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Review

An Overview of Dental Solid Waste Management and Associated Environmental Impacts: A Materials Perspective

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Abstract: Dental healthcare plays an important role in the overall health of individuals, and the sector is rapidly growing around the world due to increases in population, healthcare facilities, and improved access for economically weaker sections of society. Dental procedures and oral care generate a significant amount of biomedical waste that should be managed in an environmentally safe and sustainable manner. An overview is presented of the current status of dental solid waste management with a focus on waste composition from traditional and emerging dental treatments, new-generation dental materials, waste treatment procedures, and current options. Dental waste can be broadly divided into three categories: infectious waste, non-infectious waste, and domestic-type waste. Infectious waste contains materials contaminated with blood or other infectious mouth fluids, amalgam, and sharps, whereas non-infectious dental waste is devoid of human fluid contamination but can be potentially toxic due to the presence of amalgams, acids, metal dust, resins, etc. Suspended particulates in dental wastewater are another likely source of contamination. Appropriate segregation of this waste is essential for containing infections during waste processing. New-generation dental materials, such as nanomaterials, resin-based composites, and ceramics, are finding increasing applications in a variety of dental procedures as antimicrobial, restorative, and therapeutic agents. While incineration and landfilling have been used for processing traditional dental waste, the presence of novel materials in dental waste raises several additional concerns. Novel single/multistage recycling approaches need to be developed for dental waste towards resource recovery, thus minimizing incineration and landfilling to the extent possible.

Keywords: dental waste; management; nanomaterials; resin-based composites; biomedical; healthcare

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1. Introduction

The healthcare sector is a fast-growing global industry with a focus on patient care, treatments, goods, and services for controlling diseases and health management [1]. Healthcare waste, which refers to the waste generated by various facilities, such as hospitals, clinics, research centers, laboratories, individuals, or households, is growing faster than ever all over the world [2]. With increasing population and growth in healthcare facilities, the associated waste has been increasing at the rate of 2–3% annually [3], and this waste is expected to reach 2.5 Mt in 2023 in China alone [4]. The UK National Health Service generates 0.5 Mt of waste annually in England [5], whilst the US produces an estimated 5.9 Mt of healthcare waste per year [6]. Environmentally sustainable management of healthcare waste is a pressing issue for developing nations and emerging economies involving social, economic, technical, and environmental aspects [7].

Healthcare waste can be broadly classified as non-hazardous and hazardous waste [8]. This waste includes equipment and/or materials that have been in contact with blood, tissues, tissue fluids, excreta, or waste from infection wards [9]. Non-hazardous waste includes, among others, sterile packaging, plastic bottles, paper, cardboard, non-infectious and infectious gloves, aprons, incontinence pads, empty fluid bags, surgical dressing, masks, etc., whereas hazardous infectious waste includes medicated intravenous bags/lines, medicinally contaminated syringes, needles, cannulas, diagnostic specimens, placenta, etc. [10]. Between 75 and 90% of the waste produced by healthcare providers is non-hazardous or general waste [11]. It is estimated that by end of the 20th century, as many as 5.2 million people, including 4 million children less than 5 years of age, could die each year from waste-related diseases [12].

Inadequate management of such waste presents immediate risks for healthcare professionals and patients through contamination and cross-infection, as well as land, water, and air pollution [13]. The carbon footprint from the disposal of healthcare waste depends upon the material contents, method of disposal, and management options [14]. Non-infectious waste may be disposed of through low-temperature incineration, recycling, or landfilling. Incineration is generally carried out along with municipal solid waste at a temperature of ~850 °C, resulting in waste destruction, generation of heat, and material recovery as bottom ash and slag [15]. Infectious waste and sharps may be decontaminated first using an autoclave, steam auger, dry heat, microwave, or chemical disinfection prior to their disposal alongside non-hazardous waste streams or incinerated at temperatures above 1100 °C.

With a brief introduction to typical waste in the healthcare sector, we present an overview of waste management in dentistry, dental surgeries, and procedures, with a specific focus on dental materials in waste and their environmentally sustainable end-of-life management. Dental care plays an important role in the overall health of individuals and the population at large, and the generation of a significant amount of biomedical waste is inevitable during oral care and dental procedures. Dental waste is associated with different aspects of dentistry, such as oral diagnosis, conservative treatments, periodontology, pedodontics, orthodontics, prosthetics, dental surgeries, X-rays, etc. Dental waste typically includes swabs, latex, glass, plastics, needles, and other waste often contaminated with bodily fluids, as well as chemical hazardous waste including amalgam-derived products such as mercury, silver, and lead. It can be broadly divided into three categories: infectious waste, non-infectious waste, and domestic-type waste [16].

Infectious waste contains materials contaminated with blood or other infectious mouth fluids, amalgam, and sharps. Mercury from amalgam waste can contaminate the environment through sludge incineration, landfilling, and direct discharge into wastewater [17]. Safe management of infectious waste is essential to avoid public health issues such as cross-contamination and transmission of infectious diseases such as HIV or hepatitis. It is a common practice, especially in poor and developing regions, to dump most dental solid waste with household or municipal solid waste into landfills without any separation or recycling processes. Due to the presence of potentially hazardous components, such practices pose a significant risk to population health and the environment.

In this article, we report an overview of recent developments in the field of dental waste management, recycling approaches, and material processing in an environmentally sustainable manner. Dental materials, techniques, and various dental procedures have been undergoing a revolution in recent years. For example, use of mercury amalgams in dental fillings is being replaced by glass ionomer cements, resin formulations, etc., and the introduction of micro- and nanofillers is another major development [18,19]. These developments, in turn, have concomitant effects on the composition of dental waste, environmental impact, and waste management strategies [20].

