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LCA of Hospital Solid Waste Treatment Alternatives in a Developing Country: The Case of District Swat, Pakistan

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Abstract: Improper management of hospital waste leads to serious health and environmental issues, particularly in the case of developing countries, where, often, applied technologies are obsolete and there is a lack of compliance with respect to international best practices. The present study is designed to assess the environmental impacts of hospital waste management practices in Swath District, Pakistan. For this purpose, a life-cycle assessment (LCA) is applied for the estimation of different impacts of current and alternative hospital solid waste (HSW) treatment practices. Two scenarios are used to describe the current alternative practices (Scenario A and Scenario B), referring either to incineration or to direct landfilling of HSW without any sorting of collected materials. Conversely, Scenario C, which includes the use of pyrolysis and chemical disinfection, are considered as an up-to-date alternative, based on current international recommendations in this field. Prior to the analysis of impacts, due to the lack of available information, data were directly collected from both government and private hospitals in District Swat, involving measurements and a characterization of collected waste. In parallel, interviews were conducted, involving the hospitals' personnel. With respect to waste generation, government hospitals produce a larger amount of waste (74%) compared to private hospitals (24%). Poor regulatory indications and the absence of clear obligations for collection, disposal and management still represent a first obstacle to implement good practices. After defining the boundary of the system and the functional unit, according to standardized LCA practices, a life–cycle impact assessment (LCIA) was conducted, considering eight impact categories: human toxicity, freshwater eco-toxicity, marine aquatic eco-toxicity, terrestrial eco-toxicity, acidification potential, climate change, eutrophication and photochemical oxidation. The current practices (Scenario A and Scenario B) turned out to be the worst for all categories. In particular, the largest impact of all is recorded for human toxicity generated by incineration. In parallel, it must be considered that, currently, no recycling or reusing practices are implemented. Conversely, Scenario C (alternative up-to-date practices) would generate lower impacts. In detail, the highest value was recorded for marine aquatic ecotoxicity in relation to pyrolysis. Applying Scenario C, it would be possible to recover some materials, such as plastics, paper and sharps. In detail, considering the observed compositional characteristics, it would be possible to recover up to 78% of sharps and recycle 41% of plastic and paper from the general waste stream. Moreover, energy could be recovered from the pyrolysis process, generating a further benefit for the surrounding area. A lack of awareness, knowledge and infrastructures prevents the application of correct management practices, further degrading life and environmental conditions of this remote region of Pakistan. The huge difference in impacts between current practices and alternatives is demonstrated, showing a clear alternative for future management plans in this remote region and supporting future actions for local policymakers and hospital managers.

Keywords: hospital waste management; government hospitals; private hospitals; environmental hazards; medical waste; hospital solid waste

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1. Introduction

By definition, hospital waste is any kind of waste generated in the process of immunization, treatment and diagnosis of humans and animals, as well as in the testing of biological specimens, also for research purposes [1,2]. Its management implicates the supervision of waste generated by hospitals' activities [3]. Medical actions shield life and restore health. However, they also create a lot of medical waste and by-products, like non-sharps, infected sharps, blood, hazardous chemicals, body parts, pathological residues, medical devices, pharmaceuticals and radioactive materials [4–6]. These, in turn, might lead to hazardous human health impacts, including teratogenic, mutagenic and carcinogenic effects, reproductive and respiratory systems damages, central nervous system effects, diarrhea, typhoid, leptospirosis, cholera, human hepatitis B and C viruses and acquired immunodeficiency syndrome (AIDS). Environmental annoyance may also occur due to odors, cockroaches, flies, vermin and rodents [1,5,7].

Hospital waste management (HWM) practices are not the same in all countries. In fact, they are based on different regulations, level of education, economic conditions, accessible resources and available treatment technologies [8]. Various systems and practices are applied globally for a proper management of medical waste and for its safe disposal [7]. Good practices and regulations in developed countries support a clear classification of medical waste, indicating several conceivable approaches for waste assortment, storage, transport and disposal, with low risks to individual health as well as the environment [9]. However, current practices often are not satisfactory in the case of developing countries. There, the application of good hospital management practices is still an exception. In fact, choices for the disposal of waste are limited. Thus, low-scale incinerators are often used, or even direct unsecured landfilling [10]. Notwithstanding, the characteristic and hazardous nature of medical waste (MW), its treatment and disposal remain almost unattended. For example, hazardous hospital waste is still transported for disposal together with municipal waste, generating many risks to people and to the environment [11]. Within this framework, small hospitals contribute much, both in term of health care services and in term of poor management practices application. The generation of bio-medical waste pollution [12], is a common phenomenon in developing countries [13]. Thus, supporting the transition to a safe and lower-impact hospital solid waste (HSW) management approach is a big challenge.

Health activities can generate different kinds of waste. According to the World Health Organization (WHO), about 10%–25% of waste can be considered as hazardous [14]. This may include infectious, radiological, toxic and genotoxic items. Their improper management may lead to environmental and occupational health risks. Different treatment methods can be used for hospital waste. Common ones include both microwave radiation [15], autoclaving [16] or incineration [17], in the case of infectious wastes, and landfilling [18] or recycling [19], for general/non-infectious waste items. Data findings from the US Environmental Protection Agency reports and the operational experiences from industries show that one of the mature and reliable technologies for treating HSW is incineration [20]. Possibly, this will remain a relevant option also for the future. In fact, while reducing the waste volume, it easily enables the treatment of hazardous organic matters, as well as pathogens contained in MW. This is why, even if landfilling is often applied in developing countries as a direct solution, incineration is also used, allowing a decrease in the volume of total waste up to 90% and a reduction of the entire waste amount to 70% [21].

Current landfilling practice occupies a large portion of land, significantly degrading the environment, comprising the soil, water and the atmosphere. Some researchers mentioned the billions in precious metals discarded in landfills, as well as the underground water pollution caused by leachate, also released by landfills [22]. Nonetheless, incineration is not necessarily a better choice. In fact, several unwanted pollutants, like polychlorinated furans (PCDF), polychlorinated dioxins (PCDD) and heavy metal particulates, can be released by the incineration process if incinerators are not well designed and properly operated. Special attention is required in the case of close vicinity to urban centers, because of the presence of a higher number of receptors (i.e., the urban population) [23].

In the case of hospital waste separated collection, microwave and autoclaving, are used as sterilization alternatives [24]. These processes are applied in many countries [25,26]. Globally, autoclaving allows treatment of a variable amount, between 20% and 37%, of the HSW production. Chemical disinfection, through the use of lime, constitutes as alternate process for sterilization [27]. Due to the high environmental impacts of incineration, some countries increased the application of sterilization methods (e.g., the United State, Canada, and Greece), which also allow them to reduce the amount of discarded materials [28]. During autoclaving (occasionally indicated also as steam sterilization), a radiation or dry steam heat enters into a firmly coated chamber, where the waste is sterilized, with a temperature maintained between 121 °C and 163 °C. A certain number of hospitals and companies have considered autoclaving as a way to recycle plastic, paper and lab trash from hospital waste streams [29]. The by-products of these processes include liquids, solids (waste residue), and gases emissions. Instead, other materials can be recycled, as mentioned.

