spread of the virus is also of concern, due to the large increase in the amount of waste generated in the environment [16]. In addition to the significant rise in the volume of waste, it has been observed that a portion of this waste is improperly disposed of in the environment instead of being destined for landfills or incinerators [17].

Plastic waste dominates the composition of HCSW, accounting for 76.7% in a study conducted in Vietnam, followed by paper [18]. The increase in plastic waste and demand in plastic markets can be seen as an economic indicator to encourage government and private companies to invest in technologies that convert this waste into value-added products such as fuels and building materials [19].

3.2. Healthcare Solid Waste Contaminated by SARS-CoV-2: Impacts and Solutions

In the context of the physical environment, which encompasses soil, water, and air, the COVID-19 pandemic had several impacts. There has been an increase in the use of personal protective equipment (PPE) as solid health waste and disposable products purchased through online ordering. This situation occurred against a backdrop of stagnating policies related to the reduction in plastic products and waste recycling. In addition, there has been a surge in the incineration of healthcare solid waste, which has resulted in increased waste gas pollution.

In the biotic environment, which encompasses all living things, impacts related to the pandemic and contaminated solid waste were varied. These included higher animal movement in areas where there was previously a large human presence, such as beaches. There was also a heightened environmental risk around waste disposal sites, with potential adverse impacts on human and animal health due to exposure to highly toxic gas emissions resulting from high-temperature incineration.

In the anthropic environment, which refers to human activities and the socioeconomic context, several effects were observed, with a slowdown in human activities, impacting production sectors due to social distancing and isolation measures. There were also shocks in the supply and demand of products. In addition, there has been an increase in the amount and composition of hospital waste and disposable products, driven by the exacerbated use of e-commerce. These impacts have had diverse social, cultural, and economic ramifications.

Therefore, it is undeniable that COVID-19 has exerted a significant impact on the environmental domain, a reality underscored through an in-depth analysis of a case study conducted in the Philippines [20]. Within this study, the observation arises that the pandemic's effects have significantly extended to critical variables such as air quality and the integrity of water resources. Furthermore, it is imperative to underscore that the environmental implications transcend the immediate and could potentially influence communities' vulnerability to disease outbreaks in the future, thereby highlighting the crucial interconnection between the state of the environment and susceptibility to pandemics and epidemics.

In Brazil, the COVID-19 pandemic will leave a lasting impact on almost all aspects of society, in addition to raising concerns about the risks of contamination associated with waste management. It is evident that most of the recommendations are related to hygiene routines; the use of PPE; and the correct segregation, packaging, and final disposal of waste, which are highly dependent on the awareness and involvement of citizens, as well as the planning and support of authorities [21].

Due to the pandemic, the implementation of a continuous solid waste management strategy became even more relevant, which leads to creating a stronger and different world to tackle the solid waste problem toward its sustainable solution [22]. Some recommendations include a sustainable transition based on bioplastics instead of plastic-based fossil fuels, although this incurs additional costs, and support for waste management planning with decision-making and optimization tools, i.e., treatment methods, facilities, capacity (scalability), logistics, mobilization/automated (e.g., remote control robots), collection, and treatment design [22].

In Italy, the SARS-CoV-2 pandemic had a devastating effect on the health and socioeconomics of the population; however, there is a study showing the positive impact. The research points out the perception of safety among staff due to the technical, operational, and organizational model adopted in order to protect staff, outpatients, and inpatients in an Italian hospital with an intensive care unit dedicated to COVID-19, as a positive outcome [23].

On the other hand, the use of safety clothing or personal protective equipment (PPE), masks, gloves, and shields causes a major impact on the environment in the long term, creating microplastic pollution. It is therefore suggested to modify and modernize existing policies, plans, and guidelines on the proper management of hospital and household infectious waste; it is also recommended to carry out occupational health and safety assessments for waste management workers in hospitals and to install incinerators of adequate capacity and infrastructure for proper waste management [24]. In view of the above, the main impacts of the COVID-19 pandemic on the three environments (the physical environment, the biotic environment, and the anthropic environment) can be summarized, as shown in Table 3.

