sustainability

Review

COVID-19 Biomedical Plastics Wastes—Challenges and Strategies for Curbing the Environmental Disaster

Siddharthan Selvaraj [1,†], Somasundaram Prasadh [2,†], Shivkanya Fuloria [3,*], Vetriselvan Subramaniyan [4], Mahendran Sekar [5], Abdelmoty M. Ahmed [6,7], Belgacem Bouallegue [6], Darnal Hari Kumar [8], Vipin Kumar Sharma [9], Mohammad Nazmul Hasan Maziz [4], Kathiresan V. Sathasivam [10], Dhanalekshmi U. Meenakshi [11] and Neeraj Kumar Fuloria [3,12,*]

[1] Faculty of Dentistry, AIMST University, Bedong 08100, Malaysia; sidzcristiano@gmail.com
[2] National Dental Center Singapore, 5 Second Hospital Avenue, Singapore 168938, Singapore; e0204949@u.nus.edu
[3] Faculty of Pharmacy, AIMST University, Bedong 08100, Malaysia
[4] Faculty of Medicine, Bioscience and Nursing, MAHSA University, Kuala Lumpur 42610, Malaysia; drvetriselvan@mahsa.edu.my (V.S.); mohammadnazmul@mahsa.edu.my (M.N.H.M.)
[5] Department of Pharmaceutical Chemistry, Faculty of Pharmacy and Health Sciences, Royal College of Medicine Perak, Universiti Kuala Lumpur, Ipoh 30450, Malaysia; mahendransekar@unikl.edu.my
[6] Department of Computer Engineering, College of Computer Science, King Khalid University Abha, Abha 61421, Saudi Arabia; amoate@kku.edu.sa (A.M.A.); belgacem.bouallegue2015@gmail.com (B.B.)
[7] Department of Systems and Computer Engineering, Faculty of Engineering, Al Azhar University, Cairo 11651, Egypt
[8] Jeffrey Cheah School of Medicine & Health Sciences, Monash University, No. 3 Jalan Masjid Abu Bakar, Johor Bahru 80100, Malaysia; hari.kumar@monash.edu
[9] Department of Pharmaceutical Sciences, Gurukul Kangri (Deemed to Be University), Haridwar 249404, India; vipin@gkv.ac.in
[10] Faculty of Applied Science, AIMST University, Bedong 08100, Malaysia; skathir@aimst.edu.my
[11] College of Pharmacy, National University of Science and Technology, Muscat 130, Oman; dhanalekshmi@nu.edu.om
[12] Center for Transdisciplinary Research, Department of Pharmacology, Saveetha Institute of Medical and Technical Sciences, Saveetha Dental College and Hospital, Saveetha University, Chennai 600077, India
* Correspondence: shivkanya_fuloria@aimst.edu.my (S.F.); neerajkumar@aimst.edu.my (N.K.F.)
† The authors contributed equally to this work.

Citation: Selvaraj, S.; Prasadh, S.; Fuloria, S.; Subramaniyan, V.; Sekar, M.; Ahmed, A.M.; Bouallegue, B.; Hari Kumar, D.; Sharma, V.K.; Maziz, M.N.H.; et al. COVID-19 Biomedical Plastics Wastes—Challenges and Strategies for Curbing the Environmental Disaster. *Sustainability* **2022**, *14*, 6466. https://doi.org/10.3390/su14116466

Academic Editors: Nallapaneni Manoj Kumar, Subrata Hait, Anshu Priya and Varsha Bohra

Received: 15 April 2022
Accepted: 22 May 2022
Published: 25 May 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Abstract: The rise of the COVID-19 outbreak has made handling plastic waste much more difficult. Our superior, hyper-hygienic way of life has changed our behavioural patterns, such as the use of PPE (Personal Protective Equipment), the increased desire for plastic-packaged food and commodities, and the use of disposable utensils, as a result of the fear of transmission. The constraints and inefficiencies of our current waste management system, in dealing with our growing reliance on plastic, could worsen its mismanagement and leakage into the environment, causing a new environmental crisis. A sustainable, systemic, and hierarchical plastic management plan, which clearly outlines the respective responsibilities as well as the socioeconomic and environmental implications of these actions, is required to tackle the problem of plastic pollution. It will necessitate action strategies tailored to individual types of plastic waste and country demand, as well as increased support from policymakers and the general public. The situation of biomedical plastic wastes during the COVID-19 epidemic is alarming. In addition, treatment of plastic waste, sterilisation, incineration, and alternative technologies for transforming bio-plastic waste into value-added products were discussed, elaborately. Our review would help to promote sustainable technologies to manage plastic waste, which can only be achieved with a change in behaviour among individuals and society, which might help to safeguard against going from one disaster to another in the coming days.

Keywords: plastic pollution; waste management; COVID-19; personal protective equipment; biomedical waste

1. Introduction

Plastics in medical products, such as disposable syringes, tablets, capsule blister packaging, joint replacement prostheses, intravenous (IV) fluid tubes, blood bags, catheters, and heart valves, help in supporting human life [1]. The human body is implanted with medical devices made from plastics. While plastics' benefits are far-reaching, massive production and waste mismanagement have raised environmental concerns [2]. In 2018, plastic production totalled 359 million metric tonnes (Mt), with 6.9 Mt of waste generated (3.2 Mt for short-life products), of which approximately 22% was incinerated, 25% was recycled, and 42% was inefficiently treated (i.e., littered or improperly disposed of in dumps or open landfills) [3,4]. By 2050, an estimated 12 billion Mt of plastic litter will have accumulated in landfills and the natural environment [5], with greenhouse gas (GHG) emissions from the whole plastic lifetime accounting for 15% of the total global carbon budget [6]. Low biodegradation, combined with indiscriminate use, improper disposal, and mismanagement, has resulted in the accumulation of plastic debris in terrestrial and aquatic compartments around the world, affecting natural biota, agriculture, fisheries, and tourism, as well as posing a health and safety risk to humans [7].

The quick spike in demand, for the usage of plastic items to protect the general public, patients, and health and service employees, is one of the acute environmental repercussions of any pandemic crisis, such as COVID-19 [8]. The extensive usage of protective gear across the world, as a result of the epidemic, causes huge supply-chain interruptions and waste-disposal issues downstream. The demand trend for various plastic products, such as personal protective equipment (PPE) including gloves and masks for health workers, disposable plastic components for life support equipment, respirators, and general plastic supplies, such as syringes, is expected to follow the global pandemic curve. Used plastic goods are, commonly, infected with pathogens and should be treated as hazardous trash. Plastic waste management was, already, a serious environmental issue before the COVID-19 epidemic began, due to rising worries about contamination in terrestrial and marine ecosystems [1,9]. Garbage management systems throughout the world have, already, struggled to deal with current plastic waste, and the predicted rise in waste from the COVID-19 epidemic threatens to overload waste management systems as well as healthcare capacity. Medical waste from hospitals is particularly problematic, due to the need to destroy any residual pathogens [2,10].

Treatment facilities are, often, built to handle steady-state circumstances, in which medical waste is treated at a consistent flowrate and composition. Thermal procedures, such as cremation, steam treatment (autoclaving), plasma therapy, and microwave treatment, are used in a variety of treatment technologies. Multiple economic, technological, environmental, and social acceptability factors influence treatment selection [11]. Systems that are built for steady-state settings are likely to be disrupted by rapid waste volume scale-up. Experience in Wuhan has shown that optimization models may be utilised, to give decision assistance for the hospital waste management reverse-supply-chain problem [12]. A related issue is deciding where additional waste-handling facilities should be erected, to handle the rising volume of garbage. Economic considerations, pollution, safety, regulatory concerns, and public acceptance are all important considerations. Those sentiments, however, arrived too late, at the start of the epidemic. Since these systems were intended for trash amounts generated during regular operations, the projected volume of waste greatly exceeds the existing capability to handle hazardous medical waste. If suppressions alone are not enough, new facilities can be erected, or mobile units can be deployed to increase capacity [12,13].