Recently, policymakers and planners implemented building MW disposal plants to meet the requirements of MW management. Planning operations were also supported by life-cycle assessment (LCA), which was applied to estimate the costs of commonly-used MW treatment technologies and to provide useful insights for MW treatment alternatives [30]. To date, many analytical tools have been used to compare waste disposal strategies, including cost-benefit analysis, life cycle assessment, the analytic hierarchy process and their combinations [31]. The European Commission strategy on waste and resources already emphasized the importance of life-cycle thinking for more sustainable waste management practices. LCA can provide precious insights into the potential environmental burden of different alternatives. Waste collection and transport activities consume fossil fuels, which in turn lead to greenhouse gas emissions. LCA can be used to track the environmental impact of such activities [18]. In fact, LCA is a useful technique to assist in the assessment of different waste disposal options, based on different waste emissions [32]. It is worth remembering that greenhouse gases emissions from waste management activities are a serious environmental problem. Unfortunately, research on MW receives less attention with respect to municipal solid waste and biomass waste [33].

Currently, research and surveys on waste quantification and disposal practices in Pakistani hospitals are very limited. Only a few studies investigated the environmental impacts of waste disposal activities in Pakistani hospitals [18]. The reason is that most of Pakistan's research on hospital waste still focuses on assessing the knowledge, attitudes and perceptions of the staff, involved in medical waste handling [34]. Conversely, it would be important to identify the existing flaws in MW management practices to reduce the risks to public health and to protect the environment.

The purpose of this paper is to assess the environmental impacts of MW, generated by the hospitals located in Swat District, a remote region of Pakistan. For such a purpose, field data are collected, in order to derive an inventory and a characterization of MW generated. Then, a life-cycle assessment is developed, based on three scenarios. In particular, current MW treatment practices include two alternative scenarios, named A and B (i.e., incineration and landfilling). Conversely, scenario C refers to an ideal condition, where up-to-date alternatives are applied, such as pyrolysis and chemical disinfection. Key impacting categories and processes are identified to determine which improvement measures could be taken in the future. In particular, detailed analysis of the impacts for each process and impact category is considered, before developing a comparison between current and alternative treatment practices. The present study could, therefore, serve as a reference point for benchmarking, monitoring and comparison purposes in the future.

2. Materials and Methods

2.1. Geographical Boundaries of the Study

This research includes seven government-owned hospitals and five private-owned hospitals located in Swat District, Pakistan. These structures supply a wide range of basic medical and surgery services, as well as some specialist ones, like maternity and pediatrics. In this study, each hospital is associated with a simple alphabetical letter, to simplify its identification. Figure 1 indicates the locations of the selected hospitals.

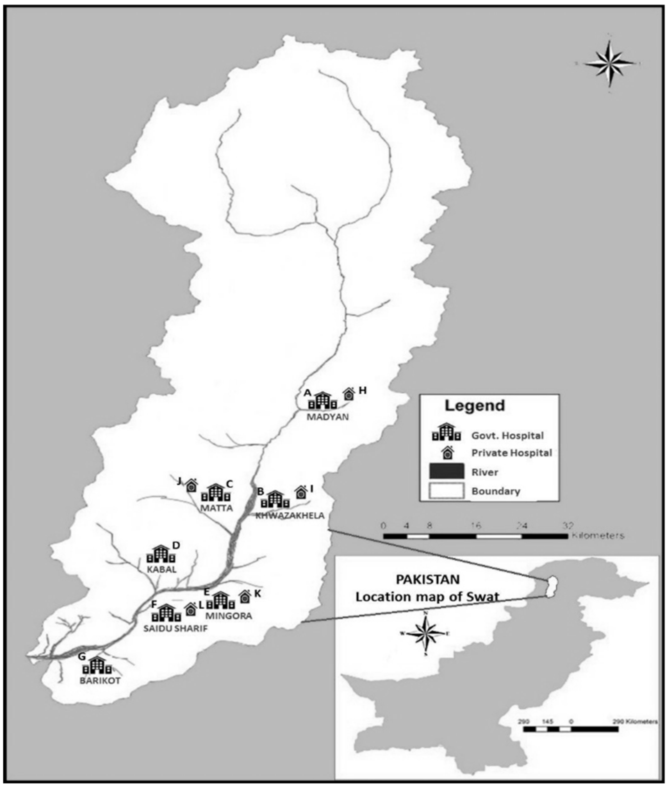

Figure 1. Location map of the study area, showing selected hospitals in Swat District, Pakistan.

2.1.1. Government-Owned Hospitals

Government-owned hospitals include: 1. Civil Hospital Madyan; 2. Civil Hospital Khwazakhela; 3. Zakir Shaheed Government Hospital Matt; 4. Civil Hospital Kabal; 5. Central Hospital Mingora; 6. Government Saidu Teaching Hospital; 7. Civil Hospital Barikot. These hospitals are coded as A, B, C, D, E, F and G (see Figure 1). Among the government-owned hospitals, E (Central Hospital Mingora) and F (Government Saidu Teaching Hospital) are the biggest, located in the cities of Mingora and Saidu Sharif. Being considered as prominent institutions for healthcare, they have the most advanced facilities compared to the other government-owned hospitals in the district.

2.1.2. Private-Owned Hospitals

Selected private-owned hospitals include: 1. Private Hospital Madyan; 2. Gull Medical Center Khwazakhela; 3. Hamdard Medical Center Matta; 4. Shifa Medical Centre; 5. Swat Medical Complex.

These hospitals are coded as H, I, J, K and L (see Figure 1). Among them, K (Shifa Medical Centre) and L (Swat Medical Complex) are the largest and leading ones.

2.1.3. Field Data Collection

Currently, the selected hospitals, as well as many other hospitals in other remote areas of Pakistan, are not compliant with any recommended standard related to waste collection and treatment management. For this purpose, on-site activities were necessary. In particular, interviews were arranged with randomly selected hospital staff, belonging to different categories (i.e., doctors, nurses, administrative personnel, cleaners, etc.). The method, used to conduct interviews, was described by [35]. It includes three instruments: survey questionnaire; site visit; in-depth interviews. Detailed information is given in Supplementary Materials A1, A2 and A3.

2.2. Medical Waste Classification and Optimal Treatment Options

Field activities allowed us to classify the collected MW, according to different standardized categories, as defined by [36]. General waste refers to solid waste, generated during activities other than direct medical ones (e.g., waste from offices, cafeteria, etc.). Infectious and potentially infectious wastes are considered as sub-component of microbiology and biotechnology waste. Pharmaceutical waste belongs to the category of medicines and cytotoxic drugs. Waste sharps (both used and unused) include blades, needles, scalpels, syringes, scalpels, glass and similar materials, which might cause cuts or punctures. Chemical waste refers to chemicals used in as treatment or disinfection materials.

Liquid waste, derived from medical activities, is not included in this study. Radioactive sources are not employed in the studied hospitals. Consequently, they are excluded from the study of impacts. On the basis of field activities, it was impossible to distinguish soiled waste (i.e., objects contaminated with blood and body fluids) from pathological or pharmaceutical ones. Better collection practice could allow such a distinction.