Table 3. Main impacts of hospital solid waste generated in the COVID-19 pandemic.

Environments	Impacts of COVID-19 Pandemic
PHYSICAL ENVIRONMENT	- Increase in the use of disposable products with the use of PPE and online ordering [8,25–27] - Stagnation of policies related to the reduction in plastic products and waste recycling [9] - Reductions in air, water, and greenhouse gas pollution during periods of lockdowns [12,27,28] - Use of deep landfill methods for disposal of HCSWs [29] - Increased use of incineration of HCSWs, which causes waste gas pollution [9,30]
BIOTIC ENVIRONMENT	- During periods of lockdown, an increase in animal movement in areas that previously had a high human presence [12] - Increased environmental risk imposed on the population around waste disposal sites [30] - Risk of adverse impact on human health due to exposure to highly toxic gas emissions with the use of high-temperature incineration [9,30]
ANTHROPIC ENVIRONMENT	- Slowdown of human activities [31] - Disruption of production supply and demand, due to social distancing and lockdown measures [31] - Increase in quantity and composition of hospital waste [8] - Economic impacts [28,32,33]

Source: Authors (2022).

Based on the results presented in Table 3, it is possible to conclude that the pandemic has had significant impacts on several aspects, with current and future consequences in the social, economic, and environmental spheres. In this sense, many recent studies have sought to mitigate these impacts through “green” solutions, as well as changes in healthcare solid waste (HCSW) management policies and strategies.

The understanding of the impact of waste on sociocultural responses to disasters, such as a pandemic, is still limited and likely to increase due to climate change [34]. It is important to note that COVID-19 HCSWs should be treated separately in order to avoid contamination of regular municipal waste with infectious agents. However, both types of waste must go through four steps: sorting, temporary storage, collection and transportation, and final disposal and treatment [34].

It is worth noting that in the first stage, solid waste from healthcare services must be classified or segregated from COVID-19 healthcare waste (typification), then be collected in separate bags or bins. Afterward, they must go through correct disinfection to be sent to a temporary storage area. At this stage, COVID-19-contaminated HCSWs must not exceed 24 h in the area. Following through, they are directed to vehicles that exclusively transport COVID-19 HCSWs, which must also be sterilized before and after transportation. At last, the solid waste goes through high-temperature disinfection treatments and/or is sent to disposal facilities [8].

It is critical that governments effectively implement COVID-19 waste management measures to prevent any type of infection. The use of artificial intelligence (AI) for the collection and segregation of post-COVID-19 solid waste is also suggested [35]. However, it is important that the development of AI is carried out with caution and rigor since there have been cases of failures in solutions developed by large technology companies such as Google, Microsoft (Washington, DC, USA), and Apple Inc. (Cupertino, CA, USA), which resulted in millions in expenses [36].

COVID-19 healthcare solid wastes are predominantly composed of plastic, and during the pandemic they cannot be recycled due to the presence of infectious residues, which may further propagate the SARS-CoV-2 virus [37]. In addition, the increase in demand for personal protective equipment during the pandemic has led hospitals to use even more disposable products, undermining sustainability.

In this context, ways to minimize hospital waste have been proposed, such as reducing the number of professionals involved in the care of patients with high viral loads and the adoption of telemedicine practices in patients previously diagnosed with the virus [25]. Another solution, already implemented by some private health centers in the United States, is the use of reusable polyester aprons, which in addition to cutting healthcare costs contribute to addressing climate change and improving resilience while preserving the safety of healthcare workers [26].

Mathematical models have been proposed for the effective management of COVID-19 healthcare solid waste, aiming at sustainable development [38,39]. These models provide decision support systems that consider the optimization of total transport time, service priorities, and the environmental risk imposed on the population in waste disposal areas [38,39]. A model for the safe and efficient transportation of HCSW has also been proposed in the city of Istanbul, Turkey, which can be adapted to other regions and sectors [39].

In a case study conducted in Wuhan, China, during the COVID-19 outbreak, the feasibility of a mathematical model for infectious waste management was demonstrated [40]. The computational results of this model showed that it was possible to meet more than double the demand at approximately 40% lower cost compared with traditional methods, in the face of increasing amounts of infectious waste [40].

