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Assessment of the Environmental and Health Impacts Arising from Mercury-free Dental Restorative Materials

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Rialtas na hÉireann
Government of Ireland

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- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

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EPA RESEARCH PROGRAMME 2021-2030

Assessment of the Environmental and Health Impacts Arising from Mercury-free Dental Restorative Materials

LESS Hg

(Looking to Environmental Sustainability and Securing Health goals)

(2017-HW-MS-11)

EPA Research Report

Prepared for the Environmental Protection Agency

by

University College Cork

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THE TEAM

The project team assembled brought together the knowledge and skills of individuals within their respective teams in clinical dentistry, dental public health and environmental science, including those involved in the analysis of wastewater streams and biofilm. The respective teams had previously demonstrated their ability to conduct research funded by the state and by industry and as part of the Cochrane Collaboration, and were committed to working together, appreciating the interplay between the environment and dental/oral health.

The Oral Health Services Research Centre (OHSRC) led on work packages 1 and 3, which centred on reviews of the literature and engaging with dental practitioners and industry that supports the practice of dentistry. The Environmental Research Institute (ERI) and School of Biological Earth and Environmental Sciences (BEES) led work package 2, which focused on the scientific determination of particulate matter in wastewater streams, initial toxicity screening of waste streams and the efficiency of existing devices and practices in "capturing" mercury-free dental materials.

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Executive Summary

This project focuses on the assessment of the environmental and health impacts arising from mercury-free dental restorative materials. The project explores (i) the evidence available with respect to potential environmental and health impacts of mercury-free dental restorative materials, (ii) quantification of the materials that enter wastewater streams after exiting the various filters and traps present on the dental chair unit, (iii) the efficacy of the international standard for amalgam separators, type 1 (ISO 11143:2008), and (iv) the toxicity of the dental wastewater stream.

The United Nations Minamata Convention on Mercury provides an international regulatory framework with the aim of protecting human health and the global environment from the harmful effects of mercury. The Convention addresses the use of mercury-containing dental filling materials and their phasedown in dental practice and has been transposed into legislation in the EU (Regulation (EU) 2017/852) and Ireland (S.I. No. 533/2018). Dental fillings are used to replace lost tooth tissue, and prior to the entry into force of the Minamata Convention there was a downward trend in the use of dental amalgam restorative materials.

This project was designed to assess the potential environmental and health impacts arising from mercury-free dental restorative materials. The project results identified that concerns exist regarding the release of small particles from wastewater treatment plants into which dental wastewater flows. Physical tests identified that the ISO 11143:2008-certified amalgam separators, types 1 and 2, used in this study did not retain the small particle constituents from mercury-free dental restorative materials. Experimental studies to determine the toxicity of the dental wastewater stream to the planktonic crustacean *Daphnia magna* demonstrated toxicity, with variability existing across the participating dental practices. Based on the limited research undertaken in this project, further research in this domain is required.

The information to date with respect to the health impacts of mercury-free dental restorative materials on dental personnel and the population focuses on occupational health and engineering controls. Since these controls and health and safety requirements were put in place in northern Europe, available data would suggest that there has not been an increase in adverse occupational health events. Further research with respect to environmental impacts will be important, however, as materials continue to evolve along with the monitoring of organic polymers.

Given the relatively recent introduction of Regulation (EU) 2017/852 on mercury and S.I. No. 533/2018 in Ireland, the importance of the appropriate maintenance and use of amalgam separators and all engineering controls should be emphasised and guidance should also include taking precautions to minimise dust aerosolisation. New dental materials are emerging onto the market, and the auditing and monitoring of the environment, the dental clinic spaces, personnel, patients and the public must be kept under scrutiny.

1 Introduction

This report presents the findings of research conducted by University College Cork to assess the potential environmental and health impacts arising from mercury-free dental restorative materials (MFDRMs).

Tooth decay (dental caries) is a preventable disease affecting both baby and adult teeth. Despite significant improvements in overall oral health, there is still a high level of tooth decay that may require treatment. The Global Burden of Disease 2017 study estimated that untreated tooth decay was the most prevalent condition of all those examined and that 2.3 billion individuals had untreated tooth decay in permanent (adult) teeth, a sizeable burden (GBD, 2018). Tooth decay occurs over time when acid-producing bacteria ferment monosaccharides and disaccharides, producing a fall in pH, a more acidic environment and loss of tooth mineral, namely calcium, phosphate and fluoride. Left to progress, a hole occurs in the tooth that requires a filling. The choice of filling material is transitioning from the traditional silver (amalgam) filling that contains ~50% mercury to mercury-free (Hg-free, tooth-coloured/white) dental restorative materials. Given the negative environmental impacts of mercury, there is a concerted effort to reduce its use in dentistry (UNEP, 2013). This reduction has seen a rise in the placement of mercury-free dental filling materials. Depending on their type, MFDRMs can contain particles of silica glass, quartz, resin polymers/monomers/nanomers or polyacrylic acid. With respect to these particles, human health is protected through health and safety legislation and engineering controls. The behaviour of these materials in terms of their impact on the environment is less well understood.

This research project addresses the needs of the environment and the promotion of health, and is referred to by the acronym LESS Hg (Looking to Environmental Sustainability and Securing Health goals). The research involved a systematic search of the literature and review of the existing information on the environmental impact of MFDRMs or Hg-free materials, testing the physical and chemical properties of dental practice wastewater and the efficacy of existing amalgam separators in removing particles/substances in MFDRM, and, lastly, a search and review of the literature on the occupational and health risks of MFDRMs.

The research was carried out with a focus on the following three areas:

1. a comprehensive review of the literature on the environmental impact of MFDRM;
2. determination of the particulate matter present in dental practice wastewater along with investigation of the ecotoxicity of dental practice wastewater and the efficacy of dental amalgam separators in retaining particles from MFDRMs;
3. a comprehensive review of the literature with respect to the occupational challenges faced by dental practitioners, other staff and patients arising from the use of MFDRMs.

MFDRMs are useful alternatives to dental amalgam, which, despite its associated environmental concerns and poor aesthetics, has remained popular because of its handling properties and cost-effectiveness (Schwendicke *et al*., 2018). The advantages of MFDRMs are that they are tooth coloured and more conservative of tooth form. They have replaced dental amalgam in many clinical applications and have been used almost exclusively and successfully in many countries for many years (Heintze and Rousson, 2012; Keane *et al*., 2020) (Table 1.1). A recent systematic review found that amalgam fillings had lower failure rates than tooth-coloured fillings; the primary research informing the review was, however, rated as being of low to moderate quality (Worthington *et al*., 2021). Some of this replacement of dental amalgam by MFDRMs is a result of the Minamata Convention on Mercury (UNEP, 2013) and its ratification by law in many countries, including Ireland (Government of Ireland, 2018, 2019).

In Europe, some countries have moved or are moving towards an almost complete phaseout, while some are still dependent on dental amalgam (Table 1.1).

The MFDRMs/Hg-free materials used in dentistry have the potential to enter the environment in a number of

Table 1.1. Amalgam usage in Europe

Usage	Country or region
Banned or almost completely phased out	Denmark Finland Italy Netherlands Norway Sweden Switzerland
Low	Austria Germany Portugal Spain
Moderate	Belgium
Significant	France Great Britain

Based on information from Keane *et al.* (2020).

ways, with possible consequences for the environment (Figures 1.1 and 1.2).

A timeline for the introduction of dental amalgam, MFDRMs and the associated legislation is presented in Figure 1.3 to orientate the reader.

The objectives of the research were to:

1. conduct a comprehensive review of the literature on the environmental impact of MFDRMs;
2. determine the particulate matter present in dental practice wastewater;
3. assess the efficacy of dental amalgam separators in retaining particles arising from the use of MFDRMs/Hg-free materials;
4. assess the ecotoxicity of dental practice wastewater;
5. conduct a comprehensive review of the literature with respect to the occupational challenges associated with the use of MFDRMs.

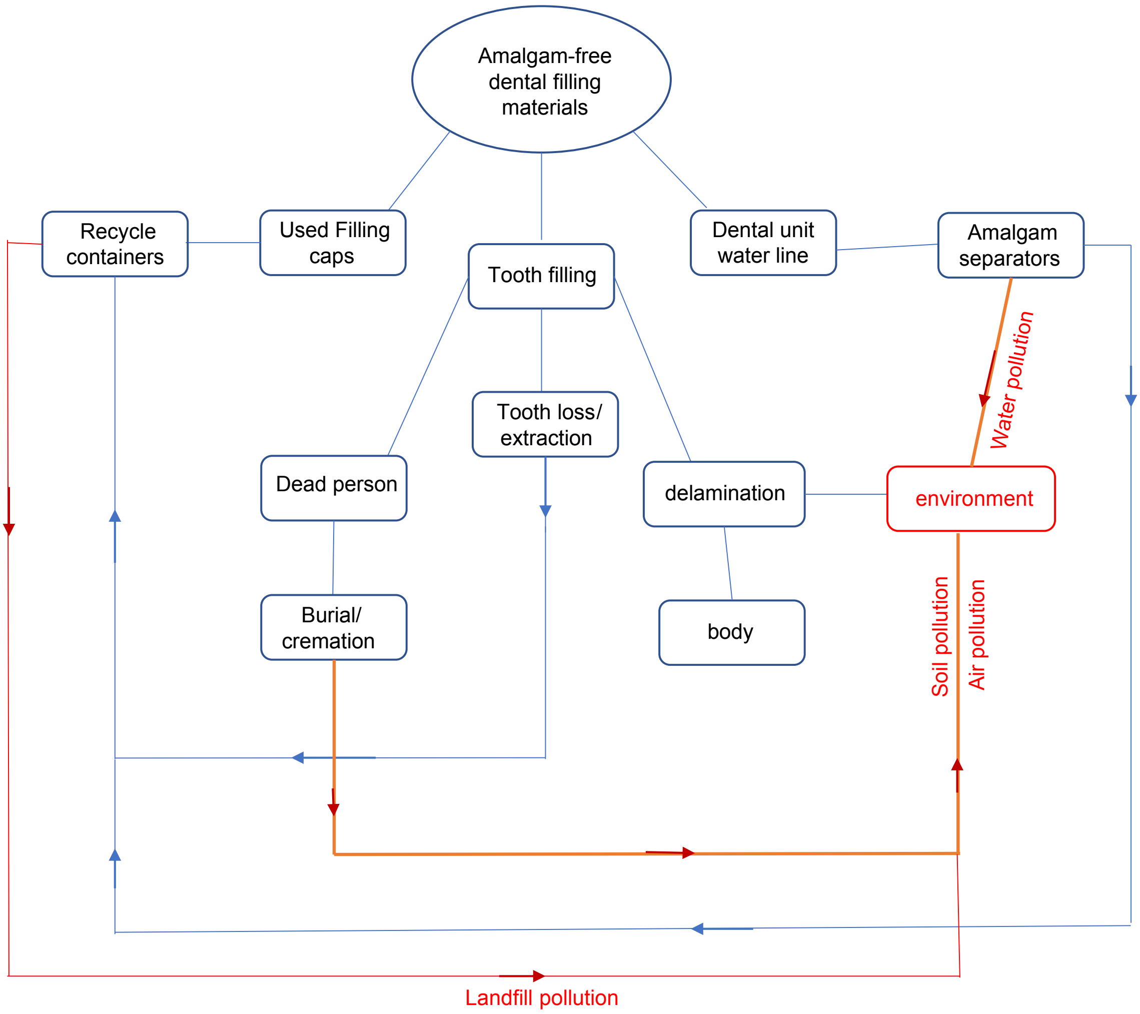


Figure 1.1. Cycle of mercury-free dental restorative materials.