Collected waste, classified according to the categories detailed by [37], should follow different treatment processes (see Table 1). According to the same authors, if soiled waste is included, it would require autoclaving as treatment and disposal in municipal landfill. Alternatively, incineration is chosen. The whole treatment process, compliant with the existing international best practices, described by [30,37], is represented in Figure 2.

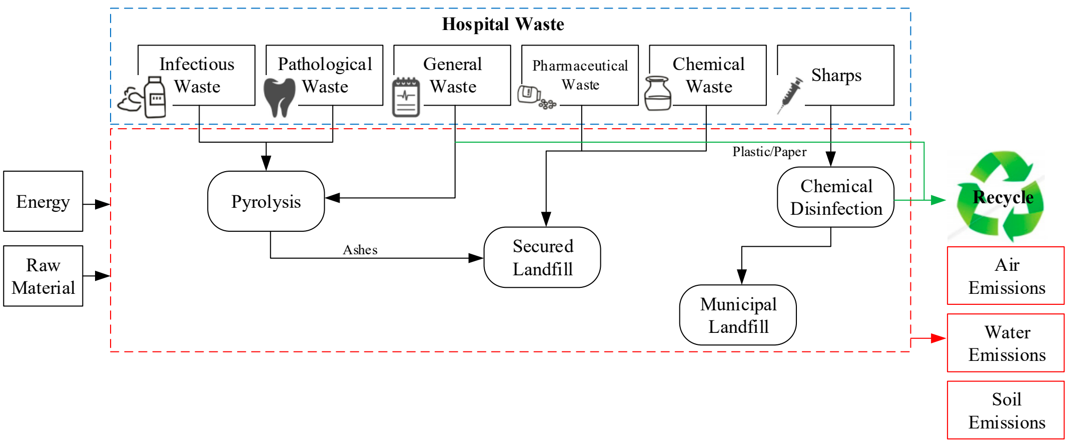

Figure 2. Optimal up-to-date HSW separate collection and treatment options, based on collected field data and according to reference guides. Inputs, in form of waste, energy and other raw materials, are represented. Air, soil and water emissions are included in the representation. The presence of a potentially recycled fraction, after chemical disinfection, is also considered.

Table 1. Hospital solid waste (HSW) categories, treatment and disposal options (source: [36]). Categories are defined according to waste classification in this study.

Waste Category	Treatment	Disposal
General	-	Municipal landfill/recycling
Infectious	Incineration	Deep burial
Pharmaceutical	-	Secured landfill
Sharp	Disinfection	Recycling
Chemical	-	Secured landfill
Pathological	Incineration	Deep burial
Incineration ashes	No treatment	Secured landfill

2.3. *Considered Scenarios*

Three alternative scenarios are fixed for this study. The first two, scenario A and scenario B, refer to current MW treatment practices, namely incineration followed by dumping in municipal landfill or direct dumping in municipal landfill. The third scenario (i.e., scenario C) refers to up-to-date practices, which can include different treatment processes, according to the nature of collected waste. Scenario C includes two treatment options, depending on the composition of collected waste. Moreover, pyrolysis is used as alternative to incineration. Instead, chemical disinfection is proposed to enable a partial recovery of collected waste.

2.3.1. Scenario A: Incineration and Landfilling

Under scenario A, HSW is burned into a semi-continuous stoker-type incinerator with no prior recovery of materials. Hospital managers refused to give further details on the existing treatment plants. Consequently, emission data for both incineration and landfilling were taken from the scientific literature [36,38–40]. Waste incineration, as represented in Figure 3a, is only active in two hospitals (B and G). The remaining hospitals opt for direct landfilling, together with municipal solid waste, without any prior treatment (Scenario B).

Treatment inputs are: mass flow, which represent the amount of waste going in to the incineration system; raw materials (limestone, NaOH, cement); energy (electricity, gas, diesel); land use for the treatment infrastructure. Treatment outputs are: direct emissions to the environment; residues, in the form of ash, which are disposed to landfills together with the municipal waste. Indirect emissions to the soil and environment are produced in the form of leachate and gases.

A report assesses emissions to air from current practices [41]: greenhouse gases (GHGs); criteria air contaminants (CACs) and acid gases. Criteria air contaminants include: ozone precursors, carbon monoxide (CO), nitrogen oxides (NOx), sulphur dioxide (SO_2), particulate matter (PM) and volatile organic compounds (VOCs). PM is further categorized as particulate matter with maximum equivalent diameter of 10 µm (PM_{10}) or 2.5 µm ($PM_{2.5}$). Fly and bottom ashes amounts vary from 5% to 20% of to the total waste mass after incineration. This value is in agreement with previous studies [42,43].

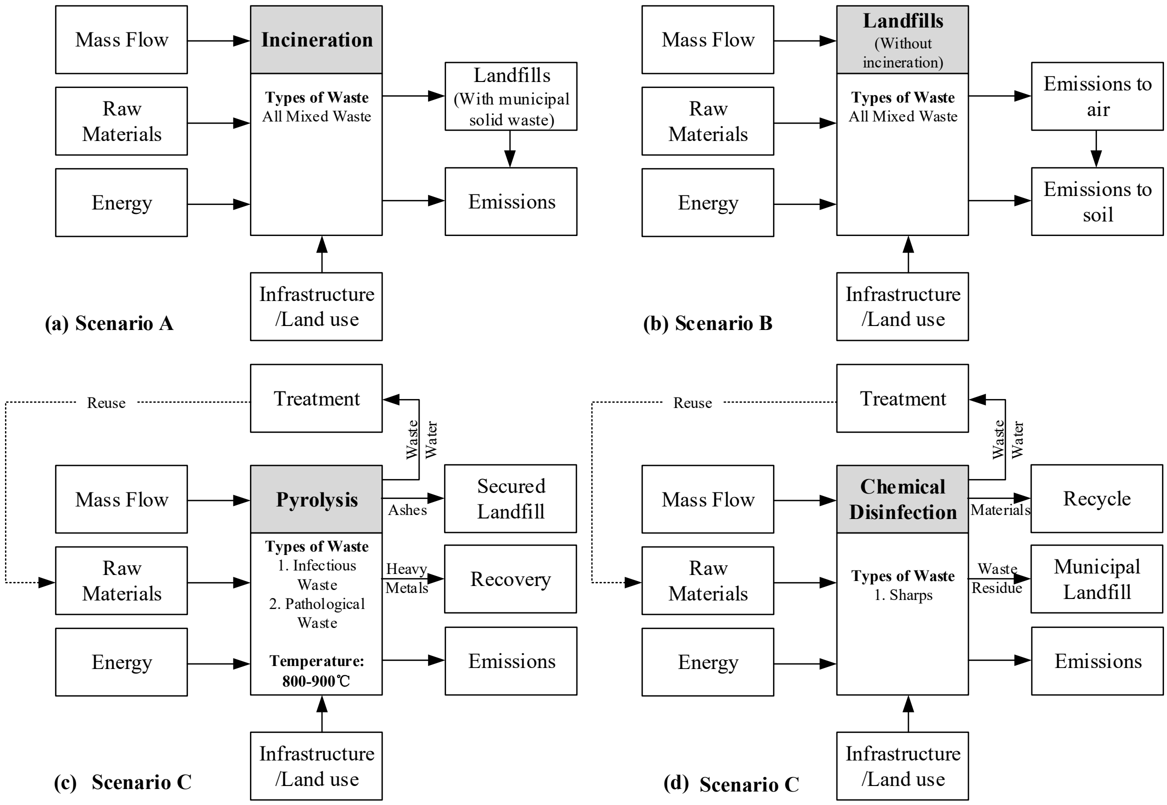

Figure 3. Flow chart of hospital waste treatment. (**a**) Scenario A: Mixed waste incineration followed by landfilling; (**b**) Scenario B: Mixed waste landfilling without incineration. (**c**,**d**) are the parallel processes of Scenario C. In particular (**c**) describes the pyrolysis treatment, which can be applied to infectious and pathological waste, while (**d**) refers to chemical disinfection treatment.