This article is organized as follows. Basic characteristics and compositions of dental waste from various dental procedures are provided in Section 2. Details on new-generation dental materials, such as nanomaterials and resin-based composites ceramics, and their associated waste are presented in Section 3. An overview of recycling and waste management practices for dental waste is reported in Section 4. The focus will be on handling infectious as well as non-infectious waste, limitations of traditional waste treatment practices, challenges associated with new dental materials, environmental damage to air, land, and waterways around recycling facilities, and impacts on human health. Conclusions, current limitations, and future directions in dental waste processing are presented in Section 5.

2. Composition of Dental Waste

2.1. Solid Dental Waste

Appropriate segregation of contaminated waste is an important first step in managing potentially infectious waste and is likely to create health hazards if executed improperly [21]. To ensure the safety and health of healthcare workers, they should be well aware of the dangers involved and be trained in protocols. All contaminated waste, like syringes and gloves, that is recyclable should be disposed of in red-colored bags. Certain solid waste that includes bodily fluids, cotton swabs, liquid waste, and laboratory waste should be disposed of in yellow bags. Infectious sharps like scrapples and needles are disposed of in white bags, and implants, ampoules, glassware, and vials are discarded in blue bags [22].

The volumes and compositions of solid waste need to be determined accurately for developing appropriate waste management strategies. As a representative example, Figure 1 shows the relative proportions of different types of dental waste as determined from private and public hospitals, private practices, and training centers in Brazil [23]. Detailed information on various waste constituents is provided in Table 1. The dental solid waste produced in one day of dental work was collected in plastic bags, labeled, and transferred to waste storage facilities. The collected waste was visually inspected, pulled apart, and manually sorted into various sub-fractions, such as infectious and potentially infectious waste, non-infectious waste, and domestic-type waste. Their relative proportions can vary significantly from one scenario to another.

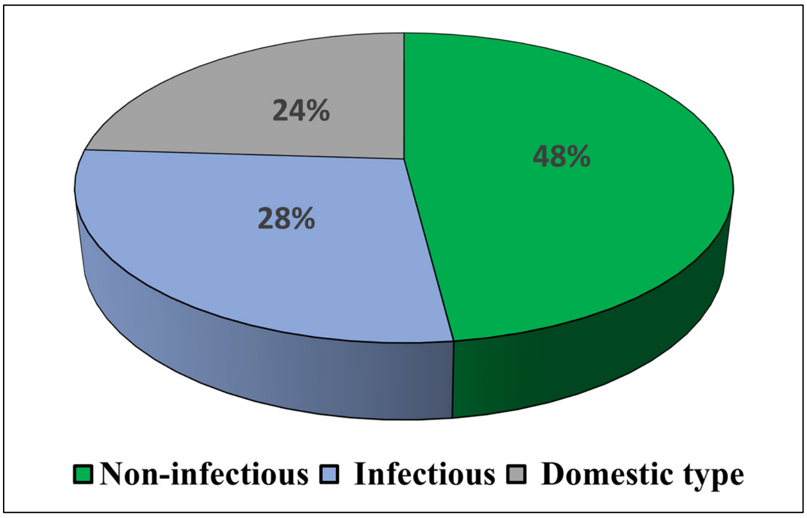

Figure 1. Typical distribution of different types of dental waste (%).

Table 1. Dental solid waste generation in three dental facilities (A, B, C) in Brazil [23].

	A	**B**	**C**
Total weight kg/d	39.6	50.6	82.8
Infectious Waste (wt.%)			
Various types of infectious waste	29	29.8	14.5

Table 1. *Cont.*

	A	B	C
		Non-infectious Waste (wt.%)	
Paper	41.6	35.4	25.2
Cardboard	3.3	2.8	2.7
Plastic Bags	4.3	3.3	1.6
Packaging	0.5	3.2	2.5
Glass Fabric	0.3	4	0.5
		Domestic-type Waste (wt.%)	
Food Waste	1.8	0.6	0.4
Garbage	17.4	15.4	34.8
Soil	-	5.3	7.5

Figure 2 shows a representative example of various metallic components present in the infectious dental waste collected in a typical dental clinic in Greece and their relative proportions [24].

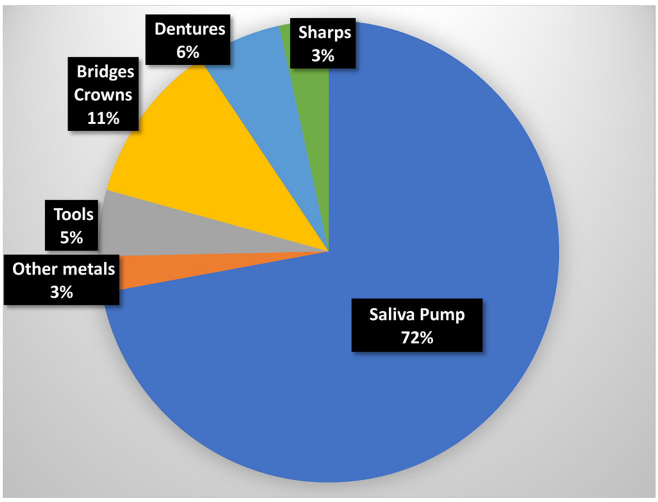

Figure 2. Various constituents of infectious metal-bearing solid dental waste and their relative proportions.