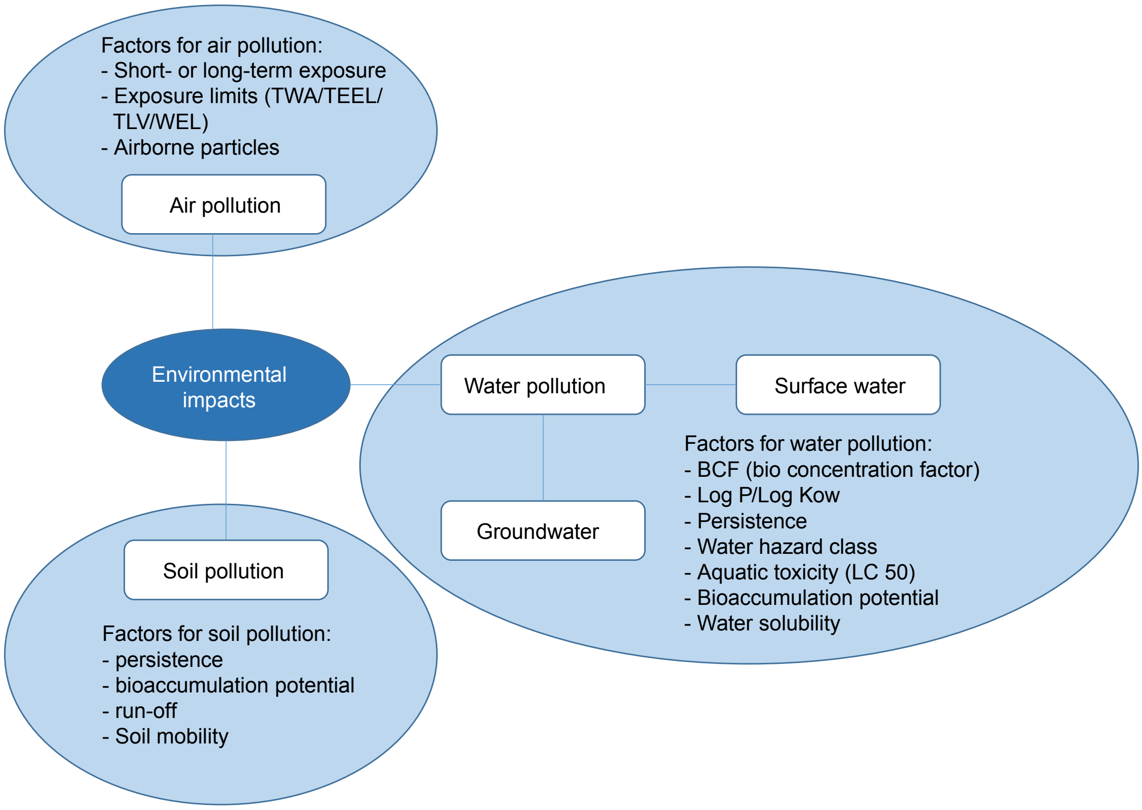


Figure 1.2. The potential environmental impact of MFDRM/Hg-free dental filling materials. LC, lethal concentration; TEEL, temporary emergency exposure limit; TLV, threshold limit value; TWA, time weighted average; WEL, workplace exposure limit.

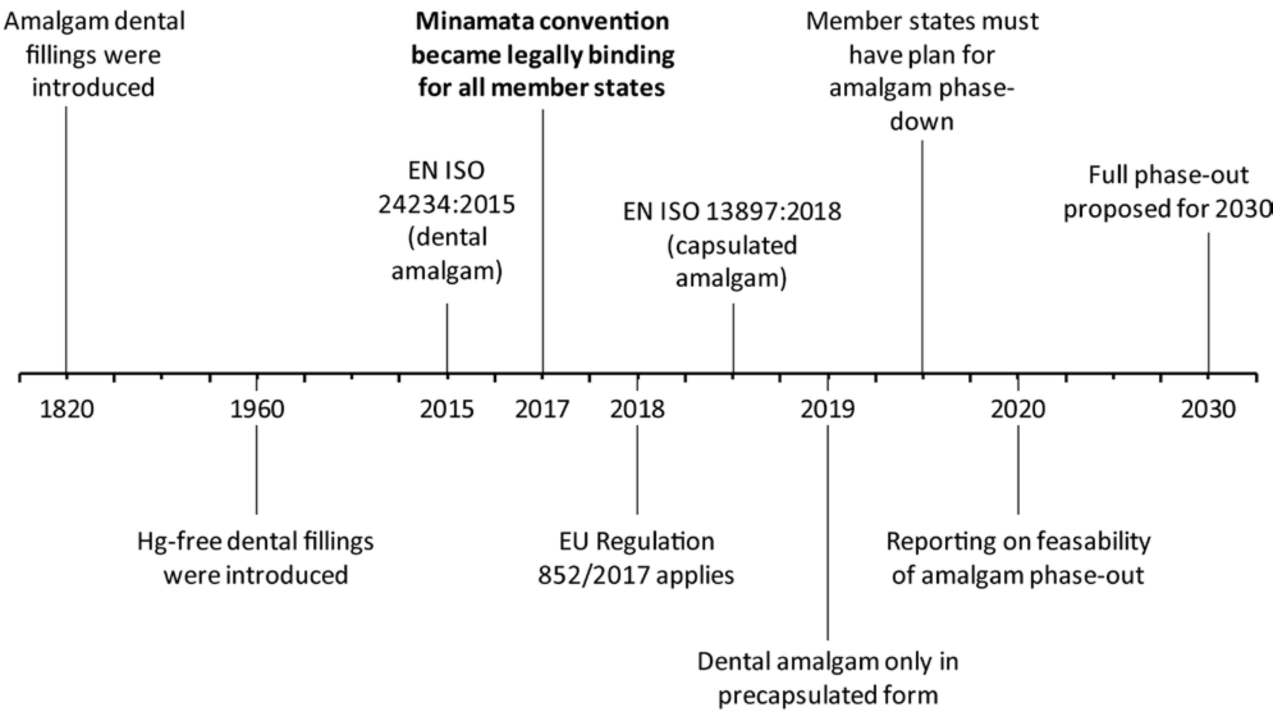


Figure 1.3. Timeline of introduction and regulation of dental materials, including the Minamata Convention, Regulation (EU) 2017/852 and S.I. No. 533/2018.

2 Background

To understand the nature of the research undertaken, it is necessary to provide some background on the dental restorative materials in use, the design of dental amalgam separators that comply with ISO 11143:2008, and the work space/environment of dental practice and the use of MFDRMs.

2.1 Dental Materials

MFDRMs are chiefly (i) resin composites (RCs), (ii) polyacid-modified resin composites (PMRCs or “compomers”), (iii) glass ionomer cements (GICs) and (iv) resin-modified glass ionomer cements (RMGICs). All are available in dentistry for different clinical applications. They have been introduced over the past 60 years and continue to evolve, with very few adverse reports from an occupational health and environmental perspective (Figure 2.1).

2.1.1 Resin composites

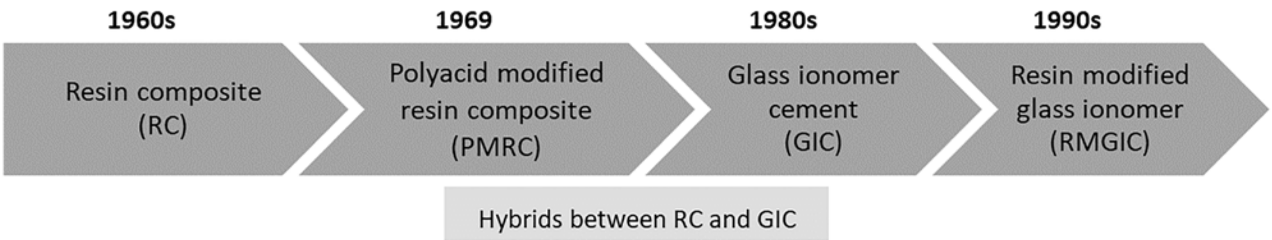
RC materials are synthetic, tooth-coloured resins available since the 1960s that may be used as an alternative to dental amalgam for the replacement of damaged tooth tissue. These materials are available in various shades and have different physical and chemical properties based on the components included in the polymer matrix (Habib *et al*., 2016). In general, resin-based composites contain two main parts: a resin matrix containing monomers and a polymeric system (Figure 2.2), and an inorganic filler, which determines the physical properties of the final product.

Polymeric system of resin composites

The polymeric system of RCs contains dimethacrylate resins. The most common monomers used in resin-based composites (RBCs) are bisphenol A diglycidylether methacrylate (bis-GMA), ethoxylated bis-GMA (bis-EMA), triethylene glycol dimethacrylate (TEGDMA) and urethane dimethacrylate (UDMA), which is a bisphenol A-free polymeric system (Gajewski *et al*., 2012; Kurt *et al*., 2018; Pratap *et al*., 2019) (Figure 2.2).