2.3.2. Scenario B: Direct Landfilling

The direct landfilling of mixed HSW without prior treatment is represented in Figure 3b. Landfill inputs are: mass flow; energy; raw materials; land use for infrastructure of landfilling. Outputs are: air emissions; emissions to soil; emissions to water. The impacts of leachate are among the most relevant. They require a continuation of the managing operation of the site up to 30 years after its closure. This is why the current regulations are very strict. The impacts derived from leachate affect the local area or a few km behind, depending on the landfill confinement. Therefore, if a large aquifer is not polluted, high damage costs are unlikely [44].

Assumptions regarding landfill emissions are described by [39]. Carbon emission to water, assessed as chemical oxygen demand (COD), is assumed to be 1% of biodegradable waste fraction [45]. This value was previously assessed, showing that approximately 3 g of COD are equal to 1 g of carbon [46]. Hydrogen sulfide gas is emitted to the atmosphere from 3% of disposed sulfur. Moreover, nitrogen content, up to 50% of total nitrogen, is assumed to be a discharge from the biodegradable fraction, while leachate only contains 1% of total nitrogen [45]. According to the literature, landfill leachate is generated, also triggered by rainfalls permeating on the landfill cover. In particular, leachate is mostly frequently formed on permeable top covers. Conversely, on impermeable 'dry tomb' top covers, leachate is formed when the top cover is removed [47].

Air and water emissions can be classified as direct and indirect. In particular, indirect discharges or emissions occur, due to the use of fuels to produce the used construction materials. In parallel, emissions, from landfill shaping, waste transport and other landfill operations, as well as from waste itself, contribute both to direct and to indirect emissions [48].

Depending on waste composition, the materials degradation and reactivity generate landfill gases, as well as leachate as liquid outflow. Reactive waste can generate gas releases up to several years. Different gases, like methane and carbon dioxide, are classified in the group landfill gas (LFG). Nevertheless, for the consistency purposes in this analysis, single compounds in the formation of sulfur dioxide, hydrochloric acid and other volatile organic compounds (VOCs) are also considered. The VOCs amount is quantified in term of hexane equivalents [40].

2.3.3. Scenario C: Up-to-Date Treatment Technologies

An alternative scenario, based on up-to-date practices, is proposed. This scenario is composed by different treatment options, defined according to the HSW classification applied in this study and treatment processes. HSW classification and treatment options are detailed in Table 1, Figure 2. This alternative scenario is thought to serve all the selected hospitals in study area. The different treatment phases composing the scenario C are described in the following sub-subsections.

Waste Combustion through Pyrolysis

Pyrolysis consists in the combustion of waste at reduced oxygen content, low air flow rate and lower temperature rate. Specific fractions of HSW can be treated, like infectious and pathological materials, at a very high temperature, ranging between 800 °C and 900 °C. Waste must be sorted very carefully, in order to avoid the inclusion of any Polyvinyl Chloride (PVC) containing plastics and mercury compounds. Residual ash, constituting 3–4% of the original burned mass, should be properly disposed in a controlled or sanitary landfill to prevent soil and water contamination [49].

A total MW input of 454 kg/day is used for pyrolysis. This amount includes organics, pathological, and infectious waste, together with textile and other components, being classified as general waste. The process inputs also include raw materials (water, $Ca(OH)_2$, NaOH, NaClO, activated carbon) and energy (diesel, electricity). The materials recovery rate reaches 2% to 3% of the MW input mass. Metals and glass amounts are very low, according to the results of field surveys. However, it is possible to recover metals, like Cu, Pb, Ni, Cd, Cr, Mn, Sn, Hg and Sb, if modern processes are used. The water used in the process can be partially reused. The total efficiency for waste volume reduction varies between 90% and 95%. Emissions to the atmosphere occur in the form of NO, CO, HF, HCl, Dioxin, PM and CO_2. These emissions cause different environmental problems and threats to human health. Residual solid waste, produced after treatment, is in inert form and can be landfilled. Energy can be produced in combination to waste combustion. Due to the applied combustion conditions, pyrolysis is easier to control than incineration. Pyrolysis is often chosen for waste treatment in developed countries, as reported by the literature [50].

Waste Chemical Disinfection

Chemicals (ozone (gas), chlorine, propylene oxide (gas), ethylene oxide (gas), formaldehyde, peripatetic acid) can be used as a sterilizing agent. The sterilization efficiency depends on the pH and temperature of each chemical agent, as well as on the presence of compounds which can interfere with disinfection. Waste is sterilized if proper exposure conditions are met [50]. In the treatment process, quicklime (CaO) can also added. Quicklime, produced by heating limestone available in the form of odorless gray or white powder, can be used in several industrial processes. After reaction with water, it forms calcium hydroxide, which can cause eyes and upper respiratory track irritation. The recommended exposure limit by NIOSH is 2 mg/m^3 [51].

It has been found that, due to their high plastic content (around 90%), plastic syringes (50 mL or 10 mL) have a high recycling potential. A research by [29] discovered that plastic syringes constitute about 21% of the whole generated plastic from MW. Another work, developed in a pathology laboratory, reported that 8.6% medical laboratory waste production consist of syringes [52]. In our study, the amount was measured, reaching 8% to 9% of the total generated waste.

Waste sharps, like glass, blades, syringes, scalpels and needles, can cause cuts and punctures. Consequently, sharps must be disinfected and mutilated after use. With at least 1% solution of sodium hypochlorite or other chemical reagent, the cut syringes, along with plastic solid waste, are put in a bucket for disinfection. Needles, instead, are moved into a puncture-proof container, having up to 1% sodium hypochlorite solution or any other chemical agent for disinfection [38].

In this study, sharp wastes, having a total mass of 439 kg/day, constitute the sterilization process input, together with raw materials (water, $Ca(OH)_2$, activated carbon, organic chemicals, ClO_2) and energy (electricity). After appropriate treatment, the water used along the process can be reused. Emissions, such as P, particulate matter (PM), chloride, VOCs and NH_3 are known, from the literature, to be minimal.