Potentially infectious dental waste consists of any waste material that came into contact with blood or other bodily fluids. It includes, among others, dental prostheses, occlusal bite blocks, and orthodontic appliances often containing human saliva and blood. Other infectious waste includes silicone for maxillofacial prostheses, gloves, plastic containers for transporting dentures and/or appliances, extracted teeth, mouth sticks, dental mirrors, suction tips, spatula, bandages, etc. The presence of microbes has also been detected on denture polishing plates, wheels, and dental impressions [25].

Non-infectious toxic dental waste is devoid of human fluid contamination but can be potentially toxic in nature. This includes materials such as amalgam alloys, acids for electrolytic polishing of metal frameworks, gypsum waste, metal dust, acrylic resin scraps, wasted metal alloys, porcelain, molding plaster, gutta-percha, X-ray films, lead shields from X-ray film packets, consumed ampoules, cardboards, plastic packaging, glass, fabric, etc. Domestic-type waste comprises paper cups, plastic, sandpaper, food waste, newspapers, packaging materials, pens, matches, styrofoam, sponges, cotton swabs, toothbrushes, and other domestic waste. Other waste properties, such as moisture content, ash content, volatiles, bulk density, and calorific values, have also been used to characterize different types of dental waste [26].

2.2. Wastewater from Dental Practices

Dental wastewater is a heterogeneous mixture of liquids (water, oral fluids, saliva, blood, mouthwash fluid, routine cleaning solutions, surfactants, etc.) and solid particles from tooth constituents, dental amalgams, soft tissues, bacteria, etc. [27]. Traditional mercury-based dental filling materials have long raised well-recognized environmental concerns [28,29] and are being replaced with resin composites and glass ionomer cements [30]. The Minamata Convention (2013) triggered the reduction of all mercury-containing products such as dental amalgam and became operational in 2017 [31]. EU regulation 2017/852 emphasized the reduction of mercury in all sectors [32], which is of specific importance to dentistry as it accounted for ~20% of global mercury consumption [33].

The process of replacing dental fillings produces fluid waste, including wastewater, aerosols, and fine and coarse particulates [34]. Dental practices use filter traps and separation technologies for dental amalgams to minimize the release of fine particulates into dental wastewater streams [35]. The filter traps are divided into spittoon and sink-type filters, capable of filtering particles 1000–2000 µm in size, and line filters, capable of catching particles 2000–4000 µm in size. Dental facilities also use amalgam separators, other devices, and mercury recovery units/mercury traps [36]. As per the International Organization for Standardization, ISO 11143:2008 certified separation technologies must have 95% separation efficacy for test slurries containing: (a) 30 wt.% amalgam particles with sizes $\leq$ 100 µm, (b) 10 wt.% amalgam particles with sizes in the range 100–500 µm, (c) 60 wt.% with amalgam particles in the 500–3150 µm size range [37]. In real-life scenarios, separation efficiencies have been found to range between 26.5% and 99.9%, depending on the filter setup and device usage in the dental facility [38].

With the introduction of novel mercury-free dental materials, such as resins, ceramics, and nano-engineered materials, dental wastewater can be a potential route of entry for these particulates and other pollutants into the environment [39]. Therefore, the current filter technologies also need to be upgraded to filter out waste from these new materials. Bisphenol-A is used for the production of glycidyl methacrylate ester of bisphenol A (Bis-GMA), which in turn is required for producing composite resins for direct dental restorations [40]. Resin composites are composed of an organic matrix containing a group of monomers, such as Bis-GMA, UDMA, and TEGDMA, as well as various inorganic supporting substances [41]. The organic matrix can be destroyed during a failed dental restoration or during grinding/polishing, resulting in the release of organic monomers [42]. The release of these monomers into patients' mouths can lead to pathogenic and allergic reactions and can also pass through the water syringe into dental wastewater, causing serious damage to the food chain, flora and fauna, and the environment [43].

The most common entry points into the environment for pollutants in wastewater arise from untreated discharge or the re-use of biosolids after wastewater treatment. Binner et al. [44] detected high levels of particulate matter and mercury-free dental filling materials in wastewater even with minimal amalgam in the dental waste. A primary constituent of dental composites, bisphenol A, has been found to leach into wastewater even after standard filtration procedures. A significant amount of inorganic matter remains suspended in wastewater and could be released into sewerage and mixed with municipal water supplies. For developing future regulations for mercury-free filling materials, the capture and removal of dissolved inorganic matter and nanoparticulates should be considered [45]. The presence of microscale and smaller-sized materials in dental wastewater with variable toxicological and physicochemical characteristics identify dental wastewater as a potential source of widespread release of engineered nanomaterials into the environment.

3. New-Generation Dental Materials and Associated Waste

3.1. Nanomaterials

Nanodentistry is the application of nanotechnology in the dental field for diagnosis, disease prevention, and treatment [46]. With characteristics like large surface areas, strong mechanical strength biocompatibility, antimicrobial and antibacterial properties, etc., a wide variety of nanoparticles have found applications in several dental applications as antimicrobial, restorative, and therapeutic agents [47]. Applications include, among others, copper-coated metal (denture framework) [48], copper amalgam alloy (amalgam restoration) [49], copper nanoparticles in glass ionomer cement (glass ionomer restoration) [50], copper nanoparticles (periodontal therapy) [51,52], nano copper-Ca_2SiO_4 (regenerative dental material) [53], nickel–titanium–copper alloy (orthodontic brackets) [54,55], ZnO:Ag nanoparticles (sealant for reducing root canal microleakage) [56], GT microparticles in ZnO nanoparticles (regenerative endodontics) [57], ZnO nanoparticles (sealing materials) [58], and GIC with AgNP (pediatric dentistry) [59].