Inorganic filler

To improve the physical properties of resin-bonded composites such as shrinkage, hardness and strength,



RC = chemically active resin + filler (glass or ceramic) + silane coupler (to bond the first two)

PMRC = Two methacrylate-based resins + reactive glass (fillers) + setting via polymerisation reaction

GIC = Acidic liquid (polyacrylic acid) + basic glass + water

RMGIC = Glass ionomer cements + resin component (achieved by grafting methacrylate groups onto the polyacrylic acid chain + adding a water-soluble methacrylate resin

Figure 2.1. Range of the most commonly used MFDRMs in order of year of introduction from the 1960s to the 1990s, with information on their chemical composition (Bonsor and Pearson, 2013; Rohani and Nicholson, 2009; Sidhu, 2010).

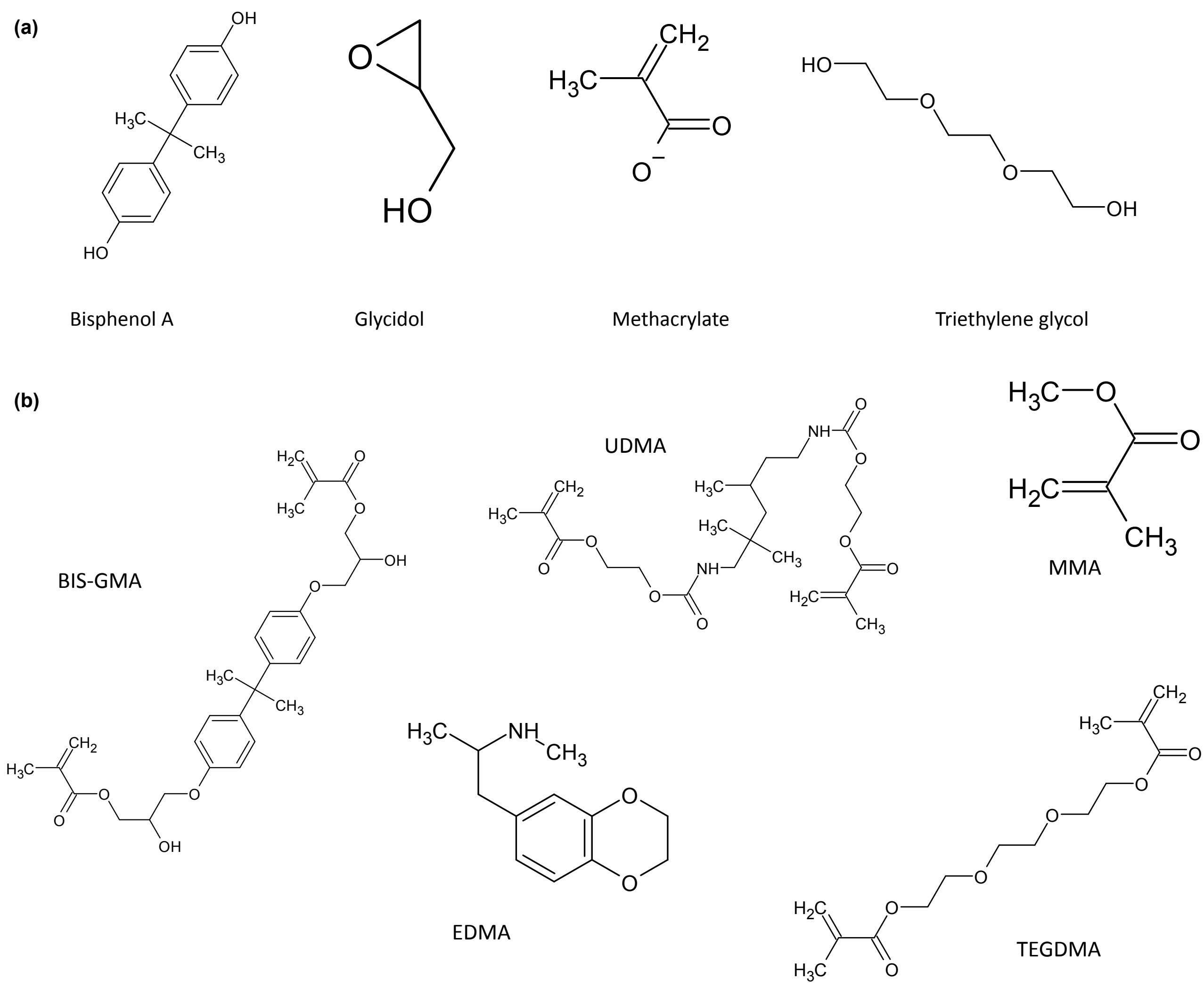


Figure 2.2. (a) Common monomeric systems in resin composite dental materials and (b) polymeric structures commonly present in resin composite materials. EDMA, ethylene glycol dimethacrylate; MMA, methyl methacrylate.

fillers were introduced. The physical properties of RCs vary based on filler materials (Van Noort, 2007). The fillers in RBCs are classified into different groups by filler size distribution, shape and the materials used. Fillers of less than 1 µm in diameter are referred to as micro-filled (10–40 µm); fillers of more than 1 µm diameter are referred to as macro-filled (8000 µm); hybrid (400–1000 µm) is a mixture of different particle sizes; and the last group, nano-filled, refers to very small particles and includes materials of 0.005–0.01 µm diameter (Table 2.1).

The most common filler materials used in dentistry are categorised into four groups: (i) oxide fillers, predominantly silica, alumina, zirconia and titanium; (ii) alkaline silicate glass fillers, which include barium and strontium glass; (iii) biomimetic (materials mimicking biological processes) fillers ($Ca_5(PO_4)_3OH$); and (iv) organic–inorganic hybrid fillers with the chemical composition of oxide-polymers (nanofillers) (Chen *et al.*, 2018) (Table 2.2). Quartz, glass, barium/strontium glass, titanium oxide, zinc oxide and ceramic are all used as RC fillers (Habib *et al.*, 2016; Van Noort, 2007). Nanofillers such as graphene, zirconium oxide and silica have been introduced

Table 2.1. Composite resin types identified based on filler content particle size (µm)

Groups by filler size	Filler size (µm)
Micro-filled	10–40
Macro-filled	8000
Hybrid	400–1000
Nano-filled	0.005–0.01

Table 2.2. Composite resin filler groups identified based on filler chemical content

Filler type	Chemicals present
Oxide	Silica, alumina, zirconia and titanium (ceramic)
Alkaline	Barium and strontium glass
Biomimetic	$Ca_5(PO_4)_3OH$
Organic–inorganic hybrid	Oxide polymers

to the resin matrixes as a recent generation of fillers (Priyadarsini *et al.*, 2018), and materials are increasingly nano-filled or densified to provide a material with high strength (Schmalz *et al.*, 2018).

2.1.2 Glass ionomer cements

GICs, available since the 1960s, are naturally bioactive acid–base cements with the advantage of being able to directly bond to dental enamel. The main ingredients of the cements are polymeric water-soluble acid, basic glass and water (Baig and Fleming, 2015; Sidhu, 2010). The setting process in GIC takes place in a concentrated solution in water in which the final structure (gel) contains significant amounts of unreacted glass as filler (Sidhu, 2010). The glasses that are used for ionomer cements must be basic in order to react with an acid for salt formation. A variety of basic glasses can be used; ideal glasses contain alumina-silicate with fluoride and phosphate additions. Examples include SiO_2, $AlPO_4$, $NaAlF_6$, CaF_2, Al_2O_3 and AlF_3, in order from high to low mass percentage (Sidhu, 2010). The polymers that are used in GICs are either the homopolymer or copolymer of acrylic acid or maleic acid (Sidhu, 2010) (Figure 2.3).

2.1.3 Polyacid-modified resin composites

These materials were first made available as commercial dental materials in the early 1990s and share features with both RCs and GICs (Meyer *et al.*, 1998; Milward *et al.*, 2011; Nicholson, 2007, containing similar filler materials and resins. PMRCs contain two methacrylate resins mixed with fillers, and a photo-activator to allow for setting via a polymerisation reaction (Bonsor and Pearson, 2013; Meyer *et al.*, 1998).

2.1.4 Resin-modified glass ionomer cements

These dental filling types are derived from GICs with the addition of light-curing and resin components (Agha *et al.*, 2017; van Dijken and Pallesen, 2010). The resin, usually hydroxyethyl methacrylate (HEMA), the polyacrylic acid and tartaric acid are used to graft together the different functional groups via acid–base and polymerisation reactions (Agha *et al.*, 2017; Bonsor and Pearson, 2013). During this process, water prevents a reaction between the polyacid and the glass. Barium, strontium and alumina-silicate glass are added to improve strength and impart radiopacity to the filling. As a last step, polyacrylic acid is added to react with the glass to form a glass polyalkenoate cement and embed the unreacted salt in a polysalt matrix (Alhalawani *et al.*, 2016). Potassium persulphate and ascorbic acid are added to function

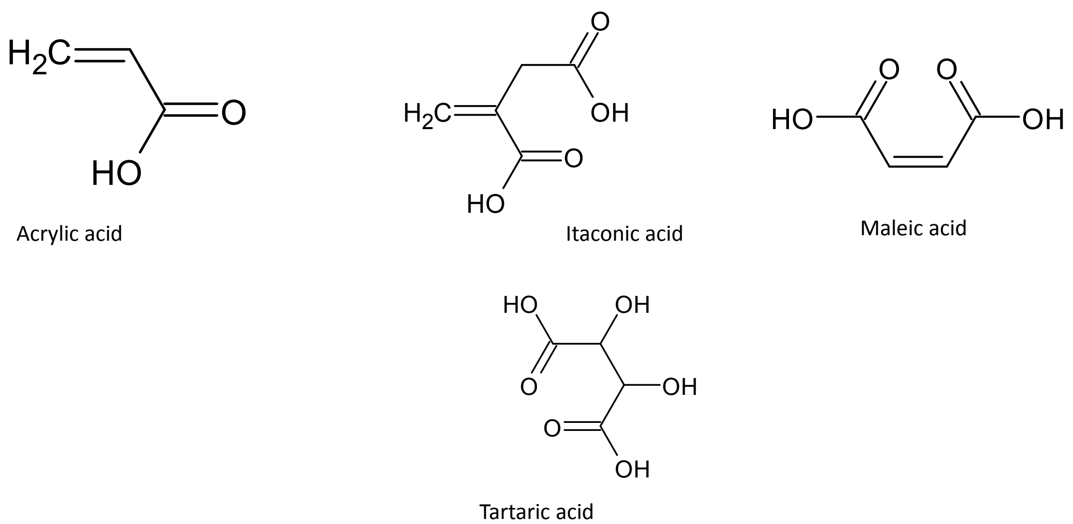


Figure 2.3. Common acid components in glass ionomer cements.

as a redox catalyst system, providing the methacrylate (dark) cure (Bonsor and Pearson, 2013).