All the data are detailed in the Supplementary Materials. They refer to both the inflows and the outflows for waste treatment. Treated waste includes sharps, stock and cultures, humans and animals' liquid wastes (including body fluid and blood), laboratory wastes (excluding chemical waste), wastes from surgery, as well as other soft wastes from patient care (gowns, beddings, drapes, bandages and gauzes) [53].

2.4. Chosen Scenarios

As described in the previous section, Scenario A and Scenario B involve the current alternative practices, in which HSW is either incinerated or dumped, together with municipal waste, in a landfill. Scenario C involves the treatment of waste applying recommended technologies, based on the type of waste collected in the selected hospitals and on the current HSW classification system [38]. These scenarios (Table 2) will be used to develop a life-cycle impact assessment (LCIA).

Table 2. Three scenarios applied in LCIA.

Scenario A (Currently Applied)	Scenario B (Currently Applied)	Scenario C (Alternative)
Incineration and landfilling	Landfilling	Incineration (pyrolysis), disinfection and landfilling

2.5. Life-Cycle Assessment (LCA) and Functional Unit Definition

A consequential LCA is developed, in order to assess the environmental impacts of current and alternative MW treatment practices in 12 selected hospitals, located in Swat District, Pakistan [54]. LCA develops the collection and evaluation of all inputs and outputs together with the potential environmental impacts of a product system throughout its life cycle, as described by International Standard ISO 14040-43.

In the case of waste management and related resources, the use of LCA implies somewhat a different focus with respect to the traditionally product-oriented LCA [55]. Nonetheless, reports and studies show the efficacy of LCA in the context of MSW management, for which a number of LCA models are already available and in use [56]. Previously, the LCA method was applied to examine different alternatives for municipal solid waste management [57–59]. On the other hand, fewer studies focused on hospital waste [59–61]. HWM LCA studies generally focused on alternative treatments or referred to particular types of MW, like infectious ones [33], to facilities, like infant carriages [62], or to surgical-derived waste or health care products [63–65].

OpenLCA software (version 1.7.2) and database Ecoinvent (2010) (version 2.2) are used for performing the assessment for this study. OpenLCA is a freely-available open source software commonly used by LCA practitioners.

For each scenario, a detailed life-cycle impact analysis (LCIA) is developed to determine the environmental impacts. The applied impact assessment method is CML (baseline) (v4.4, Jane 2015). Eight impact categories are considered: human toxicity (HT); climate change (CC); eutrophication (EP); acidification potential (AP); marine aquatic eco-toxicity (MAE); terrestrial eco-toxicity (TE); freshwater eco-toxicity (FAE); photochemical oxidation (PO). The selected data normalization, from CML alternatives, is world 2000, meaning that normalization factors are based on global data referred to the year 2000.

A functional unit needs to be "clearly outlined and measurable". This allows us to develop a comparative assessment of different processes, based on the same functional unit [66]. For the impact categorization, the functional unit is set at 1 t/day, given a specified waste composition, as defined from the data collected in this study. The present study is specifically related to hospital solid wastes. It is important to remark that hospital waste is a non-homogenous mixture. Moreover, its generation rate and components amount are different from country to country, highly depending on the available infrastructures, applied management practices and personnel involved.

3. Results

3.1. Quantitative Analysis of Waste in Concern Hospitals

3.1.1. Hospital Solid Waste Production Rate

The hospitals included in this study have different number of beds. In decreasing order, they are: 336 for (E) 138 for (F); 50 for (C); 34 for (B) and (G); 28 for (D); 19 for (K); 14 for (L); 10 for (J); 8 for (A); 2 for (H) and (I).

Hospital (E) produces a total amount of waste of 0.6 t/day. This is highest production rate on daily basis, being the largest hospital in Swat district. Doctors and staff, here, are well trained and equipment is more available than in other hospitals. The HSW daily production rate for the other hospitals are: 0.246 t/day for (K); 0.191 t/per day for (F); 0.16 t/day for (C); 0.123 t/day for (L); 0.075 t/day for (B); 0.05 t/day for (G); 0.039 t/day for (D); 0.035 t/day for (A); 0.008 t/day for (I) and (J).

Complete data are listed in Supplementary Materials (Tables S1 and S2).

3.1.2. Waste Production Percentages

The study shows that the percentage of waste generation in a government hospital is 74% of the total hospital generated waste, which is greater than private hospitals that produce the remaining 26%. Studies reveal that the greater rate of generation is due to facilities, and more patient concentration in government hospitals. The study clears that each hospital produces a different percent of the total waste.

Of the total government hospital produced (E) Central Hospital Mingora (GH) produces 52%, (F) Saidu Teaching hospital (GH) produces 17%, (G) Civil Hospital Barikot (GH) produces 4.10%, (D) Civil Hospital Kabal (GH) produces 6.50%, (C) Zakir Shaheed Government hospital Matta (GH) produces 14%, (B) Civil Hospital Khwazakhela (GH) produces 3.40%, (A) Civil Hospital Madyan (GH) produces 3%. With respect to the amount of waste generated by private hospitals, (J) Hamdard Medical Center Matta produces (PH) 2.30%, (I) Gull Medical Center Khwazakhela (PH) produces 2.30%, (H) Hamid medical complex Madyan (PH) produces 2.30%, (K) Shifa Medical Center produces (PH) 31%, and (L) Swat Medical Complex (PH) produces 62.10% of the total as shown in Figures 4 and 5.

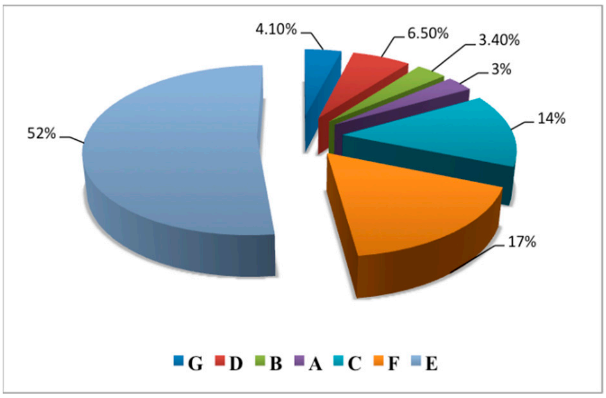

Figure 4. Relative daily waste generation rate (%) for government hospitals in Swat District, Pakistan.

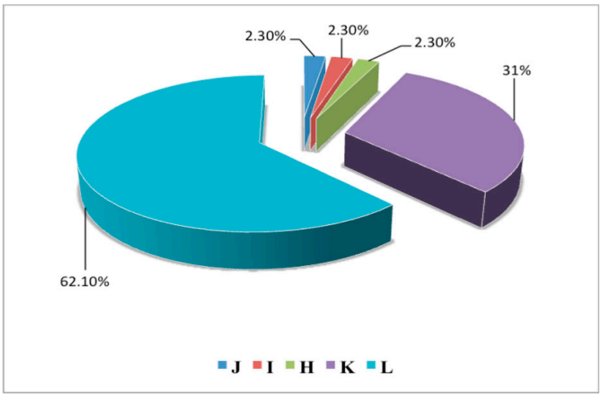

Figure 5. Relative daily waste generation rate (%) for private hospitals in Swat District, Pakistan.