Oral cavities in humans are known to be microbial swamps and could contain more than 700 different species of microorganisms [60]. Most of these bacteria are attached to teeth and mucous membranes as biofilms and their survival ability poses a significant challenge to the requisite dental treatment [61]. When new dental materials such as implants, restorations, or orthodontic brackets are added to the oral cavity, a new balance has to be established in the microbiota in order to avoid oral diseases such as dental caries, peri-implantitis, oral cancer, denture stomatitis, and periodontal disease [62]. Extensive research is being carried out towards developing suitable alternatives to traditional antibacterial approaches to overcome bacterial resistance [63]. Several antibacterials based on nanomaterials have been developed for dental applications with features such as low cost, excellent antibacterial properties, stable structures, and broad-spectrum antibacterial effects. Nanoparticles can be classified into two main classes: inorganic nanoparticles containing metals or metal oxides, e.g., copper, silver, gold, silica, zinc oxide, zirconium oxide and titanium oxide, and organic nanoparticles, e.g., nanotubes, nanocrystals, nanofibers, lipid nanoparticles, etc. [64,65]. Some examples include nano-Ag-coated Ti, PolymP-n active nanoparticles and metal ions, nano-Ag-coated PEEK, nano-Ag, and BBF-loaded poly (L-lactic acid) nanospheres [66].

Although many difficulties regarding the toxicity and production costs of nanoparticles need to be overcome, there is a wide scope for oral nanotechnology in the future. Patient procedures such as polishing, restoration, finishing, etc., can cause adverse effects and may lead to toxic effects in the lungs, liver, brain, skin, and kidneys through ingestion or inhalation [67]. The release of nanoparticles in oral cavities can occur during preparation, removal, or functioning. The making or replacement of nanocomposite fillings requires high-speed drills, which could damage the polymer matrix in the composite and release nanoparticles or their clusters into the oral cavity and patient's mouth [68]. Dental personnel should wear masks with high filtration efficiency to eliminate the risk of inhaling 38–90 nm sized airborne nano dust [69].

3.2. Resin-Based Materials

The introduction of resin-based dental materials is regarded as a major development in restorative dentistry. Esthetically pleasing and having a tooth-like appearance, dental composites are easy to handle, stable within the oral environment, and can be set on demand [70]. Major developments are taking place in dental composites due to increasing demands for minimally invasive restorative treatments along with non-toxic, low-cost, biological functionality, higher longevity, and superior esthetics to replace amalgam restorations even in most low-income countries [71]. Resin-based dental composites contain two or more distinct phases, namely an organic matrix composed of resin monomers and an inorganic filler phase chemically bonded with a coupling agent [72]. While significant progress has been achieved in structural characteristics, the physicomechanical strength, wear resistance, and volume shrinkage of these materials during polymerization remain major issues [73]. High levels of local stress could be generated when these materials undergo shrinkage in the confined spaces of root canals or tooth cavities [74], which is one of the key reasons for the failure of resin-based restorations [75].

Dental resins represent organic monomer systems where the base monomer is mixed with the dilutant monomer to achieve optimal viscosity for clinical handling. Some base monomers include UDMA (urethane dimethacrylate), Bis-EFMA [9,9-Bis[4-((2-(2-methacryloyloxy)ethyl-carbamate) ethoxy)phenyl]fluorene]; TMXDI [1,3-bis(1-isocyanato-1-methylethyl)benzene]; HEA (2-hydroxyethyl acrylate); TTM [trimethacrylate tris(4-hydroxyphenyl)methane triglycidyl methacrylate]; NBDI (norbornane diisocyanate); 2EMATE-BDI [2-hydroxy-1-ethyl methacrylate]; HMFBM [5-(hydroxymethyl)-1,3-phenylene bis(2-methylacrylate]; and HPA (2-hydroxy propyl acrylate). Diluent or comonomers include TEG-DVBE (triethylene glycol divinylbenzyl ether); BZ-AL [allyl(2-(2-(((allyloxy) carbonyl)oxy)benzoyl)-5-methoxyphenyl) carbonate], Phene [N-methyl-bis(ethyl-carbamate-isopropyl-α-methylstyryl) amine]; and BPhADAC [diallyl (propane-2,2-diylbis (1,4-phenylene)) biscarbonate] [76,77]. UDMA-based composites are more brittle with higher polymerization shrinkage than Bis-GMA due to shorter chain lengths, but UDMA allows the addition of more inorganic fillers. Integration with a hydrophobic substituent within the monomer backbone can reduce water sorption and the solubility of UDMA composite systems [78,79].

A composite material is reinforced with inorganic filler materials with properties distinct from those of the resin matrix. These fillers enhance the mechanical and physical properties of dental composites, such as the strength, modulus [80], toughness [81], surface hardness [82], etc. The impact of fillers on various composite properties is determined by the type, relative proportion, size/shape, dispersion, surface modification, and orientation of fillers incorporated in the resin matrix [83]. Typical filler materials include silica-based glass (silica nanoparticles, calcinated colloidal silica, silicate bioactive glass, glass ceramics, glass fibers, etc.) [84–86]; metals (Ag, TiO_2, and Au) [87,88]; pre-polymerized particles [89]; natural minerals (halloysite nanotube, hydroxyapatite, calcium phosphate, and zeolite) [90,91]; and cellulose crystallites [92]. The different shapes of fillers used include spheres, irregular shapes, plates, fibers, tubes, etc. Hybrid composites may use micro-sized fibers, nanotubes, or whiskers in a range of proportions to enhance mechanical strength, fracture toughness, and elastic modulus [93].