The above summaries of the typically available MFDRMs/Hg-free materials demonstrate the broad range of materials that are required to replace the form, function and aesthetics of lost tooth tissue.

2.2 Dental Amalgam Separators

Particulate matter present in dental restorative materials (both mercury containing and mercury free) is a possible source of pollution when it enters the dental unit wastewater (DWW) system and discharges to the municipal wastewater system. Research in this area has focused primarily on mercury particulate waste streams resulting from the use of dental amalgam (Fan *et al.*, 1997; Jamil *et al.*, 2016; Lutchko and Gulka, 2004; Shraim *et al.*, 2011; Tibau and Grube, 2019; Vandeven and McGinnis, 2005). In the case of mercury from dental amalgam, it has been found that the particle and pollution load entering sewers and treatment plants is substantial in the absence of a dental amalgam separator, posing an environmental risk in the event of accidental environmental exposure (Adegbembo *et al.*, 2002). Healthcare facilities may produce different types of wastewater, some containing hazardous substances, all of which discharges into the urban sewerage system and hence presents a (sometimes substantial) pollution load for treatment in a wastewater treatment plant. There was a long procession of regulations leading up to the implementation of the amalgam separators that are in use today. Starting in 1984, an EU Directive (84/156/EEC) introduced amalgam removal devices that were at least 95% efficient in removing dental amalgam in order to tackle mercury pollution of waterways in Europe (Cailas *et al.*, 2002). This was followed by ISO Standard 11143:2008, which was introduced to regulate and standardise these amalgam separators. Until this point, the installation of amalgam separators had not been internationally regulated. The recommendation for the fitting of ISO 11143:2008-approved dental amalgam separators (ISO, 2008) to reduce the discharge of dental amalgam to the environment has been in place in Ireland since 1 January 2019 (S.I. No. 533/2018) (Dental Council of Ireland, 2018). A recent survey with a low response rate (11.9%) conducted in Ireland as part of an Environmental Protection Agency (EPA)-funded research project found that 87% of those who did respond stated that they had an amalgam separator fitted in their practice (Hayes *et al.*, 2020).

2.2.1 ISO 11143:2008

ISO 11143:2008-approved dental amalgam separators (ISO, 2008) are required to trap at least 95% of dental amalgam particles and therefore considerably reduce the mass (amount) in the DWW before release to the sewage system (European Union, 2017a; Government of Ireland, 2018). The original purpose of an amalgam separator was to retain amalgam particles from DWW by separating secretions, air and amalgam particles using various methods such as centrifugation, sedimentation, filtration, ion exchange, or a combination of these, and to retain the amalgam particles in a collector vessel that allows proper disposal of the collected particles (Vandeven and McGinnis, 2005). The ISO test for amalgam removal efficiency uses 10 g of amalgam particles of three different sizes: 60% of the particles are between 0.5 mm and 3.15 mm; 10% of the particles are between 0.1 mm and 0.5 mm; and 30% of the particles are 0.1 mm (100 µm) or smaller (ISO, 2008).

At the time of the study, it was established that there are five different commercially available amalgam separators available in Ireland. These are the Dürr Dental CS1 and CAS1 centrifugation amalgam separation unit (Dürr Dental, 2020), the Cattani Microsmart and the Turbo Smart sedimentation separators (Cattani, 2020), the METASYS Type 2 ECO II sedimentation amalgam separator (METASYS, 2020) and the Amalsed sedimentation separator from Initial Medical. According to the relevant ISO standards, amalgam separators are generally classed as type 1 (centrifugation amalgam separation systems), type 2 (sedimentation systems) or type 3 (filtration systems), while types 1, 2 or 3 in any combination are classed as type 4 (amalgam separator systems) (European Union, 2017b; Government of Ireland, 2018). Using this ISO 11143:2008 classification, most amalgam separators in use in Ireland are type 1 or type 2.

Determining the efficacy of the ISO 11143:2008-approved amalgam separator (ISO, 2008) on the dental unit in retaining MFDRMs/Hg-free materials will predict whether or not the small particles enter the DWW stream, possibly giving rise to micropollutants and nanoparticles (Jírova *et al.*, 2019). Concerns surrounding the release and detection of contaminants such as microplastic and nanoparticulate dental waste in the environment have been reported in the literature (Brar *et al.*, 2010; Froggett *et al.*, 2014; Reijnders, 2009).

2.3 Mercury-free Dental Restorative Materials and Occupational Health

The dental team may be exposed to a number of occupational hazards in the work environment, and policy to manage such hazards must be in place, one example being the prohibition of non-encapsulated dental amalgam in the EU since the end of 2018 (Regulation (EU) 2017/852; European Union, 2017a). The Health and Safety Authority in Ireland lists the occupational hazards under the following headings: physical, chemical, biological and psycho-social (Health and Safety Authority, 2016), similarly to the Safety, Health and Welfare at Work Act 2005. Dental practices are regulated under the Health and Safety Authority (Health and Safety Authority, 2016) and operate within the requirements of the Safety, Health and Welfare at Work Act 2005. The focus of this research is chemical and small particle exposure that may originate from mercury-free dental materials. Reactive chemicals or small particles can be released during preparation, polishing and/or removal of restorations in the dental clinic. Acrylic resins and compounds such as bisphenol A (BPA) are also recognised as a chemical hazard (SCENIHR, 2015). These materials are used in the manufacture of resin-based composites and hybrids such as PMRCs and resin-modified glass ionomers.

Exposure routes are inhalation, dermal or contact with mucosal surfaces. Such sources may be relevant to everyone with access to the dental clinic (e.g. dental personnel, contractors, delivery personnel) but are particularly pertinent to those regularly working in the environment.

2.4 Mercury-free Dental Restorative Materials and Exposure

Figure 2.4 shows the pathways through which individuals in the clinic and externally may be exposed to MFDRMs/Hg-free dental filling materials. Concern exists that incomplete polymerisation of dental composites could give rise to degradation products in the mouth, which could then be metabolised by different enzymes such as esterases. The implications of such activities and pathways are still under examination (Gupta *et al.*, 2012; MacAulay *et al.*, 2017); however, the Canadian government has recommended that BPA exposure is kept as low as possible, especially in the case of newborns and infants (CADTH, 2018), and the American

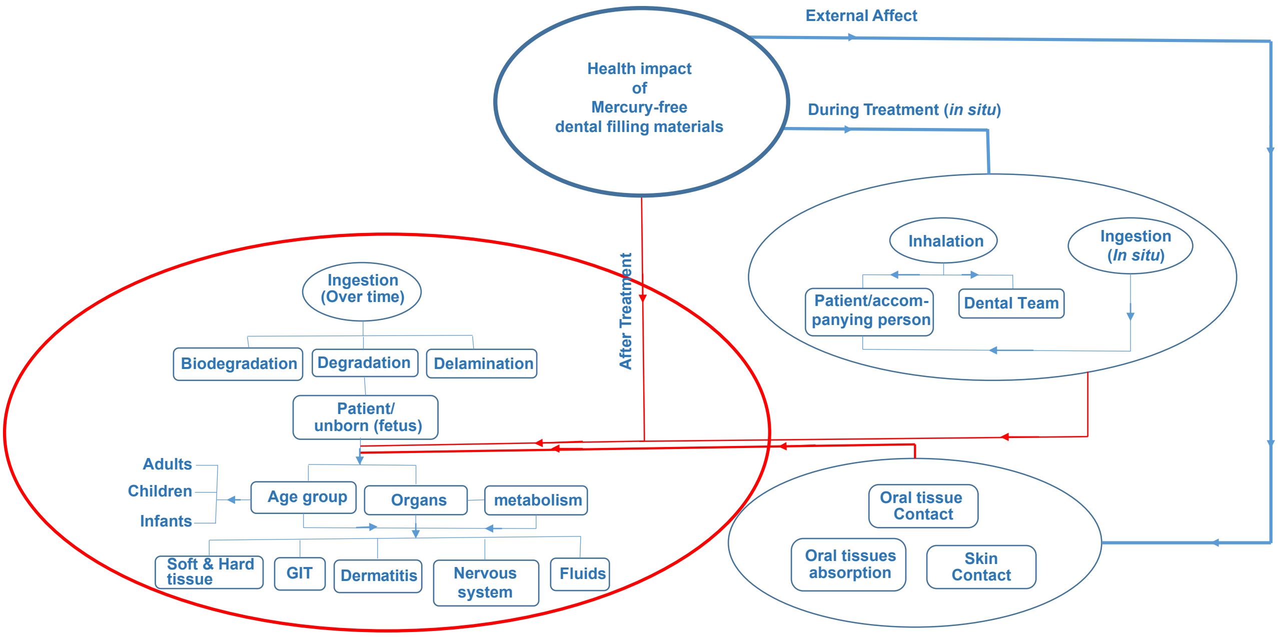


Figure 2.4. MFDRMs and health impacts. GIT, gastrointestinal tract.

Dental Association (ADA) advises following the manufacturer's directions regarding the placement and polymerisation of resin-based dental materials to minimise potential patient BPA exposure (ADA, 2020a).

The literature on the health effects of mercury-free materials is limited, with few studies focusing on the external environment to date (CADTH, 2018). The Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR, 2015) concluded that both short- and long-term exposures to BPA from dental materials are below the temporary tolerable daily intake (TDI) value of 4 μg/kg bw/day (Testai *et al*., 2016), although this value is being re-evaluated. It is envisaged that the EU Medical Devices Regulation (EU 2017/745) will assess the safety of dental amalgam and MFDRMs coming to market. Devices will not be allowed to be sold on the EU market if they are not assessed as safe.

3 Methods

This section describes the methods by which the objectives set out in Chapter 1 were achieved.