A scientometric study based on the Web of Science database also corroborated the importance of the relationship between hospital waste and the development of a sustainable society, highlighting the need to develop clear procedures for transportation, protected routes, intermediate collection points, and temporary storage in waste disposal areas [7].

Since human health is the priority in most studies, the indirect impact of the virus on the environment has been little analyzed. As mentioned above, the first studies estimated a positive indirect impact on the environment, mainly due to the social distancing policies adopted by governments after the outbreak of the pandemic. However, decreasing greenhouse gas concentrations for a short period is not a sustainable way to help the environment. In addition, there are negative secondary aspects such as reduced recycling and increased waste that must be addressed [41].

It is widely known that the COVID-19 pandemic affected all aspects of society, including issues regarding health, socioeconomics, and the environment [42]. In Brazil, this was touched upon in a study showing that more than 35% of healthcare solid waste was mishandled, increasing the risk of propagation of the SARS-CoV-2 virus. Furthermore, the mishandling of HCSWs led to an estimated loss of 781 thousand dollars with the suspension of recycling programs, overloading landfills and, therefore, causing double damage: economic and environmental [33]. The high expenses are in the scope of logistical operations related to the collection, transportation, and disposal of waste [43].

Thus, it is valid to emphasize that the pandemic, and its need to respond with health policies, resulted in two shocks for Brazil: an external shock, which includes external demand and prices, and an internal shock, represented by demand and supply affected by the need for little or no physical contact, as well as by the other restrictions on economic activities approved to avoid contagion [44]. Another important point is that Brazil, as a net exporter of oil, was hit by the crash in the price of this commodity since there was a sharp drop in demand, causing oil prices to fall by half, and some contracts reached negative numbers in April 2020 [44].

3.3. Healthcare Solid Waste Management: Treatment and Solutions

Considering traditional solutions already used for other healthcare solid waste (HCSW), studies indicate that high-temperature incineration is an important step in the management of COVID-19-related waste [45,46]. However, this practice poses risks to human health due to exposure to highly toxic gases, as well as clashing with the principles of the circular economy [46].

In this context, pyrolysis emerges as an environmentally friendly, efficient, and cost-effective technique that requires less landfill capacity and utilizes the thermal instability of the organic components of HCSWs to convert them into valuable products [8]. The application of pyrolysis technology is considered clean and safe, contributing to reducing environmental impacts, compared with traditional methods such as incineration, landfilling, and autoclaving, which release toxic gases and occupy large areas of land [47].

Studies have investigated the environmental impacts and key factors in different disposal scenarios of healthcare solid waste, such as incineration, steam, and microwave sterilization. Through life cycle assessments, it has been found that co-incineration with municipal solid waste has the lowest environmental impacts due to the benefits generated by energy generation. To add on, co-incineration with hazardous waste also showed low environmental impacts due to energy generation [48].

In India, biomedical waste incineration capacity was compromised during the COVID-19 pandemic, leading to the accumulation of waste and emissions harmful to environmental health [30]. The use of available alternative technologies for treating this waste is recommended, as well as the replacement of hazardous raw materials with innocuous substances in order to reduce chemical emissions from incineration units. It was also found that some Indian states were still using inappropriate methods, such as deep landfilling, for the disposal of HCSWs, despite the government ban [29].

In Korea, waste minimization and recycling, control of toxic emissions from healthcare solid waste incinerators, and alternative treatment methods are important challenges since incineration capacity cannot be expanded quickly enough to keep up with the increase in healthcare waste, which highlights the need to reconsider the management system as a whole [49].

On the other hand, the combination of incineration and chemical disinfection and combined chlorination and ultraviolet irradiation have been identified as the most sustainable technologies for the treatment of infectious solid waste and wastewater [50]. Case studies in India and China selected incineration as the best disposal technique for HCSW among the available alternatives, considering the socioeconomic and environmental criteria [51].