Coupling agents are used to create a strong interfacial bond between the dental resin matrix and the filler through mechanical interlocking or the formation of chemical bonds. The high surface roughness of the filler and a large micro/nanoscale contact area between the resin and filler play critical roles in enhancing mechanical interlocking. Surface roughness can be increased through chemical etching or by coating and grafting techniques [94]. Silane coupling agents and hybrid synthetic organic-inorganic compounds are used extensively to create covalent bonds between organic resins and inorganic fillers [95]. After surface treatment with silanes, fillers become hydrophobic and have increased levels of chemical compatibility and wettability with the resin matrix; the surface treatment can increase the dispersion capability of micro- and nanofillers [96]. A very wide variety of new dental materials have been developed to cover a variety of situations. The primary requirement of these composites is to ensure that the combined properties are optimized to prevent physical failure and recurrent damage in a harsh oral environment, with increased longevity and durability of dental restorations.

3.3. Ceramics

Mineralized tissues, including tooth enamel, cementum, and dentin, are the key load-bearing structures in human teeth, which provide the hardness and mechanical strength required for crushing and chewing food. Dental restorative materials are required for repairing teeth after long-term degradation processes such as fatigue, caries, wear, etc. [97]. Designed to mimic the function of natural tooth tissue, their longevity depends primarily on the wear and fatigue behavior in the oral atmosphere. These are also used in orthodontic brackets, ceramic dentures dental implants, implant abutments, etc. [98]. Dental ceramics can be classified into three groups, namely glass ceramics, resin-based ceramics, and polycrystalline ceramics.

Glass ceramics are prepared by reinforcing a certain amount of glassy phase with crystalline materials. While the glassy phase provides strong bond strengths, the crystalline phase affects the microstructure, strength, and translucency in the resin cement [99]. A few examples of these composites are given next. Leucite-reinforced glass ceramics are made from SiO_2, Al_2O_3, and K_2O-containing glass with leucite crystals ($KAlSi_2O_6$; 35–45 vol.%) as the main reinforcing material. The combination of glassy phase with crystalline phase produces restorative material with good esthetics and moderate occlusal stress for use in anterior crowns and veneer restorations [100]. ZrO_2-reinforced lithium silicate glass ceramics consist of a blend of lithium orthophosphates and metasilicates in a glassy matrix with crystalline particles of lithium silicate and are used for anterior/posterior full crowns, veneer restorations, and partial occlusal coverages [101]. Lithium disilicate-reinforced glass ceramics are another example, composed primarily of glass phase reinforced with 65 vol.% crystalline lithium disilicate [102].

Discovered in the early 1970s, glass ionomer cement (GIC) is another versatile dental material with great potential in restorative applications for its good biocompatibility, chemical adhesion to tooth surfaces, thermal expansion characteristics similar to those of dentine, etc. [103–105]. It is formed by mixing calcium fluoro-alumino-silicate glass powder with a polyacid solution. Low mechanical strength, moisture sensitivity, and limited antibacterial effect limit the use of this cement in clinical applications [106]. To overcome some of these issues, antimicrobial silver zeolite glass ionomer cement (SZ-GIC) has also been developed. SZ (1 wt.%)-GIC was found to have enhanced physical, adhesive, and antibacterial properties as compared to conventional GIC [107].

Resin-based ceramics are composed of partially sintered ceramic matrix (up to 86 wt.%) infiltrated with a polymer matrix (up to 14 wt.%) with higher compatibility than dentin and higher chemical stability [108]. These materials find applications as anterior/posterior crowns, veneer restorations, and partial occlusal coverage. Polycrystalline dental ceramics do not contain any glassy phase and are composed only of crystalline phase, such as alumina and zirconia, which possess high mechanical strength but limited translucency and bonding adhesion. Examples of dental zirconia include zirconia stabilized with 4–6 wt.% yttria (TZP) used for single crowns and multi-unit restorations, and translucent partially stabilized zirconia for monolithic restorations in the anterior/posterior regions [109]. Zirconia ceramic toughened with mica glass composite has also been reported as an indirect restorative material [110].

4. Management of Dental Waste

Key process steps in managing dental solid waste involve collection from different dental facilities, storage, segregation into infectious and non-infectious categories, further separation into polymer-rich, metal-rich, and ceramic-rich constituents, followed by appropriate end-of-life treatments. A number of methods, such as low/high temperature thermal treatments, autoclaving, incineration, chemical methods, mechanical methods, landfilling, etc., are used to dispose different types of dental waste, with the chosen approach depending on the costs involved, infrastructure, and environmental impact. Infectious waste must be disinfected first and pathogens, viruses, and bacteria removed before disposal; human tissues, sharps, and cultures must be disposed of after treatment and untreated waste sent to landfills. In dentistry, waste from dental amalgam, mercury waste, silver- and lead-containing waste are fairly common and pose severe health risks as well as environmental hazards. A brief overview is provided next of the main waste management approaches with a focus on key features and limitations.