3.1 Methods to Achieve Objective 1

To conduct a comprehensive review of the literature on the environmental impact of MFDRMs

3.1.1 Mercury-free dental restorative materials

To assist with development of the search strategy and to identify and characterise the MFDRMs available in Ireland, meetings were organised with the dental trade and suppliers and a dental engineer with a business serving Munster. In addition, a database containing the names of dental materials in use at Cork University Dental School and Hospital and material safety data sheets were accessed.

3.1.2 Searching the literature

To establish the breadth and nature of the evidence available, and informed by the MFDRMs in use, first a scoping review was carried out with the assistance of the liaison librarian in the College of Medicine and Health, University College Cork. The research question was "Do mercury-free dental restorative materials (MFDRMs) affect the environment?".

Databases for inclusion

The databases searched were Embase, MEDLINE, Web of Science and Scopus. Grey literature sources were also searched and a snowballing approach adopted. For each database a combination of controlled vocabulary and free text was used.

Search limits

The search was limited to the period from 1960 to the present.

Terms used in the search strategy

The following terms were used in the search strategy:

"Polymer-based dental material*" OR "white filling*" OR "resin composite*" OR "Bowen*" OR "mercury-free*" OR "Glass Ionomer cement*" OR "resin modified glass ionomer cement*" OR "dental restorat*" OR "dental resin*" OR "acrylic resin*" OR "dental polymethacrylic acid*" OR "dental polyacid*" OR "Composite Resin*" OR "dental Polymer*" OR "dental composite*" OR "white filling*" OR "non amalgam filling*" OR "non-amalgam filling*" OR "mercury free filling*" OR "mercury-free filling*" OR "dental cement*" OR "resin cement*" OR "amalgam free" AND "environment*" OR "water*" OR "waste water*" OR "sewage*" OR "soil*" OR "pollut*" OR "wastewater*" OR "enviro* impact*" OR "cremat*" OR "environment* impact" OR "environment* health" OR "environment* monitoring" OR "environment* pollut*" OR "biocompatibility*" OR "toxic*" NOT "mercury" OR "amalgam" OR "health".

All relevant literature was imported to Zotero (https://www.zotero.org/) and duplications removed.

3.2 Methods to Achieve Objectives 2, 3 and 4

Determine the particulate matter present in DWW with a dental amalgam separator in place Assess the efficacy of type 1 dental amalgam separators to retain particles arising from the use of MFDRMs Assess the ecotoxicity of DWW

To first establish the MFDRMs available in Ireland and the dental amalgam separators in use, meetings were organised with the dental trade and suppliers and a dental engineer.

3.2.1 Health and safety

Methods were developed to ensure the health and safety of the individuals working with DWW streams for the purposes of this research project, along with safe sample collection and handling methods.

3.2.2 Dental practices

Three dental practices agreed to participate in the project, in which two different types of ISO-certified amalgam separators were in place: type 1 (centrifugation) and type 2 (sedimentation) (ISO, 2008). A pragmatic approach was taken to the selected amalgam separators. The practices were selected in consultation with the dental engineer and information on the amalgam separators in use provided by the dental suppliers. All selected amalgam separators were ISO 11143:2008 certified. Sampling of the wastewater was achieved by installing a diversion into the waterline after the amalgam separator and before the wastewater was discharged into the sewerage system. A qualified dental engineer installed the tubes, fittings and seals for the wastewater inlet pipe coming from the dental chair unit and for the overflow pipe going into the sewer. The tubes, fittings and seals used were identical to those provided by Dürr Dental SE, typically for the dental chair unit; this ensured a high-quality standard fitting. Wastewater samples were collected as close as possible to the source of origin using a closed and sealable container made of inert high-density polyethylene (HDPE) material. Once the samples were collected, the container and all its fittings were sealed (Health and Safety Authority, 2013). Samples were then stored in a refrigerator at 4°C under minimal light conditions. As per Health and Safety Authority guidelines (2013), biohazard signs were posted on all samples and laboratory access restricted to approved users. Laboratory work benches were impervious to water and resistant to acids, alkalis, solvents and disinfectants (Health and Safety Authority, 2013). In the event of a spill, contaminated areas underwent disinfection and all spillages were removed using paper towels, which were then placed in a healthcare risk waste bag. Once the area was cleaned, it was wiped with disinfectant again and then washed with detergent and water to remove traces of the disinfectant. Protocols were devised to ensure the appropriate recording of sample collection and storage.

3.2.3 Collection of samples

DWW was collected for the analysis of (i) physical and chemical wastewater parameters, (ii) particle size and characterisation and (iii) the ecotoxic potential of the DWW streams (Figure 3.1).

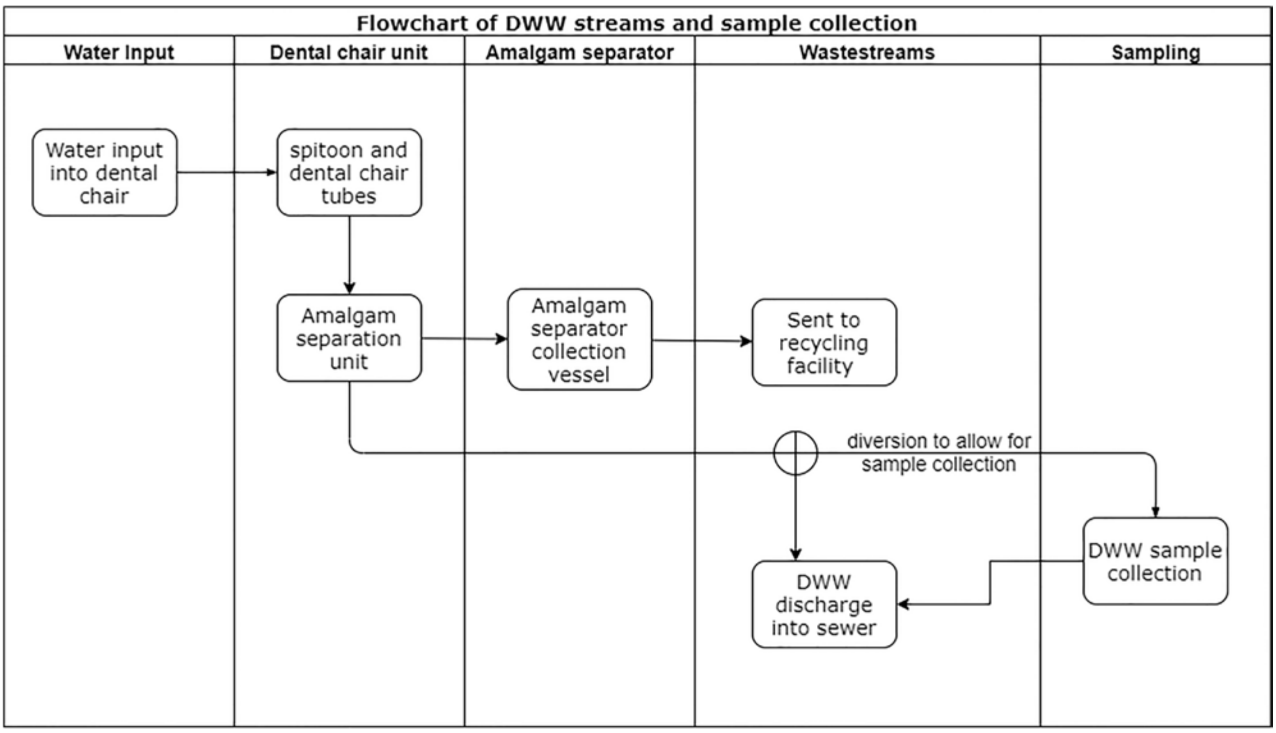


Figure 3.1. Schematic representation of dental unit wastewater streams and sample collection.

The identities of the dental practices were anonymised as dental practice 1 (DP1), DP2 and DP3. The type of amalgam separator present in each dental practice is shown in Table 3.1.

DP1 was used as a comparative base for piloting the sampling methodology and set-up. This dental practice used a Dürr Dental CA1 centrifugation amalgam separation unit (type 1) fitted to each dental chair. DP2 used a METASYS Type 2 ECO II amalgam separator (type 2), fitted to collect the combined wastewater of four dental chairs; and DP3 used a Dürr Dental CAS1 combi separator (type 1), fitted to collect the combined wastewater of three dental chairs. DP1, used for piloting the sampling methodology and set-up, had all filters renewed and efficacy tested at the beginning of the study.

Each dental chair also had a series of filters (Figure 3.2) to permit the trapping of particles,

Table 3.1. Type of ISO 11143:2008 amalgam separator present in the three dental practices taking part in the study

Dental practice	Amalgam separator type	Details
DP1	Type 1	Teaching unit with amalgam separator attached to each dental chair
DP2	Type 2	Amalgam separator for collection of wastewater from four dental chairs
DP3	Type 1	Amalgam separator for collection of wastewater from three dental chairs