A pinch point occurs, where this expanded capacity meets the suppressed curve's peak, and ensures that pathogen-contaminated waste hazards are managed. After the epidemic has passed, it is clear that there will be a substantial surplus of treatment capacity. These treatment facilities are unlikely to be incinerators with heat recovery capable of being reused for municipal solid trash. Given the variety of technological possibilities for medical waste treatment, life cycle assessment (LCA) and associated methodologies can help determine which solution is the most ecologically friendly. Medical waste incineration, combined with waste heat recovery, is one technique for recovering the chemical energy content of polymers for usable applications. An early LCA [14], with sensitivity analysis of heat-recovery efficiency, demonstrates that boosting energy recovery reduces environmental consequences. Even when non-thermal solutions, such as chemical disinfection, are considered, this has been corroborated by a more recent LCA [15]. The widespread use of incineration with heat recovery, however, has some challenges. Trace dioxin and furan emissions can cause public worry [16]. Contagion worries are expected to outweigh any concerns about environmental footprints, including GHG and pollutants, therefore, social-acceptability considerations may not play a significant role in the present epidemic. A mismatch between the supply of recovered heat and the demand for it is a major issue. Some scientists [17,18] predict that the epidemic would peak in the near future, when demand for heat in much of the Northern Hemisphere falls, owing to the colder weather. Since the safe disposal of hazardous waste takes precedence, waste-to-energy plants may not be conveniently positioned for energy recovery. Xu et al. [19] presented ideas for balancing heat supply and provided insights on imbalances towards management. However, it is unclear if systems that must be erected quickly or transportable units that must manage rapidly increasing medical waste quantities can be developed for maximum energy recovery. Even before the COVID-19 epidemic, the long-term viability of plastics had been questioned [16]. This review will give a prospective outlook on how the disruption caused by COVID-19 can act as a catalyst for short-term and long-term changes in plastic waste management practices throughout the world and measures to mitigate the plastic wastes.

2. The Impact of the Pandemic on Plastic Waste

Handling municipal solid waste (MSW) and hazardous medical waste has become extremely difficult because of the epidemic. China has the greatest information on this subject [20]. In Hubei Province, the production of medical waste surged dramatically, with a significant number of plastics. The total amount of medical waste in China was projected to be 207 kt from 20 January 2019 to 31 March 2019. Medical waste production in Wuhan grew from 40 t/d (tonnes per day) to almost 240 t/d, surpassing the maximum incineration capacity of 49 t/d [21–23]. Hazardous medical waste incineration costs in China are predicted to be 281.7–422.6 USD/t (US dollars per tonne), compared to 14.1 USD/t for MSW [21]. Treatment systems intended for normal waste quality and quantity must deal with extreme fluctuations, which compel abnormal operations. To guarantee that these systems can cope with the pandemic's dynamic and changeable character, engineering analysis is required. Another issue is that there is still a lot of unknown information about the virus, as well as what items and methods would be required to handle the pandemic. The COVID-19 problem has brought to light the importance of plastic in everyday life. Even while disposability is mostly viewed as an environmental liability, in most other uses, the virus demands single-use plastic [24]. Plastic products have significant environmental footprints, which may be summarised using a realistic evaluation technique. During the COVID-19 epidemic, demand for medical items and packaging has been skyrocketing. The amount and quality of plastic garbage fluctuates, as a result of the various mitigation or suppression strategies, undertaken in various nations. Single-use plastics are seen by consumers as a safe choice, for a variety of uses. Van Doremalen et al. [25] investigated and found that viral pathogens can be seen in various surfaces and have the ability to survive on plastics. These findings were confirmed by Kampf et al. [26]. Despite the fact that plastics are no better than other materials in terms of virus retention, customers who value hygiene see disposability as a critical benefit. Even for non-medical purposes, this has resulted in a rise in the usage and disposal of plastic items. In contrast, in the probable global economic crisis, plastic demand in other areas (such as aerospace and automotive applications) is declining. As a result of the lockdown, the amount of packaging utilised to convey food and consumables to residents has increased. These changes may intensify environmental concerns about plastics, which persisted even before the epidemic. Despite the fact that this rise is inevitable, environmental protection activities must continue. Metrics for system design and comparing alternatives, as well as footprints, should be created and properly utilised. [4]. The top 10 countries' daily global plastic waste generation, prior to management, were elucidated in Table 1.

Table 1. Estimated daily global plastic waste generation by country, prior to management [27].

Rank	Country	Population	Total Estimated Plastic Waste (Tonnes)
1	China	1,439,323,776	107,949,283.20
2	India	1,380,004,385	103,500,328.90
3	United States	331,002,651	24,825,198.80
4	Brazil	212,559,417	15,941,956.30
5	Indonesia	273,523,615	20,514,271.10
6	Japan	126,476,461	9,485,734.58
7	Russia	145,934,462	10,945,084.70
8	Mexico	128,932,753	9,669,956.48
9	Nigeria	206,139,589	15,460,469.20
10	Pakistan	220,892,340	16,566,925.50

3. Challenges in Waste Management

Many sorts of extra medical and hazardous waste are created during an epidemic, including contaminated masks, gloves, and other protective equipment, as well as a greater number of non-infected products of the same nature. Recent instances of airborne transmission [28] have prompted suggestions that people wear masks in public places. The proper handling of this waste can help to avoid negative consequences for human health or the environment. The identification, collection, separation, storage, transportation, treatment, and disposal of biomedical and healthcare waste, as well as crucial connected issues such as disinfection, staff protection, and training, are all required for effective management. Even the most modern healthcare institutions are struggling to keep up with the continually growing number of infected people. Patients who are self-isolated at home, due to minor symptoms, create polluted MSW. This necessitates a significant structural adjustment in trash management, ranging from sorting regulations, collection, and waste treatment to garbage collection personnel safety protocols, which has been followed by ACR, an international network that plays a major role in promoting the sustainable consumption of resources and management of waste among various nations around the globe [29,30], including a number of safety precautions regarding waste management.

They pose logistical obstacles for waste management systems, so other economic and environmental concerns have been pushed aside, in the wake of the coronavirus outbreak. The most prevalent methods for the thermal treatment of hazardous medical waste are incineration and steam sterilisation (90 min, 120 °C). After an effective decontamination cycle, in accordance with non-hazardous solid waste regulations, the residue from these operations can be properly handled [31,32]. In Germany, incineration temperatures must be kept at 1000 °C, to ensure safe annihilation. The WHO recommends a temperature range of 900 °C to 1200 °C for healthcare waste [33]. The fundamental issue is that COVID-19 is causing a waste spike, which might easily surpass treatment capacity. In this dire scenario, whether to use MSW incinerator capacity for medical waste remains an unanswered subject. Cement facilities in Spain are said to be able to co-incinerate waste on demand [34,35].

Due to flexibility in responding to changing demands, on-site and mobile therapy is preferred in China. There have always been benefits and costs, and they are subject to contextual limits. Plastics have similar calorific values as traditional fuels. The plastics fraction of MSW is predicted to have a calorific value of 25% [36]. The assumptions established during the development of waste management strategy (e.g., incentives, taxes, oversimplification on specific plastic composition, collection method) are, suddenly, no longer totally true. They were justified by the necessity to meet governmental goals for collection, recycling, and recovery, which resulted in the undersizing of retrieval and dumping facilities, promoting recycling, even when it was neither practicable nor sustainable, during the existing epidemic.

Pyrolysis and gasification are in development, stimulated by the request for more sustainable-waste-treatment options [37]. An economic assessment proposes that the present scenario is sustained by a tipping fee, which is continuously rising due to the high costs of transportation towards the treatment processes, both for recovery and for disposal [38]. Many countries have restricted the use of plastic bags. In the EU, even if the food packaging is plastic, the carrying bag is made of paper. However, the environmental footprint advantage of paper bags is questionable, since they, mostly, have limited potential for reuse. The typical paper bag (2.62 MJ/bag) has a higher energy footprint than a typical plastic bag (0.76 MJ/bag), which is much lighter. This reduced weight, also, incurs reduced footprints elsewhere in the supply chain [38].