In the Chinese context, a comprehensive effort in the development and implementation of six distinct technologies for the emergency disposal of waste has been extensively documented. This effort outlines a meticulous and adaptable prioritization plan that varies according to the typology of the waste in question. This ordered hierarchy of strategies is structured to optimize disposal effectiveness, considering the specific requirements of each waste category. These technologies are listed as follows: mobile microwave sterilization, followed by mobile steam sterilization; subsequently, mobile incineration takes place, and then, in certain contexts, co-incineration with hazardous waste emerges. Co-incineration, once again, appears as an alternative, this time combined with municipal solid waste, and finally, co-disposal in cement kilns concludes this hierarchical approach [52].

It is worth noting that all HCSW treatment technologies have advantages and disadvantages [9]. Incineration, for example, has a high disposal cost and causes waste gas pollution, while pressure steam sterilization is safe, effective, and low cost but is not suitable for the treatment of pathological waste [9]. The overall health impacts resulting from healthcare waste disposal methods vary according to the national level of development.

With the HCSWs elimination practices arising from the response to the coronavirus pandemic, it was concluded that COVID-19-related waste must initially go through a stage called classified packaging and pre-treatment. That phase is important to preview a series of recommendations for different types of solid waste. For example, infectious waste and pathological waste must be packed in double-layer hospital waste bags, and the surface of the bags must be sterilized by spraying chlorine-containing disinfectant and placed in capped hospital waste. The waste must be kept in temporary storage for 24 h, at maximum, so that the unit has control of the time and amount of waste being stored and can record internal and external carriers [53].

As for the collection and transportation stage, the disposal of COVID-19-related hospital waste should be carried out by specific trained professionals and with the use of special vehicles, which differ from general hospital waste. The transportation route should avoid crowding as much as possible, the deposit and vehicles should be disinfected immediately afterward, and the waste should preferably be treated by high-temperature incineration or processed in a landfill after steaming and boiling at high temperature [53].

In this light, it is evident that there is a need for a specific treatment for HCSW, taking into account its impact on the environment and human health, especially in a context of health crisis [7]. Proper management of the health care waste stream, from the global to the hospital level, is critical for sustainable development. This includes policies and practices for managing HCSW, which must be monitored and controlled in order to avoid inappropriate practices that could compromise the environment and public health.

In several countries, such as Ethiopia and Lebanon, inadequacies have been identified in the management of COVID-19-related waste, from segregation to disposal [54,55]. Such inadequate practices distinctly underscore the urgent necessity to establish continuous monitoring and stringent oversight of waste management policies. This encompasses the implementation of preventative campaigns and healthcare waste reduction initiatives, as well as the promotion of accurate sorting and segregation practices for these materials. This should be complemented by the effective enforcement of the already established norms and regulations.

It is relevant to mention that despite the innovative solutions that have emerged in the domain of healthcare solid waste disposal, a globally applicable "green" approach to this issue is not yet evident, owing to barriers such as substantial investment costs, lack of access, and sometimes impracticality [56,57]. Therefore, significant changes at all levels are needed in order to manage the healthcare waste stream more efficiently, which is a basic requirement for environmentally conscious healthcare systems [58].

3.4. COVID-19 and Policies on Healthcare Solid Waste Management

Worldwide authorities have received guidelines to address COVID-19 medical waste as a matter of utmost importance and urgency to prevent the spread of the virus and minimize impacts on public health and the environment. The spread of COVID-19 has largely been attributed to accidental contact with discarded materials by healthcare workers and patients [10]. In developed countries, hospitals and healthcare centers are required by law to carry out the proper disposal of such waste [10].

However, due to the sudden increase in the amount of healthcare waste, hospitals and healthcare centers were unable to respond quickly with adequate measures for the disposal of these materials during the pandemic. Therefore, it is crucial to develop contingency plans to deal with unforeseen changes in the flow of this waste in order to ensure greater safety for public health and the environment in the future [59].

In a brief worldwide systematic review on the COVID-19 pandemic and healthcare solid waste management strategy, it was reinforced that countries have adopted safety measures to combat COVID-19 contamination and manage healthcare waste. Nevertheless, they highlight that these measures are insufficient yet vary according to the context of each country [60]. The greatest challenges of waste collection in the USA were related to the early period of the pandemic. Thus, the greatest management challenges arose during the first quarter of the study period (March–May 2020) and persisted in the remaining three quarters (June 2020–August 2020, September 2020–November 2020, and December 2020–February 2021). The difficulties cited included (1) an increase in the volume of residential waste, (2) an increase in self-haul services, and (3) staff shortages due to illness and quarantine [61].