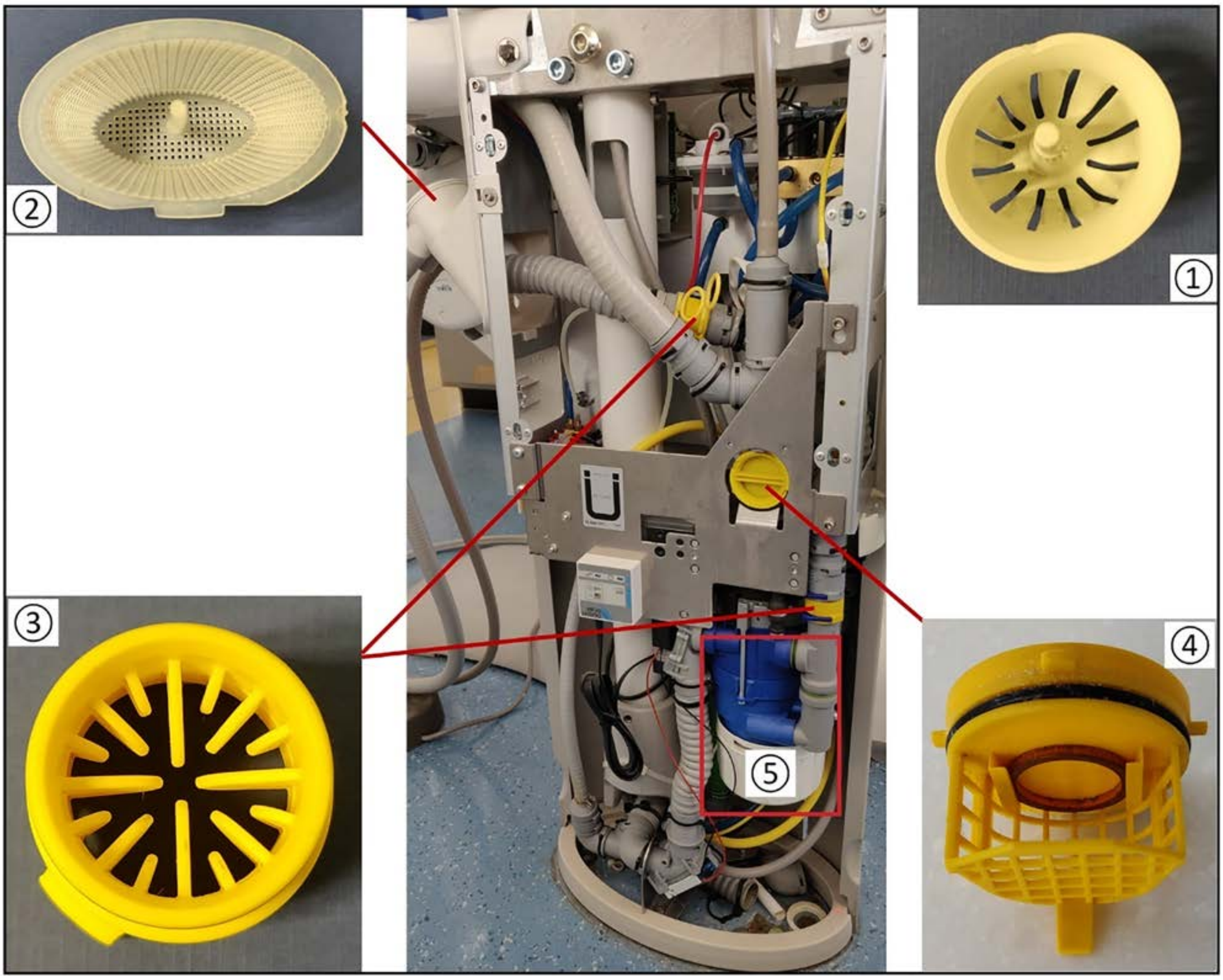


Figure 3.2. Schematic showing the dental chair unit, internal filters and amalgam separation unit in DP1. 1 = filter catching particles > 2 mm in size; 2 = 1 × 1-mm filter; 3 = filter catching particles > 4 mm in size; 4 = 2-mm mesh filter; 5 = Dürr Dental CA1 amalgam separator.

which could then be analysed. DP1 had all filters renewed at commencement and, as ISO certified (ISO 11143:2008), they were renewed again for amalgam separator efficacy testing. DP2 and DP3 operated in their normal manner. The three amalgam separators tested in this study were 95% efficient in removing dental amalgam, according to tests carried out as part of the ISO 11143:2008 certification process, which is required before these amalgam separators can be sold on the European market.

3.2.4 Data recording sheets

Data recording sheets were prepared for each dental practice setting out the information to be recorded by the dental practitioners: type of dental treatment carried out, dental materials used and the name of the dental unit waterline disinfectant used. Samples were then transported for storage.

3.2.5 Physical and chemical parameters of dental wastewater streams

Measurements of specific conductivity, pH, total suspended solids (TSS) and total dissolved solids (TDS) were taken for the wastewater of the three dental practices (DP1, DP2 and DP3). Values obtained via the Protection of the Environment Act (2003) (Government of Ireland, 2003) and EU Directive 91/271/EEC to determine permissible TSS discharge limits from urban wastewater treatment plants to surface waters were consulted to determine particle load as TSS and TDS.

These data characterised the DWW after passing through the dental chair system of filters and the dental amalgam separator and into the collection receptacle.

3.2.6 Particle size and characterisation in dental wastewater from DP1, DP2 and DP3

Particle size was determined using optical microscopy (objective lenses ×10, ×40 and ×100), and ImageJ image processing software was used to determine particle size and area (μm^2). Particle size for the purpose of this analysis ranged from ≥ 1.2 to $\leq 150\,\mu m^2$.

3.2.7 Particle characterisation using a scanning electron microscope, and efficacy testing of amalgam separator type 1

The JEOL JSM-IT200 InTouchScope scanning electron microscope (SEM) was used to image sample material from DP1. Samples comprised cured resin RCs that were placed or removed during patient care and had been flushed through the dental chair system, including the amalgam separation unit, before reaching the wastewater collection container. These particles would have undergone cutting, grinding and polishing procedures during placement or removal.

The efficacy of the amalgam separator in retaining cured RC materials located in DP1 was tested using four light-cured RC dental filling materials in common use. One gram of Ceram.X (nanoceramic composite), 0.78 g of SDR flow+ (flowable bulk fill), 0.92 g of Filtek (nanocomposite) and 0.88 g of Herculite XRV (micro-hybrid) were removed from preparations of each dental filling material. The materials were cut using a diamond burr in a high-speed air turbine dental handpiece and polished using a low-speed dental handpiece with the various grades of 3M Sof-Lex disc. The cut and polished dental filling materials then passed through the dental chair filter system and amalgam separator and were collected in the wastewater receptacle.

3.2.8 Ecotoxicity

Ecotoxicity testing is used to assess the risk to the environment of a chemical or compound that is released into the environment (Walker, 2008). The ecotoxicity testing in this study was done on DWW containing only MFDRMs. The crustacean *Daphnia magna* Straus, a water flea, was used as an ecotoxicity bioindicator (ISO, 2012; OECD, 2014). Acute 48-hour immobilisation tests using *D. magna* were carried out in line with OECD Guideline 202 for testing of chemicals in order to obtain EC_{50} values for the DWW from DP1, DP2 and DP3 (OECD, 2014). The EC_{50} is defined as the concentration of the test substance (DWW) that results in an acute immobilisation response in *D. magna* halfway between the baseline and the maximum concentration after exposure for 48 hours. A control was kept in growth medium for the duration of every test; for the test to be valid, no more than 10% of the daphnids in the control should be immobilised.

EC_{50} values were estimated from dose–response curves and calculated using GraphPad Prism (version 8.2.1). For the calculations in the Prism software, the dose variable was log transformed using the natural logarithm (ln) to normalise the data. The response variable was normalised to express the data on a common scale, with 0% and 100% representing the lowest and highest response. Non-linear regression with curve fitting was then carried out using the dose–response data and the EC_{50} was calculated, along with 95% confidence intervals (CIs).

All records were prepared contemporaneously.

3.3 Methods Used to Address Objective 5

Conduct a comprehensive review of the literature with respect to the occupational challenges with the use of MFDRMs

Information on MFDRMs was retrieved from the electronic databases MEDLINE (through PubMed), Embase, Scopus and Web of Science; the search was limited to the period from 1960 to the present. Additional information sources, including discussion with materials scientists, dental researchers, dental materials researchers and dental suppliers, also informed the key search terms. Material safety data sheets (MSDSs) available from Cork University Dental School and Hospital were used as a further source of detailed information and materials' constituents. All information assisted in the selection of appropriate key words for developing the search strategy and for database searching. The liaison librarian at the College of Medicine and Health, University College Cork, supported development of the search strategy. To identify and appraise the literature examining the impact of MFDRMs on occupational health, first a scoping review was carried out to establish the breadth and nature of the evidence available.
In scoping the literature, a significant volume of information on mercury and dental amalgam hygiene in dental practice and in relation to dental personnel was identified. Many of these papers concluded with a recommendation to move away from dental amalgam and towards MFDRMs/Hg-free materials (Nagpal *et al*., 2017). Broad, relevant headings to inform the search strategy were the degradation of MFDRMs, incomplete polymerisation, biodegradability, chemical hazards, dust and MFDRMs as allergens.

3.3.1 Search strategy terms

The following terms were in the search strategy:

"Composite Resins" OR "Compomers" OR "Resin Cements" OR "resin composite" OR "non-amalgam" OR "resin-based composite" OR "nanofilling" OR "Nanocomposites" OR "Glass Ionomer Cements" OR "resin modified glass ionomer cement" OR "bisphenol" OR "Polyhydroxyethyl Methacrylate" OR "HEMA" AND "health" OR "allergy" OR "COPD" OR "Dermatit*" OR "integument*" OR "Toxic*" OR "respiratory*" OR "biodegradation*" OR " bioaccumulation*" OR "biocompatibility*" OR "child*" OR "utero" OR "matabol*" OR "tissue" OR "Bone" OR "liver" OR "pancreas" OR "neurological" OR "intelligent" OR "cognitive*" OR "vivo" OR "cytotoxicity" OR "genotoxicity" OR "carcinogen*" OR "dermatosis" OR "placenta" OR "cellular" AND "Restorative" OR "restorative material*" NOT "plastic" OR "food package*" OR "container" OR "paper" OR "water*" OR "sewage" OR "Mercury" OR "amalgam" OR "environment".

A combination of controlled vocabulary and free text was used for each database. Sources of grey literature were searched and the snowballing approach was also adopted to identify possibly relevant material. All relevant literature was imported to Zotero (https://www.zotero.org/) and duplications removed.

The research question developed to assist with data retrieval was "Do mercury-free dental filling materials (MFDRMs) have an occupational impact?".

4 Results

In this chapter we present the results for each objective in the same order as described in Chapter 3.

4.1 Results for Objective 1

Conduct a comprehensive review of the literature on the environmental impact of MFDRMs

The carefully designed search strategies enabled searching of published literature; in addition, grey literature was searched for relevant reports and publications. There was a paucity of evidence from the published literature to identify whether or not MFDRMs have definitive environmental impacts.

Using the agreed and tested search criteria outlined in the methods (section 3.1), 403 results were returned (Figure 4.1). After the removal of duplicates, 351 papers remained. Two researchers (NK and MH) carefully examined the titles and abstracts of the papers. A further 336 papers were excluded as they were not relevant to the research question. Fifteen potentially relevant reports remained for consideration. Further review and discussion identified five published papers as helpful, but there was no paper that specifically met our research purposes. Helpful resources were as follows: a review by Canada's Drug and Health Technology Agency (CADTH, 2018); a review paper by Mulligan *et al.* (2018); the Health Research Board (Ireland) evidence review (Keane *et al.*, 2020), the SCENIHR report (SCENIHR, 2015); and the World Health Organization and Food and Agriculture Organization of the United Nations (WHO and FAO, 2011) meeting to review the toxicological and health aspects of bisphenol A. Both the review by Canada's Drug and Health Technology Agency and the review paper by Mulligan *et al.* concluded that the environmental impact of MFDRMs is not known.