4. Scientific Strategies for Mitigating Medical Waste Plastics

4.1. Recycled Polymers for 3D Printing

The worldwide manufacturing of components composed of plastics has risen significantly in the recent past, as it has soared as high as 359 million tons in 2019, per PEMRG (Plastics Europe Market Research Group); a little higher than half of the production is in Asia, and around 17% is in Europe. The production of virgin plastics requires close to 4% of the total oil that is manufactured, which is tantamount to 1.3 billion barrels annually [39]. These plastics are composed of polymers, which do not degrade and, instead, stay in the landscape for several hundred years; thus, the pollution associated with this plastic waste should be taken very seriously [40]. A maximum of 90% of the plastics can be reused, however, 80% of the wastes are dumped in the landfill, and a very minute percentage is being recycled. The primary issue is that plastics composed of PVC, PP LDPE, and HDPE are dumped, mainly, in landfills and release greenhouse gases [41]. The goods composed of polymers, such as PLA, have a weaker influence on environmental pollution, however, the usage is limited due to their low durability. These plastics' stability declines sharply upon reusing, causing harmful effects to human beings [42].

The technique of 3D printing has led to the production of complex structures on a smaller scale. This technique could be used to tackle the increasing amount of post-production waste [43,44]. Activities, such as selective material separation, decontamination, purification, grinding, re-melting, and extrusion, determine these polymers' recycling process. The logistics and economic aspects hinder this process, as no profits are gained upon recycling, and the original's market cost determines the cost of these recycled products [45]. However, given the increasing environmental restrictions and recycling of plastic waste, this could be a potential solution, despite the lack of exact economic profitability [45,46] (Figure 1).

Polypropylene (PP), polyvinyl chloride (PVC), high- and low-density polyethylene (HDPE, LDPE), polystyrene (PS), polyethylene terephthalate (PET), and the "other" category, mostly acrylonitrile-butadiene-styrene (ABS) and polycarbonate (PC), are now being recycled globally. All of the aforementioned categories have been studied for their possible application in 3D-printing filaments, according to the literature. PLA's natural origin was, primarily, investigated in comparison to other polymers. The impact of repeated material recycling [47,48], as well as the potential of adding an additional strengthening component [49–51], were investigated. The material is separated and cleansed in the primary step, before being ground. After that, the ground material is extruded at a hot concentration (subject to the polymer type). This filament material is inserted into the 3D printer, where various kinds of analysis are carried out, such as mechanical, rheological, and structural characteristics, to name a few. This tested sample is milled again [48]. If the material requires any modification, in the primary case, an additional component and a binder, such as silicone oil, are added to the mixed material, followed by extrusion [52].

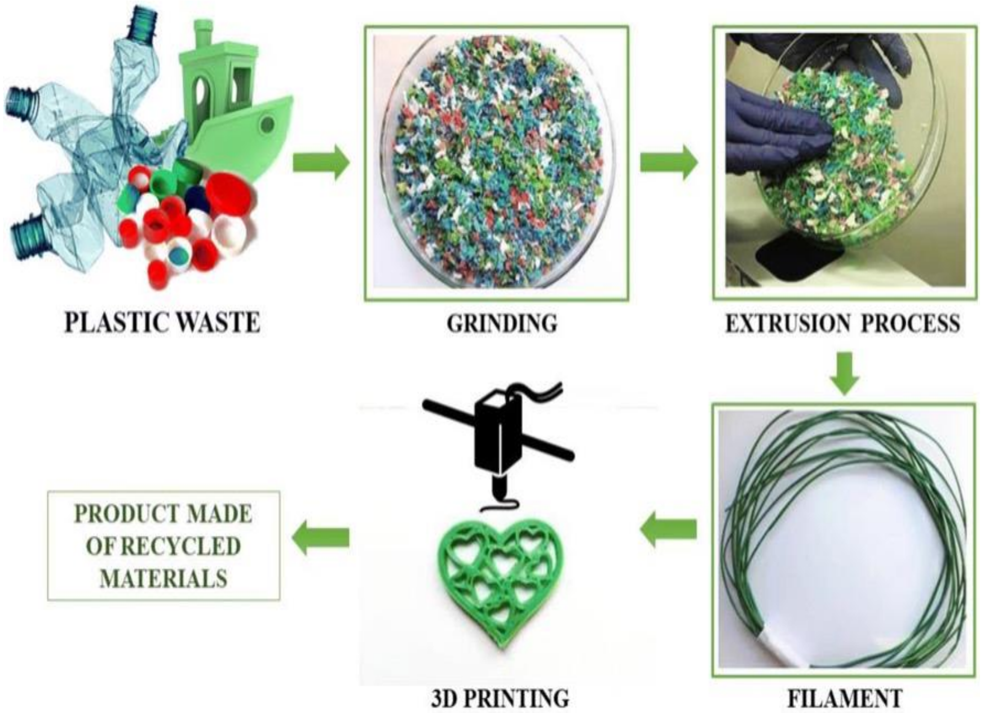

Figure 1. Strategic scheme for recycled plastics wastes [45].

4.1.1. Impact of Recycling on the Material Properties

Mechanical stresses, such as shear stress, are combined with temperature and oxygen occurrence, while extruding leads to the degradation of the polymers, such as PLA and resistant P.E. [53]. This change in physical characteristics has a considerable effect on the production of high-quality extrusion. The multiple extrusion of polymers influences their change in viscosity, molecular weight, and breaking strength. Changes in properties are generated by temperature and the amount of extrusion of one material [48].

4.1.2. Mechanical Properties

Filaments composed of polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are the most common thermoplastics available for 3D printing. Their costs are close to 200 times as much as the raw plastics [43], however, recycling thermo-mechanically leads to a lower printing cost. Despite its toxicity, ABS synthesised from oil is used for several applications. PLA, a biodegradable and biocompatible polymer, is sensitive to high temperatures, so degradation occurs upon exposure [54]. A reduction in PLA chains can be accomplished, by repeating the number of heating cycles, leading to shorter polymer chains [50]. The shorter polymer chains can, effectively, reorganise themselves into more ordered crystals, due to the increased melt flow rate. There was a small decrease observed in the tensile strength and strain, at break. The largest reduction in strain was recorded upon the first extrusion, which was 4%, and the largest decline in stress was 8%. The lower cohesion is responsible for reducing stress at break, whereas the decline of strain resulted from a reduction in the chain's length and a higher degree of crystallinity [48,50].

The decrease in the cold crystallization temperature and the decline in the melting point results in PLA's heating. A small reduction in the molecular weight is subjected to one reprocessing step [46,55]. The degradation rises to 30% after three cycles and 60% after seven cycles [50,56]. The loss of weight, repeatedly, upon extrusion was confirmed by T.G. analysis, which starts at 320 °C and continues until evaporation at 600 °C. The transesterification is encouraged in the presence of free radicals, upon thermo-mechanical recycling [48]. Furthermore, scientists have, also, discovered that the extrusion cycles increased water vapour transmission by 40% and oxygen transmission by 20%. Both activating substances are considered free radical reactions' antecedents. Hydrolysis and transesterification with residual catalysts are two further possibilities for degradation. There is a minor decrease in the intrinsic velocity, upon hydrolytic degradation without washing. On the contrary, a significant decline can be seen in the viscosity in washed PLA wastes, due to elevated temperatures and shear stress while reprocessing polymers. This degradation during accelerated aging can, also, contribute to this process [57]. The oxidative stabilisers (quinone) and residual catalyst stabilisers (tropolone) decrease rheological degradation. Upon recycling, the mechanical strength of the PLA decreases. The coating of the recycled polymer with polydopamine (PDA) can tackle this issue, where PDA is adsorbed on the water-repelling surface of PDA, thus, developing cohesive strength during self-polymerization. The thermal stability of this coated polymer exists up to 200 °C. It possesses higher tensile strength and strain at break, and its surface exhibits higher adhesion than uncoated PLA [58].

Another technique was proposed by Anderson et al. (2017) [53], where direct recycling of the utilised PLA filament was carried out by grounding and re-extrusion into 3D-printing filament. The material regains the same dimensions and surface finish, after two cycles of extrusion and one process of 3D printing, but the mechanical properties decline slightly. This process's primary limitation is reducing viscosity, due to chain scission, prohibiting the PLA filaments' utilization for further printing [51]. The lamellar structure rearranges the polymer chains' randomization, due to the reduction in the molecular weight. As a result of 3D printing, there is an increase in crystallinity as well as the number and average size of the pinholes, in twice-recycled PLA filament, contrary to the notion that repeated extrusion was the cause. Due to the thermal process, the shortening of the polymer chains led to easier crystallization, with a higher crystal population [59]. The recycled and shredded PLA filament can be enhanced by the virgin PLA addition, where the viscosity, mechanical, and thermal properties improve [51,58]. Thus, this contributes to the closed-looped recycling of PLA filament, which can be done in a benchtop machine at home [60].