4.1. Incineration and Thermal Treatments

Incineration involves the burning of waste at high temperatures (200–1000 °C) in closed environs. The waste undergoes combustion (pyrolysis) in the presence (absence) of air/oxygen, reducing combustible and organic waste to inorganic end products while significantly reducing the waste volumes of incombustible constituents. Basic requirements for incineration include reasonably high calorific value of the waste (>2000 Kcal/kg), high combustible content (>60%), non-combustible solids content less than 5%, and low moisture content (<30%). However, incinerators are known to be highly polluting, emitting toxic, hazardous gases along with generating toxic ash residues [111]. Other thermal waste treatments include the use of microwave, infrared, and plasma treatments in waste treatment [112]. A representative example of the combustible component of dental solid waste is provided in Figure 3.

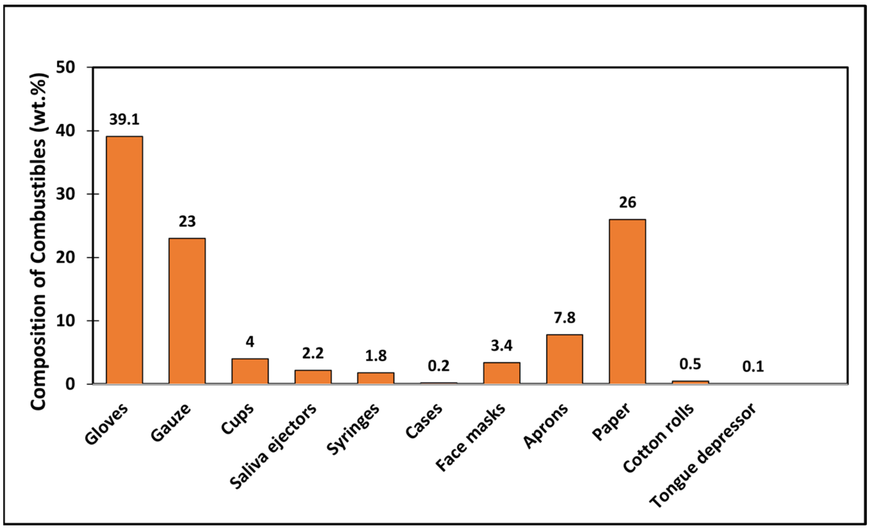

Figure 3. Composition of various combustibles in dental solid waste [113].

Specific challenges to incinerating dental waste can be attributed to its complex composition profile, which includes a variety of polymers, mercury amalgams, metals, ceramics, composites, nanomaterials, etc. These materials have very significant differences in their thermal degradation behaviors and can generate different end products depending on the heat treatment process. A very wide variety of polymers are used in dentistry for restorative, regeneration, or preventive treatments [114]; some specific examples of resin-based materials were provided in Section 3.2. While the primary focus in emerging dental polymers is on the resultant properties, e.g., mechanical, thermal, water solvation, and bio-functionality (antibacterial capability, bioactive delivery, remuneration, etc.) [115], little attention has been paid to determining their high-temperature thermal degradation, generation of toxins and dioxins, role of metals, and their eventual destruction.

The incineration of biomedical waste, including dental waste, has been identified as one of the highest known sources of dioxin-based emissions [116] and mercury emissions [117]. These pollutants are present in the atmosphere as gases as well as microparticulates [118]. Once released into the atmosphere, these can get transported over long distances, causing significant environmental damage [119]. Exposure to dioxins and furans is known to cause gastrointestinal, neurologic toxicity, hepatic, and dermal issues in humans as well as immunologic toxicity and adverse reproductive effects in animals [120]. If mercury-containing items are sent to an incinerator, mercury-based vapors will enter the global distribution cycle, thereby contaminating the environment. Mercury is known to be a potent neurotoxin; mercury levels exceeding permissible levels can lead to chronic fatigue, loss of appetite, and dizziness [121]. Mercury toxicity in the elderly population has been linked with Alzheimer's disease as well as irreversible organ damage [122].

Inorganic compounds present in incinerated ash residue include potentially toxic heavy metals, metalloids, ceramics, and other oxides [123]. Various metals and metalloids contain biologically essential elements, such as cobalt, copper, chromium, zinc, and manganese, and non-essential elements like arsenic, cadmium, lead, etc., some of which are toxic to humans, plants, or animals at high concentrations [124]. Various ceramics present in dental waste require very high temperatures (>2000 °C) for processing; as incineration temperatures are too low for their degradation, these precipitate out as ash residue [125]. The ash materials derived from the incineration of hazardous medical waste are generally disposed of in landfills after the solidification and/or stabilization process. A serious concern with respect to developing nations is the uncontrolled incineration of medical waste without flue gas treatment and extensive release of toxic emissions [126]; such practices should be avoided to the extent possible for the health and safety of the populace near waste management facilities.

Despite the advantages of the incineration process, up to 25% of residues may be generated in the form of bottom ash and fly ash from the non-combustibles present in waste [127]. As the dioxins, volatiles, and heavy metals produced during incineration tend to concentrate in these residues, these are classified as hazardous waste and should be disposed of carefully [128]. Water washing has been used as a pretreatment method to remove soluble substances such as chlorides from these residues [129]. The washing of ceramic-rich sludge produced during incineration has also been used to remove impurities and improve the efficiency of downstream processing [130]. The reutilization of these waste products further enhances the environmental sustainability of dental waste management and needs to be implemented on several fronts.