New York State also took aggressive measures to combat COVID-19 and enacted some policy changes, such as the statewide mask requirement being extended until early 2022, regardless of vaccination status in indoor public settings [62]. At the beginning of the pandemic, when there was no cure or vaccine available, countries, both developed and in development, adopted a combination of measures to contain the virus. This included COVID-19 testing, social isolation, lockdown, and the adoption of hygiene practices such as handwashing and the use of hand sanitizer. In Africa, some state governments in Nigeria, for example, have implemented partial lockdowns, closing outdoor markets and restricting movement between states. The Nigerian government has also imposed complete lockdowns in areas considered at higher risk of transmission [63].

In Brazil, by the end of March 2020, most states and large cities had implemented social distancing measures to contain the spread of the virus and later the use of masks. In addition, the federal government significantly increased the resources allocated to Sistema Único de Saúdev-SUS (National Health Service) to fight the COVID-19 pandemic, transferring, by the beginning of April 2020, BRL 16.7 billion in resources to states, hospitals, and federal government agencies [44].

Accordingly, the pandemic has led international organizations and several countries to develop new policies and guidelines to adjust their waste management strategies. Countries such as China and South Korea have become benchmarks in COVID-19 healthcare solid waste (HCSW) management for many developing nations, thanks to the implementation of effective and successful measures that have managed to contain and control the spread of the virus [9].

In China, such measures were established by the central government through the issuance of the "COVID-19 Infected Pneumonia Medical Waste Emergency Disposal Management and Technical Guide" (trial) [64], as well as the "Technical Specifications for Centralized Disposal of Medical Wastes" [65]. Some of the guidelines state that medical and healthcare institutions should store infectious hospital waste separately, keeping the storage site disinfected and respecting the maximum 24 h time limit for temporary storage [65]. In South Korea, there has also been a reduction in storage time and incineration of COVID-19-related waste [9].

A notable example is the city of Wuhan, China, which demonstrated effectiveness in the face of the COVID-19 pandemic scenario. Despite a fivefold increase in the amount of discarded healthcare solid waste during the peak of the pandemic, responses were swift in the storage, transportation, and disposal sectors, ensuring that all waste was discarded within 24 h of generation, in compliance with Chinese government guidelines. This significantly reduced the risk of virus transmission through healthcare solid waste [66]. Therefore, it is evident that improving the emergency management system for HCSW is essential in several aspects in order to minimize risks to human health by assisting in the prevention, management, and proper disposal of solid waste [17].

Although local governments in China have issued relevant reward and penalty policies, there are still problems of medical waste disposal, and these problems are generated in the match between local governments and disposal companies [67]. Thus, based on evolutionary game theory, it is proposed that the mode of static reward and dynamic penalty is considerably superior to others. That is, if the reward is static but the penalty increases dynamically, local governments tend to implement a better strategy, and disposal companies will improve the quality of medical waste disposal [67].

With the aim of promoting sustainable healthcare solid waste (HCSW) management, a rapid assessment method of the potentially infectious waste stream related to the COVID-19 pandemic in Romania was presented, recommending long-term measures for waste management policies [68]. Among these recommendations were the inclusion of health care waste management activities in the annual environmental reports of the European Commission, the creation of separate health performance reports for each country, and the provision of resources for the development and support of solid treatment facilities for HCSW as an alternative to hazardous waste incineration facilities [68]. In addition, the importance of including the HCSW management sector in circular economy policies, with clear guidelines and best practices, was emphasized [68].

However, it becomes imperative to underscore that the conception and implementation of strategies aimed at managing healthcare solid waste amid a pandemic situation present a substantially more complex challenge for the involved professionals. This complexity arises due to the need to encompass a wide range of critical factors that exert a direct influence on the formulation of such strategies. These factors span from environmental considerations to the analysis of prevailing legal statutes in the respective country, all while not disregarding aspects such as adopted energy policies, available technological capabilities, and evidently, economic considerations, among numerous other interconnected elements [50].