The combination of a recycle bot and an open-source self-replicating 3D printer [59] has made recycling of PLA and ABS wastes very promising. Computer wastes were mechanically cleaned, to remove the impurities affecting the filament consistency. It may, also, lead to clogging in the nozzle of the 3D printer. The temperature while heating was regulated, at a temperature lower than the decomposition of structures and higher than the glass-transition temperature, to ensure that the printout does not degrade [61]. ABS must be dried and crushed, to ensure no bubble creation on the filament surface. Cruz Sanchez et al. (2017) [43] reported degradation of the PLA filament in five reprocessing cycles. The data obtained showed a considerable reduction in tensile strength and breaking strength as well as nominal deformation at the break. It was reported that the decomposition of the material correlates to the reduction in the crystallinity, viscosity, and molecular composition. The degradation mechanism majorly involves the five processes, namely: (1) formation of oligomers (hydroxyl and carboxyl); (2) esterification; (3) intermolecular transesterification, including interchanging of ester units between different chains; (4) thermo-oxidation; and (5) micro-compounding process. Moreover, 3D printing plays a role in the degradation of filaments, where uneven heating and cooling lead to stress accumulation, thereby affecting mesostructured and fibre-to-fibre bond strength [62]. Among other factors, one can mention the neck's growth between filaments and layers, randomization of the polymer chains on the contact surface, molecular diffusion, and internal defects (e.g., voids and the staircase effect) to the material during printing [63].

4.2. Methods to Recycle and Reuse Biomedical Plastics Waste

The 3Rs, namely Recycle, Reduce, and Reuse, have been the significant motto used for decreasing waste accumulation. The recycling of biomedical wastes is required to avoid accumulation, as in the case of conventional waste. However, before recycling, these wastes must be sterilised, to ensure the non-transmission of pathogens. Reports have suggested that the coronavirus survives on the PPEs for four days after contact [64]. Several methods of sterilization have been discussed below. The application of these methods on a large scale is a challenge.

4.2.1. Thermal Processes

Thermal-based systems, involving low heat (93 °C to 177 °C) generated by steam and microwaves, are being used. It is widely known that exposure to heat and microwaves can degrade plastics and lead to more inferior characteristics. Moreover, very high capital is essential, for such large quantities of waste to be treated by microwaves. Besides, the contaminant degassing and a release of toxic fumes are highly likely. The pyrolysis occurs at mid-range temperatures (177 °C to 540 °C); however, it consumes a lot of energy, and the products formed are not useful. The processes involving higher heat, such as plasma, lead to plastics's incineration into carbonaceous substances, leading to an increase in the carbon footprint, thus polluting the atmosphere [65].

4.2.2. Chemical Processes

The chemical processes, majorly, involve using compounds generating chlorine, such as sodium hypochlorite and chlorine dioxides [66], however, it is slower, as the PPEs must be dismantled, before exposure to chlorine–alcohol-based solutions. PPE's metallic components must be safeguarded from corrosive chlorine mists, which are applied along with alcohol.

Battelle CCDSTM (USA) has developed a concentrated-hydrogen-peroxide system in the vapor phase, for decontaminating PPEs. They offer complete pickup of contaminated PPEs and drop off at the healthcare facility after decontamination. They decontaminate 80,000 PPEs at a time [67,68]. This technology has been approved for use by the USFDA and has already been deployed for use in the US cities of New York, Seattle, Ohio, and Washington, D.C. [67]. Moreover, Lynntech has perfected the use of ozone for disinfection of plastics. Although this is a quick method that does not leave behind much residue, plastics are more susceptible to damage due to ozone use [68]. The mist's ability to penetrate through the layer of fabrics, as seen in respirators, has made chemical systems advantageous, to ensure a greater extent of decontamination. Unlike common plastics such as LDPE, HDPE, and PP, condensation polymers, such as polyesters, nylon, and a few others, degrade [68].

4.3. Use of Ionisation and Energetic Radiation

Electron beam radiations and other ionizing radiations can harm any living organism's DNA and neutralise it, but these radiations must not be applied in streams consisting of metals. A containment system, composed of a concrete bunker several feet thick, is required, making it the most expensive and challenging to construct in a short amount of time [67]. In the recent past, the application of UV rays in PPE's disinfection has been an area of focus. In specific, the pulsed xenon ultraviolet light is useful during the removal of worn PPE [69].

The ultraviolet-light spectrum consists of three sub-classifications: UV-A (320–340 nm), UV-B (280–320 nm), and UV-C (200–280 nm), where the UV-C rays have the highest germicidal properties. RNA and DNA absorb UV-C, leading to structural damage to the molecules through photodimersation, resulting in virus inactivation. As SARS-CoV-2 is a recent find, there is not sufficient data to analyse the survival of the virus under different conditions, however, scientists have treated this virus similarly to SARS-CoV-1 [70]. Although UV-C has been significant, factors such as the inoculum size, culture medium, geometry, and size of material used in PPEs play a significant role, which leads to incoherent findings. At 360 mJ/cm^2, SARS-CoV-1 had the highest UV D90 among nearly 130 different types of viruses [71]. It has been reported that the majority of aerosols are captured on the initial layers of respirators [72]. Their efficacy remains questionable, especially in complex geometries, despite the lower costs and rapid throughput of disinfection. The mechanical degradation upon exposure to UV-C deems it unsuitable for use.

5. Environmentally Sustainable Management of Used Personal Protective Equipment

Face masks, gloves, goggles, gowns, and aprons are examples of personal protective equipment (PPE) that can help protect people from infections and toxins. PPE used against pathogens has, traditionally, been mostly in the hospital setting. However, due to the worldwide COVID-19 epidemic, personal protective equipment (PPE) is, increasingly, commonly employed in residential circumstances, resulting in supply chain shortages and a fast accumulation of potentially infected PPE in household-solid-waste streams [73]. Manufacturing, building, the oil and gas industry, transportation, firefighting, and food production have all been impacted by the enormous domestic need for personal protective equipment, in reaction to the epidemic. Since the COVID-19 epidemic, there has been a tremendous surge in the development of plastic-based PPE equipment. For example, the worldwide market for PPE grew at a compound annual rate of 6.5%, between 2016 and 2020, from around USD 40 billion to USD 58 billion [23].

The World Health Organization, on the other hand, estimates that PPE supplies will need to grow by 40% monthly, to adequately combat the COVID-19 epidemic. In total, 89 million medical masks, 76 million pairs of medical gloves, and 1.6 million pairs of goggles are among the needed PPE [74]. PPE demand is not predicted to fall much in the post-pandemic period, with the supply of face and surgical masks expected to expand at a compound annual rate of 20%, from 2020 to 2025 [23,73]. The long-term management of PPE is a major problem.

The lack of a coordinated international strategy to manage the PPE production and waste lifecycle is threatening to stymie progress, towards achieving key components of the United Nations' Sustainable Development Goals (SDGs), such as SDG 3, good health and well-being; SDG 6, clean water and sanitation; SDG 8, decent work and economic growth; SDG 12, responsible consumption and production; and SDG 13, climate action [75]. We offer product lifecycle techniques that should be included into public–private-partnership-based solutions. Increases in PPE production and distribution result in an increase in waste, which is exacerbated by health and environmental dangers along the waste treatment chain, particularly in countries with poor infrastructure (Figure 2).