4.2. Landfilling

Landfilling is one of the most commonly used disposal approaches for managing solid waste in developed as well as developing nations across the globe [131]. In addition to requiring large areas of land for dumps, the generation of leachates in the form of highly concentrated organic/inorganic liquids raises serious environmental and contamination issues. Residues from other waste management techniques, such as composting, recycling, and incineration, are also disposed of in landfills [132]. Leachate is generated from waste moisture, rainwater, and as a byproduct of waste degradation and can contain a wide range of highly toxic and potential carcinogenic toxic macro/micropollutants [133–135]. Landfill leachate contaminates nearby aquatic systems, thereby impacting the quality of waterways with detrimental effects on human health, flora, and fauna [136,137].

The European Union Landfill Directive has established the principles and rules for controlling landfill leachates, stipulating a leachate treatment system and leachate confinement at landfill sites [138]. Measures need to be taken to decrease seepage, lower interaction between the leachate and the landfill, as well as leachate harvesting wherever feasible [139]. Landfills are also known to emit methane, hydrogen sulfide, greenhouse, and other noxious gases affecting air quality, causing health issues and environmental damage [140]. Leachate composition includes inorganic macro/micro materials, dissolved organic matter, heavy metals, xenobiotic chemicals, and small amounts of mercury, lithium, cobalt, etc. Elements such as As, Cd, Pb, Hg, and Ni are known to have a wide spectrum of toxicity, including neurotoxic, teratogenic, hepatotoxic, mutagenic, and nephrotoxic effects [141]; Cd, As, and Cr are considered to be carcinogenic [142]. When a number of discarded mercury-based products are dumped in landfills along with other waste, mercury is released during waste decomposition and can be transported over long distances or become a part of leachate [143]. Proper monitoring of landfills, leachate treatment, and risk assessment are essential to prevent ecological harm as well as to avoid leachate toxins from contaminating groundwater, surrounding soil, and the environment [144].

4.3. Disposal Challenges for New Dental Materials

While incineration and landfilling have been used for managing traditional dental/healthcare sector waste, the presence of novel dental materials (see Section 3) in dental waste, their degradation behaviors, waste treatment, and associated environmental effects raise new concerns and need to be addressed separately.

4.3.1. Nanomaterials

A wide variety of nanomaterials (1–100 nm in size) are being used in various aspects/applications of dentistry, such as copper-based nanomaterials, including copper-coated metals, copper amalgam alloys, glass ionomer cements, nano copper-Ca_2SiO_4, nickel-titanium-copper alloys, etc., and zinc oxide nanoparticles, silver-based alloys, etc. End-of life nanomaterials are typically referred to as nanowaste [145]. Nanowaste is an emerging problem, as little is known about the sustainable waste management options for the diverse range of nanomaterials with distinct characteristics [146]. The fate and extent of nanoparticles in incineration plants are poorly understood. During waste incineration, the behavior of nanoparticles can be quite complex, as these can behave like gases when airborne creating no sedimentation or be carried along with larger particles and diffuse as nanopollutants [147,148]. Nanowaste needs to be treated as a separate category of waste as uncertainties due to extremely small sizes, a variety of shapes, chemical reactivity, and biocompatibility makes it significantly different from standard waste types [149]. The liberation of nanoparticles in dental waste, their chemical and mechanical interactions, and toxicity can lead to environmental damage and serious risk to the health and safety of health workers [150]. To better understand the risks from nanowaste, the behavior of nanomaterials in traditional waste management processes, i.e., incineration, recycling, wastewater treatment, and landfilling, needs to be investigated in great detail and evaluated for sustainable treatment of nanowaste [151].

4.3.2. Resin-Based Materials

The three main constituents of resin-based dental composites are an organic matrix composed of resin monomers, inorganic fillers, and coupling agents. A very wide variety of organic monomers/polymers are used in dental applications (see Section 3.2 for details). While developing these resin-based materials, focus is always on the requisite dental applications and their basic/key requirements [152]. Little is known about the high-temperature (up to 1000 °C) degradation behavior of these materials during incineration, as such high temperatures are never encountered during the utilization/application of these materials [153]. Similarly, there are negligible experimental, theoretical, or modeling investigations of their degradation and/or leachate behavior when buried in a landfill as a mixed waste. This points to a major gap in knowledge for the sustainable management of dental waste.

The pyrolytic decomposition of polymeric waste into char, gasoline-based fuel, and synthetic gas is a key industrial approach, wherein the hydrogen generated from polymer degradation is used for the hydrogenation of unsaturated intermediates during thermal cleavage of polymer chains [154,155]. During thermal treatment, most polymer degradation was found to reach completion by 450–550 °C [156,157]. Metals present in resin-based dental waste can have a catalytic influence on the polymer degradation behavior as well as thermal stability [158]. There is also a strong likelihood of the generation of harmful particulates and toxic emissions [159]. Dioxins are highly stable and may require high temperatures (>700 °C), excess oxygen, and long residence times (>2 s) for destruction. Once these enter the human body, these tend to be absorbed in the fatty issue and stored for a long time [160].

In-depth investigations need to be carried out on the thermal degradation behavior of resins used in various dental applications towards identifying suitable and optimal routes for managing their end-of-life waste. While there are challenges galore in the incineration of these products, landfilling such resinous waste is not a good option either. These organics are most likely to be non-biodegradable and are likely to persist in landfills for long periods of time. Significant research needs to be carried out in this field towards environmentally sustainable waste management.

4.3.3. Ceramics

Cordeiro et al. [161] investigated the recycling of zirconia waste powder generated during the manufacture of dental prostheses. These powders were calcined at 500 °C and de-agglomerated in a rolling mill to produce micron-sized powders. These were later sintered in the temperature range of 1300–1500 °C and their strengths and mechanical properties were determined. These sinters were found to be suitable as an alternative low-cost and high-strength material in ceramics.