In order to simplify the process of the disposal of HCSW, which is systematic and complex, the principles of green governance have been proposed for the management of this waste [9]. These principles involve teamwork, in a participatory and cooperative manner, of the professionals involved, aiming to govern public affairs and achieve the objectives of sustainable development [9]. The segregation of HCSWs is highlighted as a fundamental step in the management of COVID-19 waste, highlighting the importance of guidelines promoting public awareness of the risks of this waste and encouraging segregation at the source [69]. Governments, local bodies, and waste treatment facilities should carry out awareness programs using various media to directly reach the population [70].

In March 2020, the World Health Organization released guidelines for the safe handling and management of COVID-19 waste, which include the collection of waste in clearly identified containers and safety boxes, by trained staff designated for the management of this waste [71]. The use of personal protective equipment such as sturdy boots, splash-proof aprons, goggles, masks, and face shields, as well as hand sanitization after handling the waste, is also recommended [71]. The WHO guidelines establish a robust foundation for the management of COVID-19-related waste by providing a set of standardized and rigorous procedures. The Pan American Health Organization (PAHO), operating as the WHO's regional office for the Americas, has reinforced these guidelines by adapting them to regional needs, fostering collaboration among countries, and facilitating the sharing of information and best practices. These directives not only address the protection of healthcare professionals but also primarily aim at preserving public health and minimizing adverse environmental impacts. Therefore, they represent a crucial contribution to the safe and effective management of such waste in pandemic situations.

In Brazil, the technical note GVIMS/GGTES/ANVISA n°4/2020 [72] provides guidelines for the management of solid health waste during the pandemic, in line with ANVISA's Collegiate Board Resolution n°. 222/18 [73]. One of the main guidelines is the segregation of waste at the place of generation, classifying it as infectious, chemical, common, and sharps [72,73]. A survey conducted in Brazil showed that although the hospitals analyzed and correctly forwarded infected waste for proper treatment, they were not prepared for situations that would alter the flow and volume of this waste, and it is therefore essential to establish contingency plans aligned with the municipal public authorities and society in general, in order to guarantee the safety of all [59].

A support tool was designed to assist in the identification of deficiencies in the generation of solid waste from hospitals, developing the Health Services Waste Management Index from the selection of indicators in the area. This index was implemented in six hospitals in the state of Minas Gerais, Brazil, in which the greatest difficulty found was in the adequate training of employees, which becomes even more alarming in a pandemic period [74]. Finally, it is important to review the protocols and recommendations as local contexts change since the number of contaminated people fluctuates significantly, but one should always seek to maintain and expand the engagement of citizens in selective collection and even in waste reduction actions [21].

4. Discussion

The COVID-19 pandemic has once again highlighted the importance of the relationship between hospital waste management and environmental safety, underscoring the ongoing need for research to address this topic. This is especially relevant as it is a relatively recent and continually evolving subject. The significance of this topic gained even more prominence when initial studies indicated a positive indirect environmental impact, largely attributed to the social distancing measures implemented by governments in response to the pandemic. However, more recent research has revealed that the temporary reduction in greenhouse gas emissions is not a sustainable solution to environmental challenges, emphasizing the complexity of the relationship between public health and environmental health. Thus, the continuous development of strategies and policies that effectively balance these concerns is crucial.

The results of this study also revealed that the pandemic will have a long-term impact on environmental sustainability due to the increase in the amount of hospital waste, especially infectious waste, and the increase in consumption of plastic-packaged products due to the growth of online shopping. This outcome is concerning since the incineration capacity of this waste cannot be expanded as quickly as the surge in healthcare waste generation, and high-temperature incineration is an important and widely used step, despite the risks of adverse impacts on human health.

Therefore, the major challenge of the COVID-19 pandemic crisis is to deal with the huge amount of ordinary waste that has become hazardous and requires special treatment, resulting in additional costs and the reduction in recyclable materials, leading to a global crisis in waste management, given that the existing treatment capacity was not designed to cope with such a sudden and substantial surge. Hospital waste treatment systems, such as incineration, possess physical and logistical constraints that impede a swift or sufficient expansion to match the accelerated waste production.