3.1.3. Waste Composition

Waste characterization data are represented in Figure 6. The mean waste production rate, according to collected data, is 0.337 t/day. Collected waste is mainly composed of food residues, paper, plastic and textile. Food residues constitute the highest fraction (31 %/day). Plastic is ranked second (30 %/day), while the amount of collected textile is 29 %/day. The cardboard/paper is collected up to 11 %/day.

Infectious waste production rate is 0.129 t/day, while pathological waste is produced with a rate of 0.126 t/day. Generated pharmaceutical waste amount is 0.349 t/day, while sharps waste is produced at a rate of 0.439 t/day. Chemical waste is generated at a rate of 165 t/day.

During the study, field activities proved that, currently, no specific regulations and recommended practices are followed in collecting HSW. Waste is generally thrown in bins with no separate collection system. In some hospitals, WHO standard bins are available, but not used in the proper way. Instead, they are used for the collection of mixed waste, due to the lack of personnel training.

Collected waste is generally disposed of in open areas within the hospital. Moreover, infectious waste is not separated from the other waste streams. In the case of sharps, they are generally separated in all surveyed hospitals, where rigid, puncture-proof containers are used in 25% of cases. For the remaining 75%, cardboard boxes are used.

Typical incinerators are present in some of the government hospitals, but they are malfunctioning. In laboratories, the generation of chemical waste is mostly in liquid form. No rule for separate collection is followed. Instead, chemicals are often dispersed through the public sewerage system. The transportation system is also null, because all the collected waste is finally disposed into a common municipal collection point.

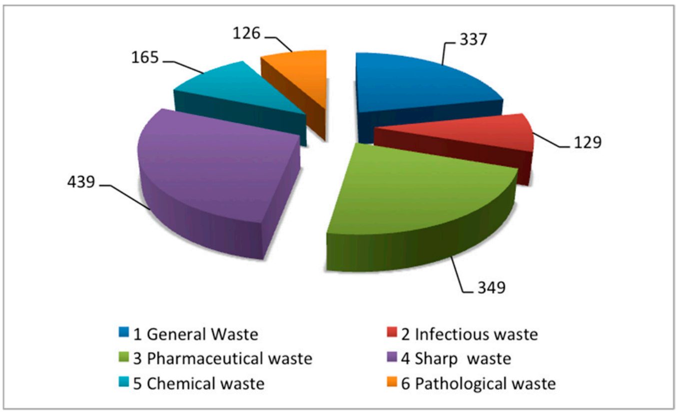

Figure 6. Production rate (kg/day) of different waste fractions for all hospitals in Swat District, Pakistan.

3.2. Life-Cycle Impact Assessment

Impact Estimation and Quantification

Eight impact categories are included the analysis, according to CML baseline scenario. Normalized data are compared to assess the relative relevance of each impact category. Normalized values, referred to all the considered categories and to each treatment process included in the analysis, are reported in Table 3.

Table 3. Normalized impact values (CML, baseline scenario, referred to global-scale normalizing factors for year 2000) for the MW treatment processes included in the analysis (i.e., incineration; landfilling; pyrolysis; chemical disinfection) for each impact category.

Impact Category	Process			
	Incineration	Landfilling	Pyrolysis	Chemical Disinfection
AP	2.16×10^{-9}	8.58×10^{-11}	1.26×10^{-9}	1.48×10^{-14}
CC	2.06×10^{-8}	2.15×10^{-8}	7.17×10^{-10}	0
EP	8.46×10^{-10}	2.69×10^{-9}	1.97×10^{-10}	5.13×10^{-15}
FAE	9.00×10^{4}	1.96×10^{-12}	2.29×10^{-10}	0
HT	7.50×10^{-1}	1.13×10^{-9}	1.90×10^{-7}	7.52×10^{-15}
MAE	1.53×10^{3}	2.10×10^{-7}	4.14×10^{-7}	0
PO	7.83×10^{-10}	5.84×10^{-9}	1.96×10^{-10}	0
TE	1.10×10^{-5}	2.70×10^{-15}	2.75×10^{-12}	0

Most frequently, human toxicity and marine aquatic ecotoxicity are the highest impacting categories, considering all the selected treatment processes. Acidification potential is also relevant in the case of up-to-date technologies (i.e., Scenario C). In more detail, in the case of incineration, the highest impact is related to human toxicity, followed by marine aquatic ecotoxicity, freshwater ecotoxicity, terrestrial ecotoxicity, climate change, acidification potential, eutrophication and photochemical oxidation. In the case of landfilling, marine aquatic ecotoxicity has the highest impact, followed by climate change, photochemical oxidation, eutrophication, human toxicity, acidification potential, freshwater ecotoxicity and terrestrial ecotoxicity. Considering the recommended treatment practices, with respect to pyrolysis, marine aquatic ecotoxicity represents the highest impact, followed by human toxicity, acidification potential, climate change, freshwater ecotoxicity, eutrophication potential, photochemical oxidation and terrestrial ecotoxicity. Finally, in the case of chemical disinfection, the highest impact is referred to acidification potential, being followed by human toxicity, eutrophication potential, climate change, freshwater ecotoxicity, marine aquatic ecotoxicity, photochemical oxidation and terrestrial ecotoxicity.

Normalized impact values for all processes, as reported in Table 4, are ranked, in order to identify the most impacting technology in relation to each impact category. Considering the top 10 impact values, incineration appears to be the most widely-impacting technology, followed by pyrolysis and landfilling.

The normalized impacts for landfilling and incineration are represented in Figure 7. In parallel, Figure 8 represents the normalized impacts of pyrolysis and chemical treatment. Due to the great difference in impact values, two scales are used in both figures, each referred to a different treatment process.

Both of the figures allow us to understand the presence of prevailing impacts in each treatment process. In detail, human toxicity prevails in the case of incineration. Instead, marine aquatic ecotoxicity is predominant in the case of landfilling. Considering pyrolysis, marine aquatic ecotoxicity is the predominant impact category. Finally, acidification potential, human toxicity and eutrophication are particularly relevant in the case of chemical disinfection.

Table 4. Top ten impacting categories, in relation to analyzed treatment process alternatives. Incineration, pyrolysis and landfilling appear to be the most impacting processes.