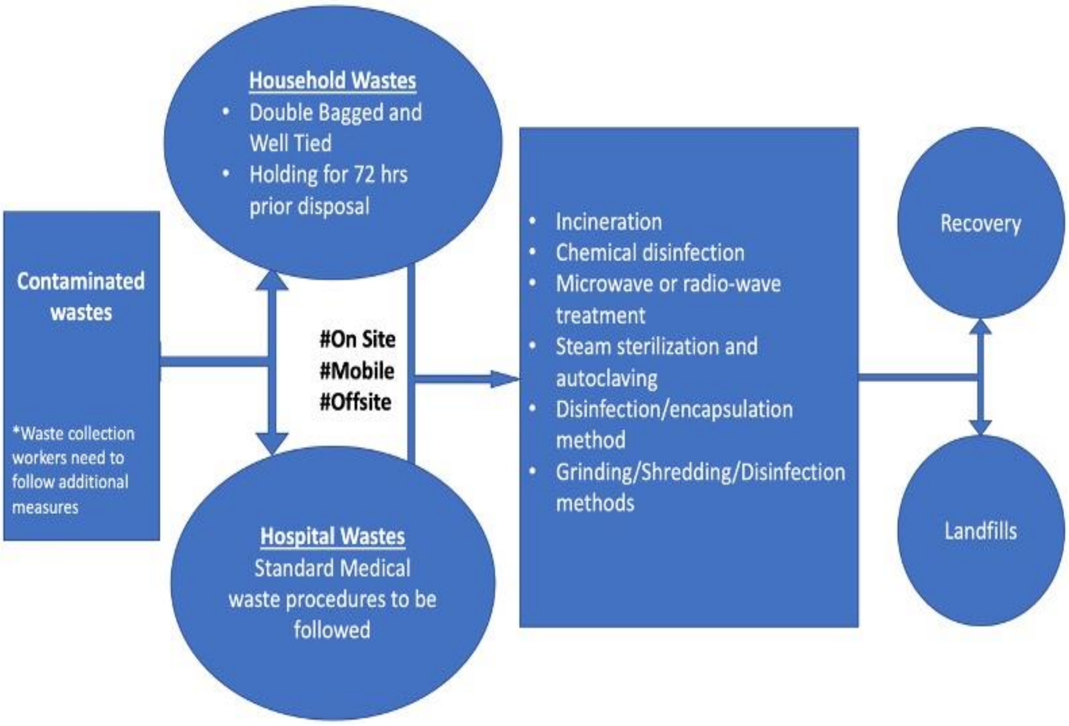

Figure 2. Methods for handling contaminated wastes in pandemic situations.

At the peak of the pandemic in Wuhan, China produced 240 tonnes of medical waste per day, which was six times more than before the epidemic. As a result, the city's waste management department set up mobile incinerators across the city to dispose of the massive amounts of abandoned face masks, gloves, and other contaminated single-use protective equipment. Across the globe, similar increases in the number of abandoned face masks, hand gloves, and safety eyewear have been reported. Moreover, over seven million Hong Kong residents, for example, use single-use masks on a regular basis. Discarded masks have been reported in the water and on Hong Kong's beaches and nature paths [76]. The outbreak has had an impact on how solid waste management is handled. Waste management and resource recycling were declared non-essential and placed on lockdown.

This interruption of normal waste management services has been observed across the world, and it has been compounded by China's previous limits on importing "recyclable" solid waste, which were imposed in 2019. As a result, several governments have implemented informal protocols for collecting and recycling discarded PPE, a practise that may pose a risk, owing to insufficient decontamination [77]. Viral infections can be transmitted to healthcare and recycling employees, if infected trash is improperly disposed of or handled. It has been estimated that up to 30% of hepatitis B rates, 13% of hepatitis C rates, and 0.3% of HIV rates have been transmitted from patients to healthcare workers, as a result of incorrect medical waste disposal. A higher-than-normal incidence of viral infection among solid waste collectors may be related, directly, to pathogens in contaminated wastes, according to studies undertaken in Pakistan, Greece, Brazil, Iran, and India [23]. The Basel Convention on the Transboundary Movement of Hazardous Wastes and their Disposal, a treaty by the United Nations, has recently urged member countries to treat waste management as an urgent and essential public service, in the wake of COVID-19, in order to minimise potential secondary effects on health and the environment. As a result, safe and long-term recovery as well as treatment of PPEs should be prioritised. It is essential to clarify the role of informal recyclers in developing countries, where medical waste has not been, adequately, regulated.

The PPE reaction to the COVID-19 epidemic has had an influence on plastic recovery and recyclability, as well as landfilling and pollution. PPE materials have polymers as a main ingredient, accounting for 20–25%of the total weight. If they are not recycled, they contribute, significantly, to dangerous environmental contaminants, such as dioxins and toxic metals [73]. Contrary to World Health Organization recommendations, which encourage safe practises that reduce the volume of waste generated and ensure proper waste segregation at the source, plastic-based PPEs discarded from households are mixed with other domestic plastic wastes, such as single-use plastic bags, the use of which has increased rapidly, since grocery stores prohibited customers from bringing their own bags for fear of introducing additional virus-transmission routes. PPEs, such as N-95 masks, Tyvek protective suits, gloves, and medical face shields, all include polypropylene. Polypropylene, also, accounts for a significant amount of the nearly 25 million tonnes of plastic materials disposed of in US landfills each year, with just 3% of the polypropylene plastic created being recovered and recycled [13,78–80]. It is difficult to recover polymers from mixed healthcare waste, which includes PPE. Individuals operating as recyclers in middle- and low-income countries are constrained in their ability to recycle, without risking infection, due to the low proportion (15–25%) of healthcare waste that is not contaminated. Furthermore, poor plastic waste recycling rates throughout the world, as well as a lack of coordinated government laws requiring minimum recycling content in new goods, will almost certainly result in an increase in virgin plastic manufacture in the post-pandemic period. The plastics manufacturing industry in the United States has asked more than USD 1 billion in emergency financing to deal with the increased demand caused by COVID-19 [79]. Restriction of emergency funding is necessary to promote investments in the research and development of used PPE collecting, sorting, and recycling, to ensure that growing plastic PPE manufacturing does not lead to greater pollution. Public–private collaborations will help to implement a long-term PPE waste management strategy. The importance of artisanal solid-waste collectors and recyclers in nations in transition is unquestionable. It is difficult to develop safe and sustainable PPE management, outside of healthcare settings (hospitals and clinics) in emergency situations, since it necessitates a thorough understanding of best practises, as well as the monitoring and enforcement of laws and regulations. Thermal, chemical, irradiative, and biological processes can be applied locally or scaled up in regional facilities, where waste collection and transportation are viable in healthcare settings. Single-use PPE is not a sustainable practise, so addressing the PPE pollution problem will need multidisciplinary technical skills, encompassing biological sciences, environmental science, public health, materials science, and engineering. PPE disinfection and reuse can be done on a large-scale, using methods such as infusion of hydrogen-peroxide vapour, ultraviolet or gamma irradiation, ethylene-oxide gasification, application of spray-on disinfectants, and infusion of base materials with antimicrobial nanoparticles, according to new research published since the start of the current pandemic [81–84]. Many disinfection technologies are, still, in the early stages of development, and they must be calibrated to guarantee that material deterioration during each disinfection cycle does not jeopardise the fundamental purpose of PPEs, which is to prevent pathogen penetration and human exposure. During and after the present epidemic, the circular economy idea of reducing, reusing, and recycling materials should govern PPE management policy development. Plastic producers should be required to include a minimum recycling content in new items under national rules, and product price should reflect environmental and health externalities. Policy implementation, monitoring, and enforcement should also include public education initiatives, to encourage proper PPE stewardship. In low-income nations, infrastructure development is critical to ensure the safety of informal garbage collection and recycling. PPE management policies must be linked into economic models that encourage the use of green technology and alternative evaluations, to find and implement safer methods based on thorough material-life-cycle assessments and customer preferences, if they are to be sustainable. In conclusion, the COVID-19 epidemic has put pressure on worldwide solid waste management, as well as emphasising supply chain bottlenecks in PPE manufacturing, demand–supply, usage, and disposal. PPEs will continue to be in high demand, thus, now is the time to invest in innovative PPE materials that decrease waste creation and enhance methods for the safe and sustainable storage of worn PPE, with worldwide policy guidelines [75].

6. Conclusions and Future Perspective

Every country in this globe is, currently, focusing on tackling the COVID-19 epidemic. This requires consideration of the economic and environmental factors as well. In this paper, the issues pertaining to PPE disposal and safe disposal strategies have been elaborated. The precipitous rise in plastic waste, especially for protection and healthcare purposes, has been one of the significant consequences of this coronavirus outbreak. The measurement of environmental issues, in terms of footprints as PF and PWF, along with the strategy for safe disposal, has been discussed in this paper.