Furthermore, the expansion of waste treatment resources necessitates substantial financial investment to acquire and implement additional infrastructure, as well as supported human resources to operate and monitor these systems. During a pandemic, healthcare systems are already under pressure, and allocating resources for treatment capacity expansion can prove challenging. Another aspect to consider is that proper healthcare waste treatment is a complex process that demands specific precautions to ensure the safe elimination of pathogens and other hazardous risks. Thus, the simple expansion of treatment capacities cannot be swiftly realized due to safety considerations and environmental and health regulations, in addition to specialized infrastructure and equipment requirements.

Moreover, the growing awareness of the pandemic's environmental impact, such as the increased usage of single-use plastic products, underscores the interconnection between public health and planetary health. The concentrated management of hospital waste can lead to environmental harm, including water and soil contamination, directly or indirectly affecting population health. Confronted with these challenges, the pandemic emphasizes the need for policies and practices aimed at effective, secure, and environmentally responsible hospital waste management. Such an approach safeguards not only public health but also contributes to environmental preservation, highlighting the intrinsic significance of the relationship between hospital waste treatment and environmental safety.

Throughout the pandemic, both the World Health Organization (WHO) and the Pan American Health Organization (PAHO) have played an active role in coordinating global efforts, strengthening healthcare systems, and disseminating reliable information. Their essential role extends to future pandemics, where their guidance, research, and coordination will remain pivotal in safeguarding global public health.

Therefore, it is observed that in addition to the environmental impact, the pandemic also has current and future socio-economic consequences. However, recent studies, such as Cleaning up from the COVID-19 Response [34], Research on Optimization of Healthcare Waste Management System Based on Green Governance Principle in the COVID-19 Pandemic [9], and Stop doing needless things! Saving healthcare resources during COVID-19 and beyond [25], have been dedicated to mitigating these impacts by seeking green solutions and promoting changes in healthcare waste management policies and strategies, aiming at the containment of the virus and the reduction in secondary effects on society's health and the environment.

Proposals to minimize the impact of COVID-19 on society and the environment include the use of sustainable strategies, the recovery of biodiversity, eco-friendly lifestyles, improvement of health infrastructure, public awareness, and waste management, as well as the planning and support of local authorities to deal with proper waste management, preventing future outbreaks. In addition, it is important to utilize available alternative technologies for waste treatment and replace hazardous raw materials with innocuous substances, reducing emissions of noxious chemicals in incineration plants.

Recommendations such as transitioning to bioplastics, supporting waste management planning with decision-making tools, and implementing technologies such as artificial intelligence are mentioned as possible solutions. However, rigorous care is needed in the development and implementation of these solutions, taking into account the failures that have occurred in artificial intelligence solutions developed by large technology companies, shown in the study "Discussion on 'Challenges, opportunities, and innovations for effective solid waste management during and post COVID-19 pandemic, by Sharma et al. (2020)' " [36].

Thus, during the COVID-19 pandemic, the importance of proper HCSW management became evident, from classified packaging and pre-treatment to collection, transportation, and destruction. Actions such as the correct packaging of waste, the use of specific vehicles, the disinfection of deposits and vehicles, and the choice of appropriate treatment methods, such as high-temperature incineration or landfill processing after steam cooking and high-temperature boiling, are essential to ensure safe and sustainable management of COVID-19-related HCSW.

In this way, it is crucial to highlight that the pandemic has exposed complex challenges related to the management of healthcare solid waste, leading hospitals and healthcare institutions to confront emerging difficulties, including an increase in the quantity of generated healthcare waste, the need for stringent biosafety measures, and the impact of human and financial resource constraints. Thus, the study highlights these critical obstacles, providing a solid foundation for understanding the complexities involved and the need to address them effectively.

Furthermore, the study can assist in the development of guidelines and recommendations for addressing future challenges, which involve the evolution of management strategies and practices that not only ensure health safety but also address the environmental aspects related to healthcare waste management in a sustainable manner. Thus, this research not only sheds light on the past but also paves the way for safer, more sustainable, and effective waste management in future healthcare crisis scenarios, thereby contributing to the resilience of the healthcare system.