Category	Value	Process
HT	7.50×10^{-1}	Incineration
MAE	1.53×10^{-3}	Incineration
FAE	9.00×10^{-4}	Incineration
TE	1.10×10^{-5}	Incineration
MAE	4.14×10^{-7}	Pyrolysis
MAE	2.10×10^{-7}	Landfilling
HT	1.90×10^{-7}	Pyrolysis
CC	2.15×10^{-8}	Landfilling
CC	2.06×10^{-8}	Incineration

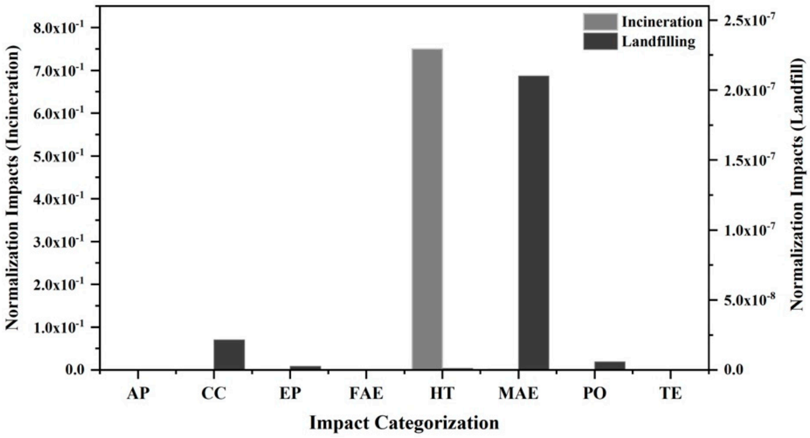

Figure 7. Environmental impacts of current treatment practices (Scenario A and Scenario B), constituted by landfilling and incineration.

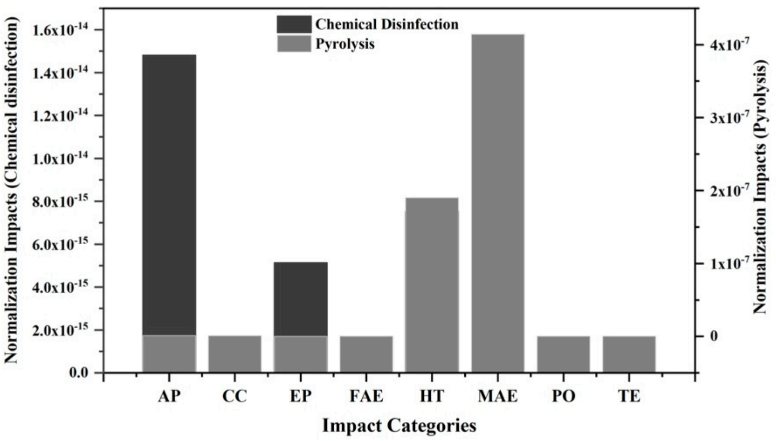

Figure 8. Environmental impacts of Scenario C, showing pyrolysis and chemical disinfection as separate components of the same scenario.

4. Discussion

4.1. Comparative Analysis of Cumulative Impacts

The cumulative impacts of current practices (Scenario A and Scenario B) and alternative up-to-date treatment options (Scenario C) are compared. As observed from the results, impact values derived from current practices are significantly higher than those related to alternative treatment technologies. In particular, uncontrolled incineration and landfilling cause high emissions to the environment, with consequent high impact values. In contrast to these practices, the use of recommended treatment technologies, such as pyrolysis and chemical disinfection, would cause a lower damage to the environment. Alternative recommended treatment technologies yield significantly better scores for not damaging environment under all impact categories as shown in Figure 9. Conversely, the current practices scenario A and B yield the maximum scores in all impact categories for causing damages to the environment.

Considering both materials recycling and the reuse of wastewater, together heavy metal recovery, derived from the application of alternative treatment technologies (Scenario C), the findings in this study show that a higher recovery of materials, like plastics, sharps and paper, generate a decrease in emissions and decline in relation to all impact categories. Thus, the impact comparison results show that, current practices cause many environmental burdens in all categories with respect to the alternative treatment technologies.

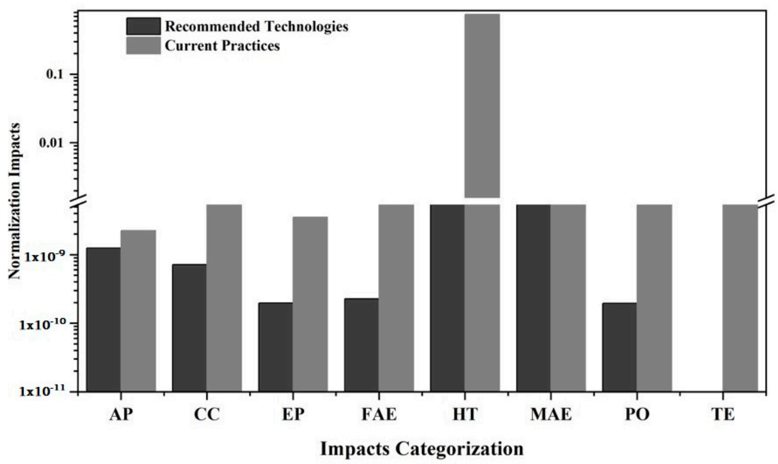

Figure 9. Comparative cumulative environmental impacts from combined Scenario A and Scenario B (current technologies) and Scenario C (recommended practices). The most relevant impacts are human toxicity, in the case of current practices, and marine aquatic ecotoxicity, in the case of recommended technological alternatives. The impacts of these two categories largely overcome the others. Human toxicity, derived from the application of current treatment technologies, represents the highest impacting category.

4.2. Comparison with Previous Literature Results

Currently, the literature regarding LCA applied to solid HWM in developing countries, such as Pakistan, is poorly developed. A life cycle impact assessment, developed through CML and Eco-indicator 99 databases, revealed that, using microwave sterilization, greater values in climate change and human health (Disability-Adjusted Life Year, DALY) categories were recorded [67]. These outcomes were individually inveterate, applying a similar approach, determining that, in its place, steam autoclave would generate less impacts. Another research, where LCA was conducted using CML1999 LCIA baseline approach, referred to steam autoclave sterilization and incineration technology for treatment of HSW followed by sanitary landfill [33]. In this work, incineration technology displayed higher environmental impacts.

Generally, hazardous waste incineration practice has higher global warming, freshwater aquatic ecotoxicity and eutrophication impact values. Instead, generated residues, which are landfilled, contribute much to human toxicity. However, another study stated that environmental impacts of traditional incineration technologies are lower than pyrolysis [68]. This was confirmed also in another study, comparing the performance of different treatment processes [69]. Nonetheless, pyrolysis and gasification are more efficient, considering the impact categories of human health, human toxicity, terrestrial eutrophication and photochemical ozone creation. This study shows that incineration has higher impacts. However, the relevance of pyrolysis impacts are also confirmed.

Comparing different treatment options, a research demonstrated that the environmental impacts of pyrolysis are comparable to the ones of chemical disinfection [70]. Our study does not support this statement, showing that pyrolysis would have a higher impact.

With respect to sterilization, autoclaving of hospital waste is considered the most suitable technology. However, it is observed that its costs would be higher with respect to incineration [71]. In fact, an additional treatment process is required for autoclaved waste [72]. Moreover, a large amount of infectious waste cannot be handled by this technology. Furthermore, some chemicals and infectious substances, like mercury, compounds and materials from chemotherapy care, VOCs, semi-volatile organic compounds and radioactive waste cannot be treated by autoclaving [73]. The same fact holds for large body parts, as well as for animal and other larger bio-derived remains. This depends both on the temperature which would be required and on the necessary treatment time-scale [74].

In our study, autoclaving was excluded from Scenario C, depending on the characteristics of collected waste, as well as considering its higher economic impacts. However, considering a transition toward more up-to-date treatment alternatives, more environmental-friendly technologies were considered, to avoid also an excessive use of traditional incineration.