A wide variety of ceramics are used in a range of dental applications, e.g., glass ceramics; leucite-reinforced glass ceramics based on SiO_2, Al_2O_3, and K_2O; ZrO_2-reinforced lithium silicate glass; lithium disilicate glass; etc. [162,163]. Ceramics are known as highly stable refractory oxides that require very high temperatures for their degradation. For example, the melting and boiling points of SiO_2 are 1713 °C and 2700 °C, respectively; the corresponding data for ZrO_2 are 1850 °C and 4409 °C. With incinerations of dental waste typically taking place at temperatures below 1000 °C, various ceramics present in dental waste will be completed unaffected by the heat treatment. While the polymeric parts in the waste will degrade at these temperatures, the ceramic components are likely to be decoupled as loose fractions. Most of these are likely to end up in the ash residue as waste products or slag.

4.4. Additional Aspects

A few additional aspects of dental solid waste are considered next. As a specific example, we consider the case of single-use plastic (SUP) waste generated in clinical dental practices. The adoption of single-use plastics is a relatively recent development, the role of which became significant during the coronavirus (COVID-19) pandemic, especially as personal protective equipment (PPE) for cross-infection control.

To highlight the enormity of the issue, Martin et al. [164] reported on the SUPs (PPE, face masks, gloves, etc.) generated from oral healthcare and clinical dental settings in the UK and established baseline data/volumes of SUPs used. Most of the SUP waste was disposed of via either landfill or incineration with adverse environmental effects. Appropriate legislation may be necessary for limiting the environmental damage from SUPs without compromising patient safety during clinical care.

While some energy can be recovered from waste incineration, little effort has been made towards resource recovery from dental waste. Recovery of nickel from orthodontic implants using the hydrometallurgical route has been reported [165]. On the other hand, electronic waste is also a complex waste containing polymers, metals, ceramics, and hazardous elements, wherein a variety of recycling approaches have been developed to process waste and extract copper, precious metals, rare-earth elements, etc. [166,167].

Toxicity in dental settings is another serious issue of concern. Toxicological studies are carried out to screen dental materials in terms of their biocompatibility and possible adverse effects. There is convincing evidence for the toxic effects of mercury amalgam on human health, such as anorexia, weight loss, weakness, fatigue, etc. [168]. Resin-based composites contain organic matrix, fillers (SiO_2, Al_2O_3, glass, etc.), ceramic particles, and coupling agents; these are considered to be good alternatives to amalgams. Saliva enzymes, chewing, thermal changes, dietary changes, and oral microorganisms can cause the degradation of composites and release of monomers in the body [169]. Being soft and flexible, bisphenol A (BPA)-based monomers are commonly used in root canal sealers, adhesives, composites, and sealants; these are associated with increased incidences of developmental disorders, breast cancer, and diabetes [170]. Titanium is one of the most commonly used materials in dental implants due to its strength, biocompatibility, and stress resistance. In the oral cavity, titanium implants can undergo chemical reactions in the body causing corrosion, wear, and the release of titanium particles in the body [171]. The presence of toxic elements in dental solid waste needs to be handled very carefully.

Efforts are also being made to manage dental solid waste from the perspective of the circular economy. Waste management plays a key role in the circular economy by determining the order of waste treatment hierarchies, e.g., prevention > preparation for reuse > recycling > energy and material recovery > sanitary landfilling. Although the delivery of high-quality care is the top priority in healthcare, recycling programs and waste minimization can play a significant role in enhancing the economic and environmental sustainability of organizations. Some of the key steps in the circular economy model include, among others, establishing a green team, quantitative determination of waste production, waste minimization, safe reutilization, recycling, and reprocessing [172].

Another challenge to the sustainability of healthcare waste management practices that needs to be addressed is the example of 'sustainable washing'. Some researchers/operators might label themselves as sustainability experts without adequate qualifications, experience, research publications, and/or project reports. Without appropriate training, sustainable washing of qualifications could limit the extent to which various environmental issues are likely to be addressed [173]. There is also a need for incorporating interdisciplinary pathways, different knowledge and skill bases, resources, and perspectives.

5. Conclusions

An in-depth overview has been presented from a materials perspective of dental waste, such as composition, new materials, emerging developments, end-of-life disposal, and waste processing techniques. In addition to being infectious, dental waste can be fairly complex due to the simultaneous presence of polymers, metals, ceramics, and some hazardous elements. Incineration and landfilling are currently the two main waste treatment options for dental waste. However, landfilling and incineration are no longer the preferred treatment options for electronic waste; similar efforts should be made in the healthcare sector as well.

Another area requiring further research is the thermal degradation behavior of new dental materials. A range of new nanomaterials, resins, composites, and ceramics are being developed to satisfy various criteria/characteristics required in different dental applications. However, little is known about the fundamental characteristics of the individual constituents of these materials. Such knowledge will be invaluable during end-of-life disposal of these dental materials, resource recovery, and assessing technical issues and environmental impacts.

It is recommended that new single or multistage recycling technologies/approaches be developed for dental as well as healthcare waste towards enhanced resource recovery and to reduce the use of high-temperature incineration and landfilling to the extent possible. Systematic, eco-friendly, and economically sustainable management of healthcare waste needs to be implemented for minimizing its negative impact on human health and the environment, especially in poor and developing economies of the world.

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