5. Conclusions

The COVID-19 pandemic has acted as a catalyst for the intricate interplay between healthcare solid waste treatment and environmental safety, underscoring the need to delve into the depths of this theme. The findings of this study emphatically emphasize that the pandemic will have enduring repercussions on environmental sustainability. The exponential increase in hospital waste, particularly infectious waste, and the surge in plastic consumption due to the expansion of online purchases emerge as areas of concern.

Furthermore, the growing disparity between the waste generation and incineration capacity stands as a significant challenge. Incineration, although widely accepted, carries with it risks of adverse effects on human health, engendering a complex dilemma. The central challenge lies in the appropriate management of the substantial volume of now-categorized hazardous waste, leading to additional costs and a reduction in recyclable materials, which could trigger a global waste management crisis.

Beyond the environmental consequences, the pandemic has extended into the social and economic domains. Nevertheless, contemporary research has endeavored to mitigate these effects, aiming for ecological solutions and promoting alterations in healthcare waste management policies and strategies to contain the virus's efficacy and mitigate the societal and environmental impacts.

Hence, proposals have arisen to mitigate the impact of COVID-19 on society and the environment. These encompass adopting good practices, revitalizing biodiversity, promoting ecologically responsible lifestyles, enhancing healthcare infrastructure, and fostering public awareness. Support and planning from local authorities are pivotal to effectively confront future outbreaks. Additionally, the incorporation of alternative waste treatment technologies and the substitution of harmful raw materials with innocuous alternatives emerge as resilient strategies.

These alternative technologies for healthcare waste treatment play a crucial role in pursuing safer and more sustainable disposal, aiming to destroy pathogens, reduce waste volume, and neutralize hazardous substances, thereby diminishing the environmental impacts and associated risks of conventional treatment, such as incineration. However, careful consideration is required when implementing these solutions, necessitating rigorous assessments of the strength, safety, and sustainability of these technologies before widespread adoption. This is especially relevant for technologies like artificial intelligence, taking into account lessons learned from the failures of previous large-scale technology implementations.

Thus, the pandemic has clearly highlighted the critical importance of proper healthcare waste management, spanning from generation to collection, transportation, and final disposal. This research further underscores the need for additional scientific studies on the subject, particularly at the national level. Since each region and country face specific challenges regarding healthcare waste management due to cultural, infrastructural, regulatory, and resource differences, context-specific research will aid in a deeper understanding of local challenges and the development of tailored strategies. Furthermore, built upon the lessons derived from the ongoing pandemic, research can contribute to the development of waste management strategies that are more effective in preparing for future pandemics, helping to make informed decisions that balance public health protection and environmental preservation.

Hence, it becomes evident that the pandemic has brought forth challenges in healthcare waste reduction worldwide and has led to stagnation in policies related to plastic reduction and waste recycling, owing to the surge in online shopping and food delivery services. This presents a concern that could cause severe environmental harm in the future, and it has been noted that the pandemic's indirect impacts on the environment have received limited scrutiny.

In this vein, this research provides vital recommendations and insights to enhance the management of healthcare solid waste during the COVID-19 crisis. It can also aid in future health crisis management as it promotes strategies that consider both public health and environmental preservation, striking a balance between present needs and those of future generations. This alignment advances the pursuit of sustainable development that does not overly strain ecological and social resources.

Furthermore, these strategies seek to ensure that the effects of the pandemic do not disproportionately fall upon various societal segments and that negative effects do not further exacerbate existing inequalities. Last, in crafting these strategies, it is possible to educate and raise public awareness about the significance of proper waste management, the protection of health, and the preservation of the environment. This could lead to behavior and habit changes that benefit society as a whole.

Thus, the distinctiveness of this article resides in its combination of systematic literature review, comprehensive analysis of healthcare waste management's pandemic-related impacts, and proposal of solutions to enhance sustainable waste management within a global health crisis context.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151914462/s1, PRISMA. Frame S1: Checklist items to be included in reporting a systematic review.

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