This absence of information does not, however, mean an absence of effect; it suggests that we may have

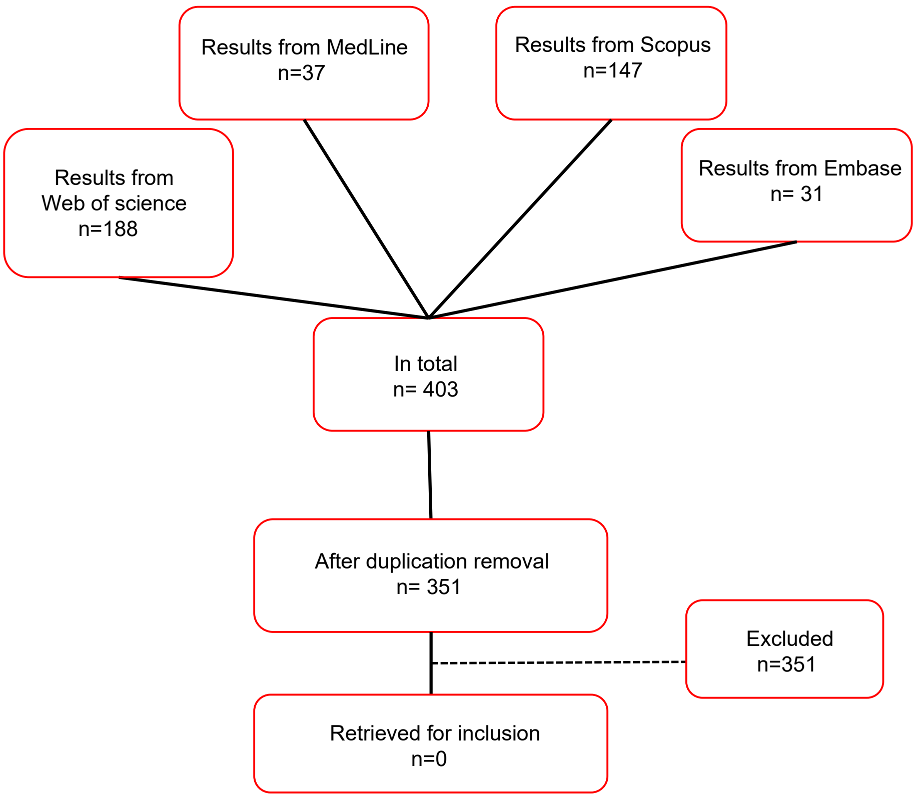


Figure 4.1. Flow diagram showing the databases searched and number of articles retrieved.

insufficient information at present and that ongoing surveillance or monitoring is important. We do, however, know that these materials have been used at high volumes for many years as an alternative to amalgam with no increase in occupational health effects (Table 1.1). A number of papers have discussed the possible environmental impact of cured/uncured polymer-based dental restorative materials (ADA, 2020b; Gupta *et al*., 2012; SCENIHR, 2015; WHO, 2010). However, further surveillance, monitoring and research are required where the focus is on the MFDRM and whether methods of disposal have an impact on the environment – water, air and soil.

4.2 Results for Objectives 2, 3 and 4

Determine the particulate matter present in DWW
Assess the efficacy of dental amalgam separators in retaining particles arising from the use of MFDRMs
Assess the ecotoxicity of DWW

To assess the potential environmental impacts of MFDRMs, access to dental facilities was sought and access to the wastewater line at each dental practice achieved. Practices used either a type 1 (centrifugation) or a type 2 (sedimentation) dental amalgam separator.

4.2.1 Physical and chemical parameters of dental wastewater streams

To assess the particulate matter content of DWW, measurements of specific conductivity, pH, TSS and TDS were taken from the wastewater of the three dental practices (DP1, DP2 and DP3) (Figure 4.2). The specific conductivity of the DWW from the three practices varied: DP1 recorded a mean of 4.4 mS/cm, DP2 a mean of 2.5 mS/cm and DP3 a mean of 5.1 mS/cm.

Similarly, there was variation in the range of pH values recorded. The pH of DWW ranged from 1.2 to 5.5 in DP1, from 2.6 to 9.2 in DP2 and was recorded as 1.9 in DP3 (Figure 4.3).

TSS and TDS measurements were obtained in triplicate per sample from each of the three dental practices. Particulate matter load again varied between the practices. The mean TSS in DWW was recorded as 20 mg/L in DP1, 115 mg/L in DP2 and 133 mg/L in DP3. The mean TDS in DWW followed the same trend, with 5 g/L in DP1, 6 g/L in DP2 and 7 g/L in DP3. The DWW in DP1 was observed to be more dilute than that in DP2 and DP3, explaining the differences in particle loads. However, the particle load was high and justified using light microscopy and scanning electron microscopy for further investigation of particle sizing (Figure 4.4).

Table 4.1 summarises the results for the physical and chemical parameters of the dental materials present in

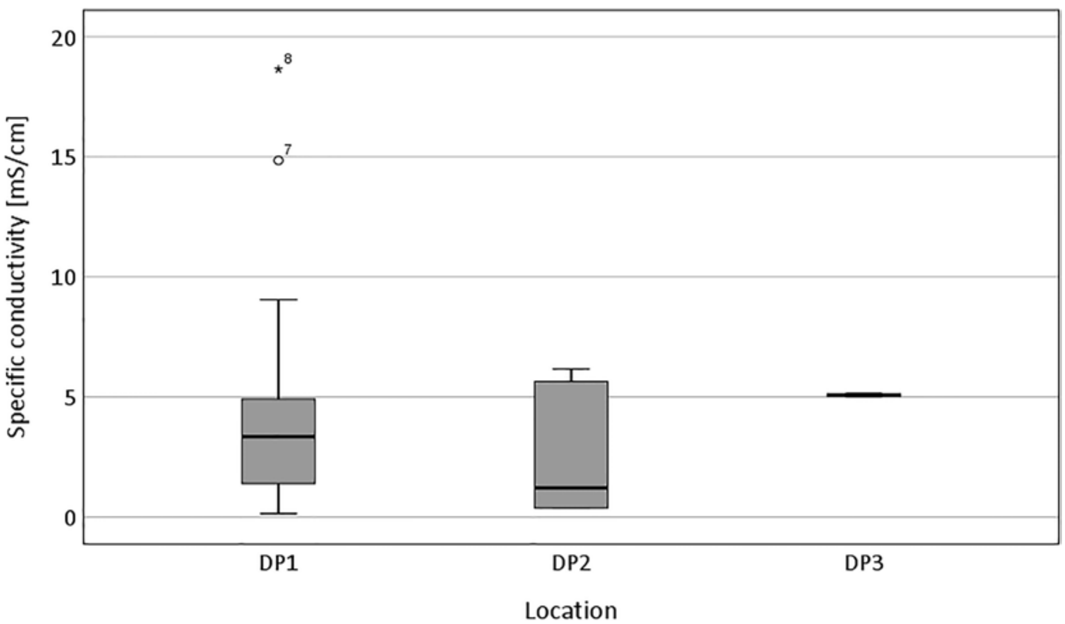


Figure 4.2. Boxplots showing the specific conductivity (in mS/cm) of the wastewater samples from DP1 ($n = 19$), DP2 ($n = 6$) and DP3 ($n = 2$).

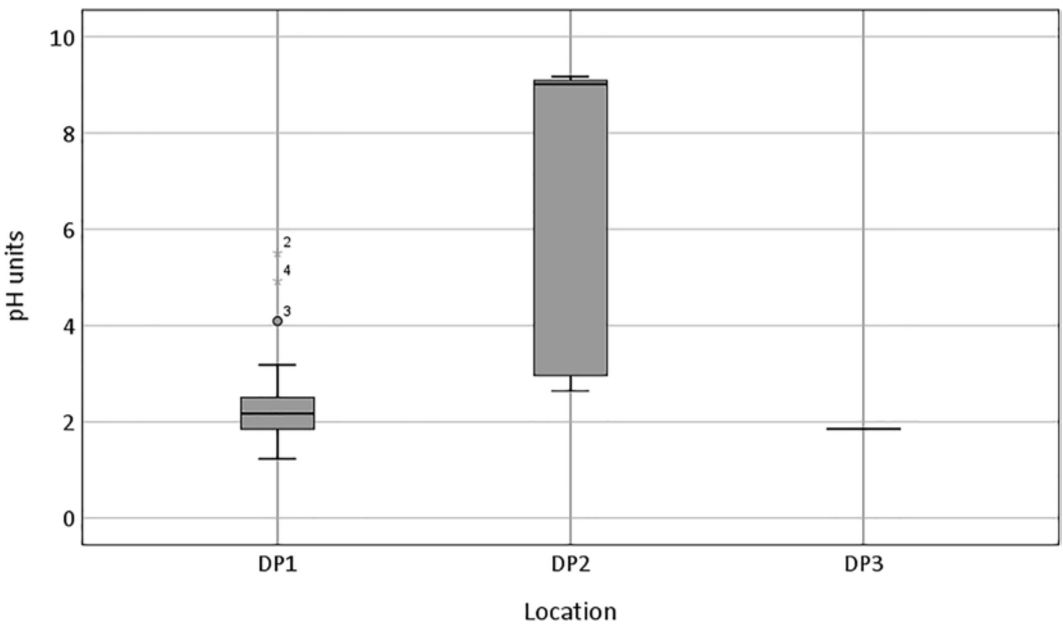


Figure 4.3. Boxplots showing the pH (scale 0–14) of the wastewater samples from DP1 (*n* = 19), DP2 (*n* = 6) and DP3 (*n* = 2).