Considering the current trend, it is necessary to, immediately, reassess goals and priorities, without harming the environment, society, or economy. Massive quantities of plastic waste are landfilled or incinerated. Only a small part is recycled, leading to the disposal of 4–12 million tonnes/year of plastics into the seas and oceans [85,86]. The health of our environment and human beings is interdependent. To ensure a future, sustainability is essential. Scientists must guide world leaders and corporations' management, to implement an efficient plastic waste management system for plastic waste recovery, governed by strict rules and regulations in the manufacture and consumption of plastic products. It is, also, vital to seek sustainable techniques to reduce plastic waste. One way is to use biobased plastics; however, more research has to be carried out, to scale up the economic and environmental aspects. Besides, the manufacture of sustainable products must be complemented by the producer's responsibility, and the cost of waste management must be adopted by the distributors and sellers. Therefore, in every country, it is essential that plastics are of primary political concern, to minimise plastic wastage as well as promote a circular economy and sustainability.

This circular economy principle should centre on reducing, reusing, and recycling principles for PPE management, throughout the pandemic and post-pandemic situations. National policies ought to be devised, to ensure that plastic production involves minimum recycling content in new products. However, the cost of the products must reflect environmental and health externalities. In lower-income countries, the advancement of infrastructure is necessary, to safeguard informal waste collection. To ensure sustainability, PPE management policies need be incorporated into fiscal policies, to encourage green technology as well as find and implement safer practices.

Author Contributions: Conceptualization, S.S. and S.P.; methodology, S.P.; validation, S.P.; data curation, S.P.; writing–original draft preparation, S.S. and S.P.; writing–review and editing, S.S. and S.P.; supervision, N.K.F., S.F., V.S., M.N.H.M., M.S., A.M.A., B.B., D.H.K., V.K.S., K.V.S. and D.U.M.; funding acquisition; N.K.F., S.F., V.S., M.N.H.M., M.S., A.M.A., B.B., D.H.K., V.K.S., K.V.S. and D.U.M. All authors have read and agreed to the published version of the manuscript.

Funding: No funding was received to carry out this research.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

IV	Intravenous
Mt	Metric tonne
GHG	Greenhouse gas
PPE	Personal protective equipment
LCA	Life cycle assessment
MSW	Municipal solid waste

References

1. Rajmohan, K.V.S.; Ramya, C.; Viswanathan, M.R.; Varjani, S. Plastic pollutants: Effective waste management for pollution control and abatement. *Curr. Opin. Environ. Sci. Health* **2019**, *12*, 72–84. [CrossRef]
2. Windfeld, E.S.; Brooks, M.S.-L. Medical waste management—A review. *J. Environ. Manag.* **2015**, *163*, 98–108. [CrossRef] [PubMed]
3. Plastics Europe—The Facts 2016. An Analysis of European Plastics Production, Demand and Waste Data. *Plast. Eur.* **2016**, 1–38. Available online: https://www.plasticseurope.org/application/files/4315/1310/4805/plastic-the-fact-2016.pdf (accessed on 26 April 2020).
4. Hahladakis, J.N.; Velis, C.A.; Weber, R.; Iacovidou, E.; Purnell, P. An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. *J. Hazard. Mater.* **2018**, *344*, 179–199. [CrossRef] [PubMed]
5. Geyer, R.; Jambeck, J.; LAW, K. Producción, uso y destino de todos los plásticos jamás fabricados. *Sci. Adv.* **2017**, *3*, 1207–1221.
6. Zheng, J.; Suh, S. Strategies to reduce the global carbon footprint of plastics. *Nat. Clim. Chang.* **2019**, *9*, 374–378. [CrossRef]
7. Jambeck, J.; Geyer, R.; Wilcox, C.; Siegler, T.; Perryman, M.; Andrady, A.; Naray, R. Plastic waste inputs from land into the ocean. *Science* **2015**, *347*, 768–771. [CrossRef]
8. MacKenzie, D. COVID-19 goes global. *New Sci.* **2020**, *245*, 7. [CrossRef]
9. Babaji, P.; Singh, A.; Lau, H.; Lamba, G.; Somasundaram, P. Deletion of short arm of chromosome 18, Del (18p) syndrome. *J. Indian Soc. Pedod. Prev. Dent.* **2014**, *32*, 68. [CrossRef]
10. Selvaraj, D.; Raja, J.; Prasath, S. Interdisciplinary approach for bilateral maxillary canine: First premolar transposition with complex problems in an adult patient. *J. Pharm. Bioallied Sci.* **2013**, *5* (Suppl. 2), S190. [CrossRef]
11. Liu, H.-C.; You, J.-X.; Lu, C.; Chen, Y.-Z. Evaluating health-care waste treatment technologies using a hybrid multi-criteria decision making model. *Renew. Sustain. Energy Rev.* **2015**, *41*, 932–942. [CrossRef]
12. Yu, H.; Sun, X.; Solvang, W.D.; Zhao, X. Reverse Logistics Network Design for Effective Management of Medical Waste in Epidemic Outbreaks: Insights from the Coronavirus Disease 2019 (COVID-19) Outbreak in Wuhan (China). *Int. J. Environ. Res. Public Health* **2020**, *17*, 1770. [CrossRef] [PubMed]