In parallel, the development of appropriate plans for separation of hospital waste constituents is recommended. In fact, currently, behaviors enabling the subsequent recycling of materials (e.g., glass, plastic) are not encouraged enough. Instead, they would be highly beneficial, if supported by appropriate policies to admit the reuse and recycling of several hospital waste components [72].

In this study, the amount of plastic and paper, which could be recovered from waste streams, is quantified as 40% of the general waste collected in the studied hospitals. With respect to the entire medical waste, plastic materials constitute 12.3% by mass sent to landfills. However, a larger fraction could be recovered, considering that it amounts to 25.1% of the total medical solid waste. This value is consistent with that of 27.3%, being reported in the literature as a mean value from other case studies [75]. In fact, medical waste plastic content can range from 20% to 50% by mass [76,77]. Hence, plastic recycling should be boosted for lowering MW disposal costs [29].

In our findings, it is clear that, by applying alternative scenarios, it would be possible to recover 78% of sharps, after chemical disinfection treatment. Moreover, 41% of plastic and paper, generated from general waste stream, could be recycled. This would also generate some economic benefits. In fact, according to [32], some different material prices, considering the current exchange rate between Pakistani rupees (Rs) and US dollars ($) are: US$0.30/kg for plastic; US$0.07/kg to US$0.08/kg for paper; US$ 0.08/kg for glass; US$0.35/kg to US$ 0.40/kg for metal. Expanding the analysis framework of this research, additional lessons could be learnt from other experiences. In the view of the transition toward circular economy patterns, it would be essential to close significant loops through recycling and reuse of materials [78]. Instead, plastic waste still creates high impacts, in contrast to the existing treatment opportunities [79]. The same is true for paper. Considering this perspective, the present work preliminarily assesses the potential amounts of recyclable paper and plastics generated by the hospitals studied.

4.3. Consequences for Hospital Solid Waste (HSW) Treatment Management in Swat District

This work shows that current HSW treatment practices, which include incineration and landfilling, are greatly inappropriate and impacting. Incineration creates emissions, like SO_2, NO_x HCl, particulate matter (PM), mercury and dioxins. In parallel, landfilling produces greenhouse gas (GHG) emissions and also leachate. Moreover, the residues of incineration, mostly comprising exhausted sorbent and fly ashes, before final disposal in landfill, should be stabilized [80]. This is why there is a crucial need to apply alternative solutions, which are already available.

Among the causes of the existing inertia, in the case of Pakistan, economic development occupies a special place. This is, for example, the reason for which currently it is not possible to plan the installation of up-to-date technologies in each hospital site. Nonetheless, coordinated planning could be developed and applied at a regional scale. In particular, different sites could be chosen, considering their characteristics, positions with respect to the hospitals, as well as on the basis of existing transport infrastructures, which might require an upgrade. The development of scenario C, as a potential alternative, could generate also other benefits. For example, energy could be recovered from pyrolysis treatment. This is why this option should be an objective of future roadmaps and planning initiatives. Some of the materials, derived from general and sharps waste streams, may also be recycled.

The findings of this work enable to identify both existing opportunities and challenges. It is clear that, considering scenario C, different types of waste could be recovered, recycled and reused, as graphically synthesized Figure 3c,d. Consequently, for obtaining safer environmental conditions, reliable material recycling is necessary. This would also reduce the illegal trade and recycling of Pakistani MW [81]. However, the first step would be an appropriate training of personnel to guarantee the separation and effective management of generated waste.

The consideration of environmentally friendly collection and treatment processes, together with the potential economic benefits, should play a meaningful role in policymaking and supportive decisions. This assessment shows the key drivers and reasons behind this accomplishment. In all of the aforementioned aspects, the production rate of wastes varies from one another. Conversely, as confirmed from other literature studies referred to MNW, incineration with no energy and material recovery is more damaging to the environment and economy than other treatment options [32,33,67].

5. Conclusions

The safe management of HSW is very important with respect to the environment and to public health. Considering the current lack of compliance with up-to-date safe practices, this study investigates the HSW generated by Upper and Lower Swat District hospitals, in Pakistan. After defining the composition and daily generation rates of HSW, current treatment practices are compared with respect to alternative up-to-date ones to assess their environmental impacts. In particular, an LCA was conducted for such a purpose.

As a result, it has been confirmed that, at present, waste collection, storage, transport and disposal have a high impact and are non-compliant in terms of state-of-the-art international recommendations. In fact, hospital solid waste is either incinerated or, more frequently, directly landfilled together with municipal solid waste. Considering current practices (scenarios A and B), incineration and landfilling have higher environmental impacts, causing a great burden to the environment with respect to an alternative (scenario C), where recommended treatment processes are applied. Moreover, incineration has the highest impact, specifically related to human toxicity.

One of the practical difficulties faced in the research process is the lack of data availability, as well as a lack of separate accounting for different generated waste streams. After our field surveys, despite the guidance and training provided to health workers, several dangerous materials are still mixed together with general waste. This poses a threat to the health and well-being of scavengers and urban waste transporters. Thus, a first suggestion would be to implement a standardized data collection system, based on the outcome of this research.

As a further recommendation is that remotely-located health centers, as the ones considered here, should develop appropriate local and regional plans and policies for treatment, management and waste disposal. Within these plans, the possibility of recovering different materials, such as plastics, sharps and paper, should be carefully considered, given the potential economic benefits generated from recycling processes. The installation of future plants could eventually include the option of energy co-generation. This would further increase the beneficial effects of a technological upgrade. However, existing pre-conditions should be evaluated carefully during the planning phase, in order to optimize the management of HSW treatment. Finally, these plans should be integrated into training programs, continuous education and evaluation schemes of health management procedures both for organizations and staff. Additionally, local and central administrations in Pakistan should require all hospitals to prepare and distribute waste management and disposal plans as a condition of safer conditions for workers and the population, as well as to improve the environmental quality and sustainability of the area.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/13/3501/s1, Supplementary Materials 1: Field on-site collection of data: A.1 Inventory Analysis; A.2 Questionnaire surveys and field investigations; A.3 Ethical consideration and participants consent; Table S1: Hospital waste generation (kg/day) in Lower Swat, Khyber Pakhtunkhwa, Pakistan, Table S2: Hospital waste generation (kg/day) in upper Swat, Khyber Pakhtunkhwa, Pakistan.

Author Contributions: Each author equally made a substantial contribution to this study. Each author is responsible for the given contribution and its accuracy, as well as for the accuracy of the overall work. All the authors are equally responsible for the conceptualization and the decisions concerning the method used in this study. R.A., K.K. and J.N. are responsible for the data collection and validation. G.L., R.S., S.U., M.L. and M.C. are responsible for designing the chosen LCA scenarios. The formal analysis was conducted by R.A., K.K., J.N., J.X., R.S. and G.L. The original draft was prepared by R.A., K.K., J.N., J.X., G.L. and M.C. Writing—Review and Editing was performed by G.L., M.C., M.L., S.U. and R.S. The work was supervised by G.L. and M.C. Funding supporting this study were acquired by G.L. and S.U.

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