13. Kumar, N.M.; Mohammed, M.A.; Abdulkareem, K.H.; Damasevicius, R.; Mostafa, S.A.; Maashi, M.S.; Chopra, S.S. Artificial intelligence-based solution for sorting COVID related medical waste streams and supporting data-driven decisions for smart circular economy practice. *Process Saf. Environ. Prot.* **2021**, *152*, 482–494. [CrossRef]
14. Zhao, W.; Van Der Voet, E.; Huppes, G.; Zhang, Y. Comparative life cycle assessments of incineration and non-incineration treatments for medical waste. *Int. J. Life Cycle Assess.* **2008**, *14*, 114–121. [CrossRef]
15. Hong, J.; Zhan, S.; Yu, Z.; Hong, J.; Qi, C. Life-cycle environmental and economic assessment of medical waste treatment. *J. Clean. Prod.* **2018**, *174*, 65–73. [CrossRef]
16. Makarichi, L.; Jutidamrongphan, W.; Techato, K.-A. The evolution of waste-to-energy incineration: A review. *Renew. Sustain. Energy Rev.* **2018**, *91*, 812–821. [CrossRef]
17. Bertschinger, N. Visual explanation of country specific differences in COVID-19 dynamics. *arXiv* **2020**, arXiv:2004.07334.
18. Saha, S.; Samanta, G.P.; Nieto, J.J. Epidemic model of COVID-19 outbreak by inducing behavioural response in population. *Nonlinear Dyn.* **2020**, *102*, 455–487. [CrossRef]
19. Xu, Z.; Wang, R.; Yang, C. Perspectives for low-temperature waste heat recovery. *Energy* **2019**, *176*, 1037–1043. [CrossRef]
20. Dincer, B.; Inangil, D. The effect of Emotional Freedom Techniques on nurses' stress, anxiety, and burnout levels during the COVID-19 pandemic: A randomized controlled trial. *Explore* **2021**, *17*, 109–114. [CrossRef]
21. Huang, H.; Tang, L. Treatment of organic waste using thermal plasma pyrolysis technology. *Energy Convers. Manag.* **2007**, *48*, 1331–1337. [CrossRef]
22. Singh, N.; Tang, Y.; Ogunseitan, O.A. Environmentally Sustainable Management of Used Personal Protective Equipment. *Environ. Sci. Technol.* **2020**, *54*, 8500–8502. [CrossRef] [PubMed]
23. Singh, N.; Tang, Y.; Zhang, Z.; Zheng, C. COVID-19 waste management: Effective and successful measures in Wuhan, China. *Resour. Conserv. Recycl.* **2020**, *163*, 105071. [CrossRef] [PubMed]
24. Tikkinen, K.A.O.; Malekzadeh, R.; Schlegel, M.; Rutanen, J.; Glasziou, P. COVID-19 clinical trials: Learning from exceptions in the research chaos. *Nat. Med.* **2020**, *26*, 1671–1672. [CrossRef]
25. Van Doremalen, N.; Bushmaker, T.; Morris, D.H.; Holbrook, M.G.; Gamble, A.; Williamson, B.N.; Tamin, A.; Harcourt, J.L.; Thornburg, N.J.; Gerber, S.I. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. *N. Engl. J. Med.* **2020**, *382*, 1564–1567. [CrossRef] [PubMed]
26. Kampf, G.; Todt, D.; Pfaender, S.; Steinmann, E. Persistence of coronaviruses on inanimate surfaces and their inactivation with biocidal agents. *J. Hosp. Infect.* **2020**, *104*, 246–251. [CrossRef]
27. Benson, N.U.; Bassey, D.E.; Palanisami, T. COVID pollution: Impact of COVID-19 pandemic on global plastic waste footprint. *Heliyon* **2021**, *7*, e06343. [CrossRef]
28. Bourouiba, L. Turbulent gas clouds and respiratory pathogen emissions: Potential implications for reducing transmission of COVID-19. *JAMA* **2020**, *323*, 1837–1838. [CrossRef]
29. Petrov, A.; Petrova, D. Sustainability of Transport System of Large Russian City in the Period of COVID-19: Methods and Results of Assessment. *Sustainability* **2020**, *12*, 7644. [CrossRef]
30. Prüss, A.; Giroult, E.; Rushbrook, P. Treatment and disposal technologies for health-care waste. In *Safe Management of Wastes from Healthcare Activities*; WHO: Geneva, Switzerland, 1999; pp. 77–111.
31. Moriarty, D.G.; Zack, M.M.; Kobau, R. The Centers for Disease Control and Prevention's Healthy Days Measures–Population tracking of perceived physical and mental health over time. *Health Qual. Life Outcomes* **2003**, *1*, 1–8. [CrossRef]
32. *Obtenido de Project Management Guide*; CDC: Centers for Disease Control and Prevention: Atlanta, GA, USA. Available online: https://www2a.cdc.gov/cdcup/library (accessed on 26 April 2020).
33. Klemeš, J.J.; Van Fan, Y.; Tan, R.R.; Jiang, P. Minimising the present and future plastic waste, energy and environmental footprints related to COVID-19. *Renew. Sustain. Energy Rev.* **2020**, *127*, 109883. [CrossRef] [PubMed]
34. Chapple, K. *Planning Sustainable Cities and Regions: Towards More Equitable Development*; Routledge: London, UK, 2014.
35. Ravetz, J. Integrated assessment for sustainability appraisal in cities and regions. *Environ. Impact Assess. Rev.* **2000**, *20*, 31–64. [CrossRef]
36. Al-Salem, S. Energy production from plastic solid waste (PSW). In *Plastics to Energy*; Elsevier: Cambridge, MA, USA, 2019; pp. 45–64. [CrossRef]
37. Vanapalli, K.R.; Samal, B.; Dubey, B.K.; Bhattacharya, J. Bhattacharya, Emissions and environmental burdens associated with plastic solid waste management. In *Plastics to Energy*; Elsevier: Cambridge, MA, USA, 2019; pp. 313–342. [CrossRef]
38. Mastellone, M.L. Technical description and performance evaluation of different packaging plastic waste management's systems in a circular economy perspective. *Sci. Total Environ.* **2020**, *718*, 137233. [CrossRef] [PubMed]
39. Singh, N.; Hui, D.; Singh, R.; Ahuja, I.P.S.; Feo, L.; Fraternali, F. Recycling of plastic solid waste: A state of art review and future applications. *Compos. Part B Eng.* **2017**, *115*, 409–422. [CrossRef]
40. Gu, L.; Ozbakkaloglu, T. Use of recycled plastics in concrete: A critical review. *Waste Manag.* **2016**, *51*, 19–42. [CrossRef]
41. Aboulkas, A.; El Harfi, K.; El Bouadili, A. Thermal degradation behaviors of polyethylene and polypropylene. Part I: Pyrolysis kinetics and mechanisms. *Energy Convers. Manag.* **2010**, *51*, 1363–1369. [CrossRef]
42. Lithner, D.; Larsson, Å.; Dave, G. Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition. *Sci. Total Environ.* **2011**, *409*, 3309–3324. [CrossRef]

43. Cruz Sanchez, F.A.; Boudaoud, H.; Hoppe, S.; Camargo, M. Polymer recycling in an open-source additive manufacturing context: Mechanical issues. *Addit. Manuf.* **2017**, *17*, 87–105. [CrossRef]
44. Vatsal, A.; Prasadh, S.; Deepamala, S.; Patil, A.; Sulochana, K.; Shruthi, D. Comparative evaluation of dimensional changes of elastomeric impression materials after disinfection with glutaraldehyde and microwave irradiation. *J. Int. Oral Health* **2015**, *7*, 44–46.
45. Hopewell, J.; Dvorak, R.; Kosior, E. Plastics recycling: Challenges and opportunities. *Philos. Trans. R. Soc. B Biol. Sci.* **2009**, *364*, 2115–2126. [CrossRef]
46. Mikula, K.; Skrzypczak, D.; Izydorczyk, G.; Warchoł, J.; Moustakas, K.; Chojnacka, K.; Witek-Krowiak, A. 3D printing filament as a second life of waste plastics—A review. *Environ. Sci. Pollut. Res.* **2020**, *28*, 12321–12333. [CrossRef] [PubMed]
47. Saravanan, P.; Ettappan, M.; Kumar, N.M.; Elangkeeran, N. Exhaust Gas Recirculation on a Nano-Coated Combustion Chamber of a Diesel Engine Fueled with Waste Plastic Oil. *Sustainability* **2022**, *14*, 1148. [CrossRef]
48. Anderson, I. Mechanical properties of specimens 3D printed with virgin and recycled polylactic acid. *3D Print. Addit. Manuf.* **2017**, *4*, 110–115. [CrossRef]
49. Żenkiewicz, M.; Richert, J.; Rytlewski, P.; Moraczewski, K.; Stepczyńska, M.; Karasiewicz, T. Characterisation of multi-extruded poly (lactic acid). *Polym. Test.* **2009**, *28*, 412–418. [CrossRef]
50. Gkartzou, E.; Koumoulos, E.; Charitidis, C.A. Production and 3D printing processing of bio-based thermoplastic filament. *Manuf. Rev.* **2017**, *4*, 1. [CrossRef]
51. Pillin, I.; Montrelay, N.; Bourmaud, A.; Grohens, Y. Effect of thermo-mechanical cycles on the physico-chemical properties of poly (lactic acid). *Polym. Degrad. Stab.* **2008**, *93*, 321–328. [CrossRef]
52. Zhao, X.G.; Hwang, K.-J.; Lee, D.; Kim, T.; Kim, N. Enhanced mechanical properties of self-polymerized polydopamine-coated recycled PLA filament used in 3D printing. *Appl. Surf. Sci.* **2018**, *441*, 381–387. [CrossRef]
53. Pan, G.-T.; Chong, S.; Tsai, H.-J.; Lu, W.-H.; Yang, T.C.-K. The Effects of Iron, Silicon, Chromium, and Aluminum Additions on the Physical and Mechanical Properties of Recycled 3D Printing Filaments. *Adv. Polym. Technol.* **2018**, *37*, 1176–1184. [CrossRef]
54. Yuan, X.; Kumar, N.M.; Brigljević, B.; Li, S.; Deng, S.; Byun, M.; Lee, B.; Lin, C.S.; Tsang, D.C.; Lee, K.B.; et al. Sustainability-inspired upcycling of waste polyethylene terephthalate plastic into porous carbon for CO_2 capture. *Green Chem.* **2022**, *24*, 1494–1504. [CrossRef]
55. Badia, J.; Strömberg, E.; Karlsson, S.; Ribes-Greus, A. Material valorisation of amorphous polylactide. Influence of thermo-mechanical degradation on the morphology, segmental dynamics, thermal and mechanical performance. *Polym. Degrad. Stab.* **2012**, *97*, 670–678. [CrossRef]
56. Chariyachotilert, C.; Joshi, S.; Selke, S.; Auras, R. Assessment of the properties of poly (L-lactic acid) sheets produced with differing amounts of postconsumer recycled poly (L-lactic acid). *J. Plast. Film Sheeting* **2012**, *28*, 314–335. [CrossRef]
57. Brüster, B.; Addiego, F.; Hassouna, F.; Ruch, D.; Raquez, J.-M.; Dubois, P. Thermo-mechanical degradation of plasticized poly (lactide) after multiple reprocessing to simulate recycling: Multi-scale analysis and underlying mechanisms. *Polym. Degrad. Stab.* **2016**, *131*, 132–144. [CrossRef]
58. Beltrán, F.; Lorenzo, V.; Acosta, J.; de la Orden, M.; Urreaga, J.M. Effect of simulated mechanical recycling processes on the structure and properties of poly (lactic acid). *J. Environ. Manag.* **2018**, *216*, 25–31. [CrossRef]
59. Zhao, P.; Rao, C.; Gu, F.; Sharmin, N.; Fu, J. Close-looped recycling of polylactic acid used in 3D printing: An experimental investigation and life cycle assessment. *J. Clean. Prod.* **2018**, *197*, 1046–1055. [CrossRef]
60. Baechler, C.; DeVuono, M.; Pearce, J.M. Distributed recycling of waste polymer into RepRap feedstock. *Rapid Prototyp. J.* **2013**, *19*, 118–125. [CrossRef]
61. Di Maria, A.; Eyckmans, J.; Van Acker, K. Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC to support sustainable policy making. *Waste Manag.* **2018**, *75*, 3–21. [CrossRef]
62. Zhong, S.; Pearce, J.M. Tightening the loop on the circular economy: Coupled distributed recycling and manufacturing with recyclebot and RepRap 3D printing. *Resour. Conserv. Recycl.* **2018**, *128*, 48–58. [CrossRef]
63. Tymrak, B.M.; Kreiger, M.; Pearce, J.M. Mechanical properties of components fabricated with open-source 3D printers under realistic environmental conditions. *Mater. Des.* **2014**, *58*, 242–246. [CrossRef]
64. Sun, Q.; Rizvi, G.; Bellehumeur, C.; Gu, P. Effect of processing conditions on the bonding quality of FDM polymer filaments. *Rapid Prototyp. J.* **2008**, *14*, 72–80. [CrossRef]
65. Derraik, J.G.; Anderson, W.A.; Connelly, E.A.; Anderson, Y.C. Rapid evidence summary on SARS-CoV-2 survivorship and disinfection, and a reusable PPE protocol using a double-hit process. *MedRxiv* **2020**, *17*, 6117.
66. Nema, S.; Ganeshprasad, K. Plasma pyrolysis of medical waste. *Curr. Sci.* **2002**, *83*, 271–278.
67. Jinadatha, C.; Simmons, S.; Dale, C.; Ganachari-Mallappa, N.; Villamaria, F.C.; Goulding, N.; Tanner, B.; Stachowiak, J.; Stibich, M. Disinfecting personal protective equipment with pulsed xenon ultraviolet as a risk mitigation strategy for health care workers. *Am. J. Infect. Control* **2015**, *43*, 412–414. [CrossRef] [PubMed]
68. Uloma, A.A.; Nkem Benjamin, I.; Kiss, I. Knowledge, Attitude and Practice of Healthcare Workers Towards Medical Waste Management: A Comparative Study of Two Geographical Areas. *J. Waste Manag. Dispos.* **2022**, *5*, 101.
69. Mahanwar, P.A.; Bhatnagar, M.P. Medical Plastics Waste. 2020. Available online: https://www.scirp.org/(S(351jmbntv-nsjt1aadkposzje))/reference/referencespapers.aspx?referenceid=2812826 (accessed on 26 April 2020).

70. Puro, V.; Pittalis, S.; Chinello, P.; Nicastri, E.; Petrosillo, N.; Antonini, M.; Ippolito, G. Disinfection of personal protective equipment for management of Ebola patients. *Am. J. Infect. Control* **2015**, *43*, 1375–1376. [CrossRef]
71. Coronaviridae Study Group of the International. The species Severe acute respiratory syndrome-related coronavirus: Classifying 2019-nCoV and naming it SARS-CoV-2. *Nat. Microbiol.* **2020**, *5*, 536. [CrossRef]
72. Kowalski, W. *Ultraviolet Germicidal Irradiation Handbook: UVGI for Air and Surface Disinfection*; Springer Science & Business Media: Berlin, Germany, 2010.
73. Ogunseitan, O.A. The Materials Genome and COVID-19 Pandemic. *Jom* **2020**, *72*, 1–3.
74. Tan, G.S.E.; Linn, K.Z.; Soon, M.M.L.; Vasoo, S.; Chan, M.; Poh, B.F.; Ng, O.-T.; Ang, B.S.-P.; Leo, Y.-S.; Marimuthu, K. Effect of extended use N95 respirators and eye protection on personal protective equipment (PPE) utilization during SARS-CoV-2 outbreak in Singapore. *Antimicrob. Resist. Infect. Control* **2020**, *9*, 1–3. [CrossRef]
75. Vijayakumar, V. Personal Protection Prior to Preoperative Assessment—Little more an anaesthesiologist can do to prevent SARS-CoV-2 transmission and COVID-19 infection. *Ain-Shams J. Anesthesiol.* **2020**, *12*, 1–2. [CrossRef]
76. Mahmood, S.U.; Crimbly, F.; Khan, S.; Choudry, E.; Mehwish, S. Strategies for Rational Use of Personal Protective Equipment (PPE) Among Healthcare Providers During the COVID-19 Crisis. *Cureus* **2020**, *12*, e8248. [CrossRef]
77. Mallapur, C. Sanitation Workers at Risk from Discarded Medical Waste Related to COVID-19, IndiaSpend. URL. Available online: https://www.indiaspend.com/sanitation-workersat-risk-from-discarded-medical-waste-related-tocovid-19/ (accessed on 26 April 2020).
78. Wu, S.; Montalvo, L. Repurposing waste plastics into cleaner asphalt pavement materials: A critical literature review. *J. Clean. Prod.* **2021**, *280*, 124355. [CrossRef]
79. Prasadh, S.; Raguraman, S.; Wong, R.; Gupta, M. Metallic Foams in Bone Tissue Engineering. In *Nanoscale Engineering of Biomaterials: Properties and Applications*; Springer: Singapore, 2022; pp. 181–205.
80. Prasadh, S.; Parande, G.; Gupta, M.; Wong, R. Compositional Tailoring of Mg–2Zn–1Ca Alloy Using Manganese to Enhance Compression Response and In-Vitro Degradation. *Materials* **2022**, *15*, 810. [CrossRef] [PubMed]
81. Saini, J.; Choudhary, S.; Kataria, P. Awareness of Biomedical Waste Management among Nursing Students: A Hospital Based Study in Haryana. *Indian J. Prev. Soc. Med.* **2020**, *51*, 8.
82. Kujur, M.S.; Manakari, V.; Parande, G.; Prasadh, S.; Wong, R.; Mallick, A.; Gupta, M. Effect of samarium oxide nanoparticles on degradation and invitro biocompatibility of magnesium. *Mater. Today Commun.* **2021**, *26*, 102171. [CrossRef]
83. Prasadh, S.; Suresh, S.; Hong, K.L.; Bhargav, A.; Rosa, V.; Wong, R.C. Biomechanics of alloplastic mandible reconstruction using biomaterials: The effect of implant design on stress concentration influences choice of material. *J. Mech. Behav. Biomed. Mater.* **2020**, *103*, 103548. [CrossRef]
84. Prasadh, S.; Krishnan, A.V.; Lim, C.Y.; Gupta, M.; Wong, R. Titanium versus magnesium plates for unilateral mandibular angle fracture fixation: Biomechanical evaluation using 3-dimensional finite element analysis. *J. Mater. Res. Technol.* **2022**, *18*, 2064–2076. [CrossRef]
85. Price, A.D.; Cui, Y.; Liao, L.; Xiao, W.; Yu, X.; Wang, H.; Zhao, M.; Wang, Q.; Chu, S.; Chu, L.F. Is the fit of N95 facial masks effected by disinfection? A study of heat and UV disinfection methods using the OSHA protocol fit test. *medRxiv* **2020**. [CrossRef]
86. Prasadh, S.; Gupta, M.; Wong, R. In vitro cytotoxicity and osteogenic potential of quaternary Mg-2Zn-1Ca/X-Mn alloys for craniofacial reconstruction. *Sci. Rep.* **2022**, *12*, 8259. [CrossRef]