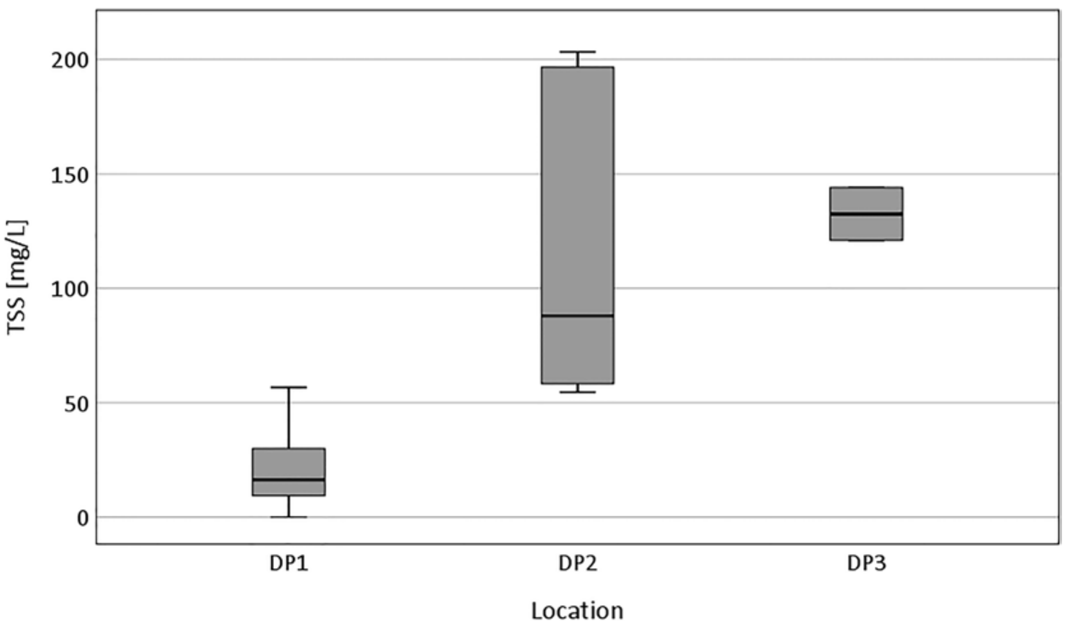


Figure 4.4. Boxplots showing the TSS content (in mg/L), measured in triplicate, of the wastewater samples from DP1 (*n* = 19), DP2 (*n* = 6) and DP3 (*n* = 2).

DWW streams, with details of particulate matter load, size and characterisation. The four major groups of dental materials in DP1 identified from the analyses were RCs, resin-modified (RM) composites, GICs and amalgam (Ama). When no detail was available on the treatment carried out and the dental materials used, they were classed as "other". Variation in the specific conductivity, pH, TSS and TDS attributed to dental materials in DP1 showed that the highest particle load (TSS and TDS), pH and specific conductivity resulted from the use of GICs. Moreover, shown in bold in Table 4.1 are those parameters that are above permissible limits according to the Protection of the Environment Act (2003) and EU Directive 91/271/EEC. Note that these values are not specifically designed for assessment of effluent from dentistry.

Table 4.1. Specific conductivity, pH, TSS and TDS measurements from the wastewater samples of DP1 (*n*=19), DP2 (*n*=6) and DP3 (*n*=2) and TW (tap water) blanks

				TSS (mg/L) (*n*=3)		TDS (g/L) (*n*=3)	
Dental practice	Dental material	Spec. cond. (mS/cm)	pH	Mean	SD	Mean	SD
DP1	RC	5.16	**2.02**	30.00	±0.01	**3.82**	±0.22
		0.17	5.50	10.00	±0.01	0.19	±0.01
		0.15	4.09	10.00	±0.01	0.15	±0.01
		0.15	4.92	**39.00**	±1.73	0.16	±0.01
		3.87	**2.30**	8.89	±1.92	N/A	N/A
	RC+GIC	3.68	**2.09**	20.00	±0.01	N/A	N/A
	GIC	**14.85**	**1.23**	**56.67**	±5.77	N/A	N/A
		18.65	**1.31**	**46.67**	±5.77	**39.22**	±0.68
		3.04	**1.71**	**36.67**	±5.77	**1.24**	±0.07
		3.36	**2.17**	3.33	±5.77	N/A	N/A
	RM	4.77	**2.05**	16.67	±5.77	**4.07**	±0.39
	Ama	1.98	**2.26**	16.33	±0.58	**1.63**	±0.04
		4.45	**1.43**	N/A	N/A	**3.36**	±0.12
		5.06	**1.45**	3.33	±5.77	**4.41**	±0.26
	Other	1.94	**2.39**	16.67	±5.77	N/A	N/A
		9.05	**1.98**	30.00	±0.01	**10.47**	±0.27
		0.86	**2.37**	16.00	±2.00	0.66	±0.03
		2.10	**2.62**	10.33	±0.58	**1.54**	±0.03
		0.49	**3.18**	6.67	±1.15	0.43	±0.01
	TW blanks	0.18	6.60	0.00	±0.00	0.03	±0.05
		0.16	5.81	0.00	±0.00	0.08	±0.05
		0.15	7.00	N/A	N/A	N/A	N/A
DP2	All	5.64	2.96	196.67	±5.77	N/A	N/A
		2.04	2.64	203.33	±5.77	7.22	±0.18
		6.17	9.17	111.00	±9.17	6.52	±0.17
		0.38	9.03	54.67	±3.06	6.40	±0.56
		0.38	9.00	58.33	±1.53	5.58	±0.24
		0.40	9.09	65.00	±1.73	4.92	±0.09
DP3	All	5.03	1.85	144.00	±2.65	6.76	±0.07
		5.14	1.85	121.00	±3.00	7.11	±0.10

TSS and TDS measurements carried out in triplicate and restricted by analytical balance to four significant figures.
N/A, not available; SD, standard deviation.

4.2.2 Particulate matter, load, size and characterisation in dental wastewater streams

Particle size and characterisation of DWW from DP1, DP2 and DP3

Particle size was determined using optical microscopy (objective lenses ×10, ×40 and ×100), and ImageJ image processing software was used to determine particle size and area (μm^2). Particle size for the purpose of this analysis ranged from from ≥1.2 to ≤150 μm^2 (Table 4.1).

In all three dental practices, the proportion of particles decreased as particle size increased from 1.2 to 150 μm^2, and in all practices the size category 1.2–5 μm^2 accounted for the majority of particles, with 53% of particles in DP1, 66% of particles in DP2 and 64% of particles in DP3 falling into this category (Figure 4.5). Between 17% and 21% of the particles were in the size class 5–10 μm^2, and between 14% and 22% of the particles were in the size

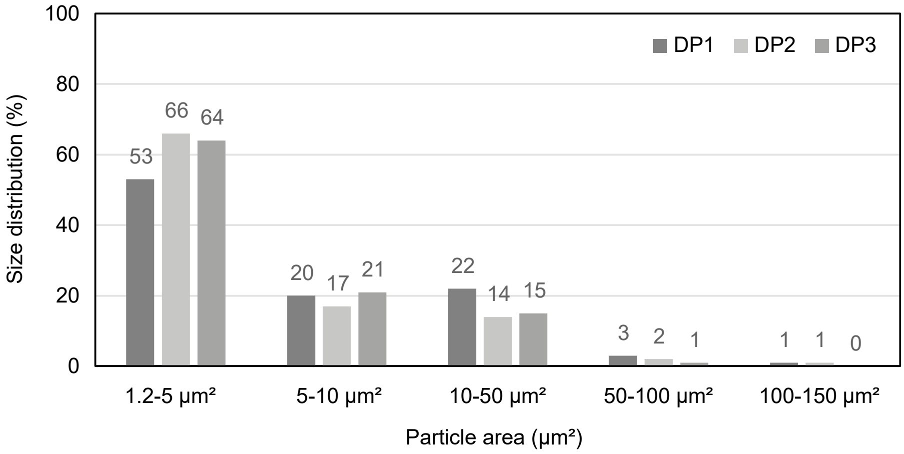


Figure 4.5. Size distribution (%) of particles between 1.2 and 150 µm² in the wastewater samples from DP1 (n=19), DP2 (n=6) and DP3 (n=2).

class 10–50 µm². The proportions of particles sized 50–100 µm² were below 3%, and particles sized 100–150 µm² were below 1%.

4.2.3 *Particle characterisation using the scanning electron microscope*

The JEOL JSM-IT200 InTouchScope SEM was used to image sample material from DP1. The samples comprised materials that had been either placed or removed during patient care and had been flushed through the dental chair system, including the amalgam separation unit, before reaching the wastewater collection container. These particles would have undergone cutting, grinding and polishing procedures during placement or removal. The observed particles had ragged ends and sharp corners and varied in size from 1 to 150 µm² (Figure 4.6).

4.2.4 *Efficacy testing of the amalgam separator*

The efficacy of the amalgam separator (type 1) in retaining MFDRMs located in DP1 was tested using four commonly used RC dental filling materials (Figure 4.7). One gram of Ceram.X (nanoceramic composite), 0.78 g of SDR flow+ (flowable bulk fill), 0.92 g of Filtek (nanocomposite) and 0.88 g of Herculite XRV (micro-hybrid) were removed from the preparations of each dental filling material. The RC dental restorative materials used were light cured, then cut using a diamond burr in a high-speed air turbine dental handpiece and finally polished using a low-speed dental handpiece with the various grades of 3M Sof-Lex disc. The cut and polished dental filling materials then passed through the dental chair system and dental amalgam separator and were collected in the wastewater container. A total of 5 L of wastewater was collected during this test. The frequency of particle sizes detected using the light microscope based on particle area (µm²) from eight images is shown in Figure 4.8. A total of 1128 particles were detected, of which 44% were between 1.2 and 5 µm² in size, 18% were between 5 and 10 µm², 33% were between 10 and 50 µm², and 5% were above 50 µm² (Figure 4.8). Analysis of the particles' circularity index showed that the particles in the efficacy test had a mean and median circularity index of 0.68. This size trend is consistent with that observed during sampling, which showed that the majority of particles were between 1.2 and 5 µm² in size and that the frequency of occurrence declines as size increases (Figure 4.8). These results suggest that a large number of smaller particles (potentially nanoparticles) not typically associated with dental amalgam pass through type 1 dental amalgam separators and are present in the DWW.

4.2.5 *Ecotoxicity testing of the dental wastewater streams*

The results of the ecotoxicity testing using *D. magna* as a bioindicator, after 48 hours' exposure to different concentrations of DWW from the three dental practices, are shown in Table 4.2. The immobilisation percentage of each sample is given, as well as the estimated and calculated EC_{50} values and 95% CIs, where available.

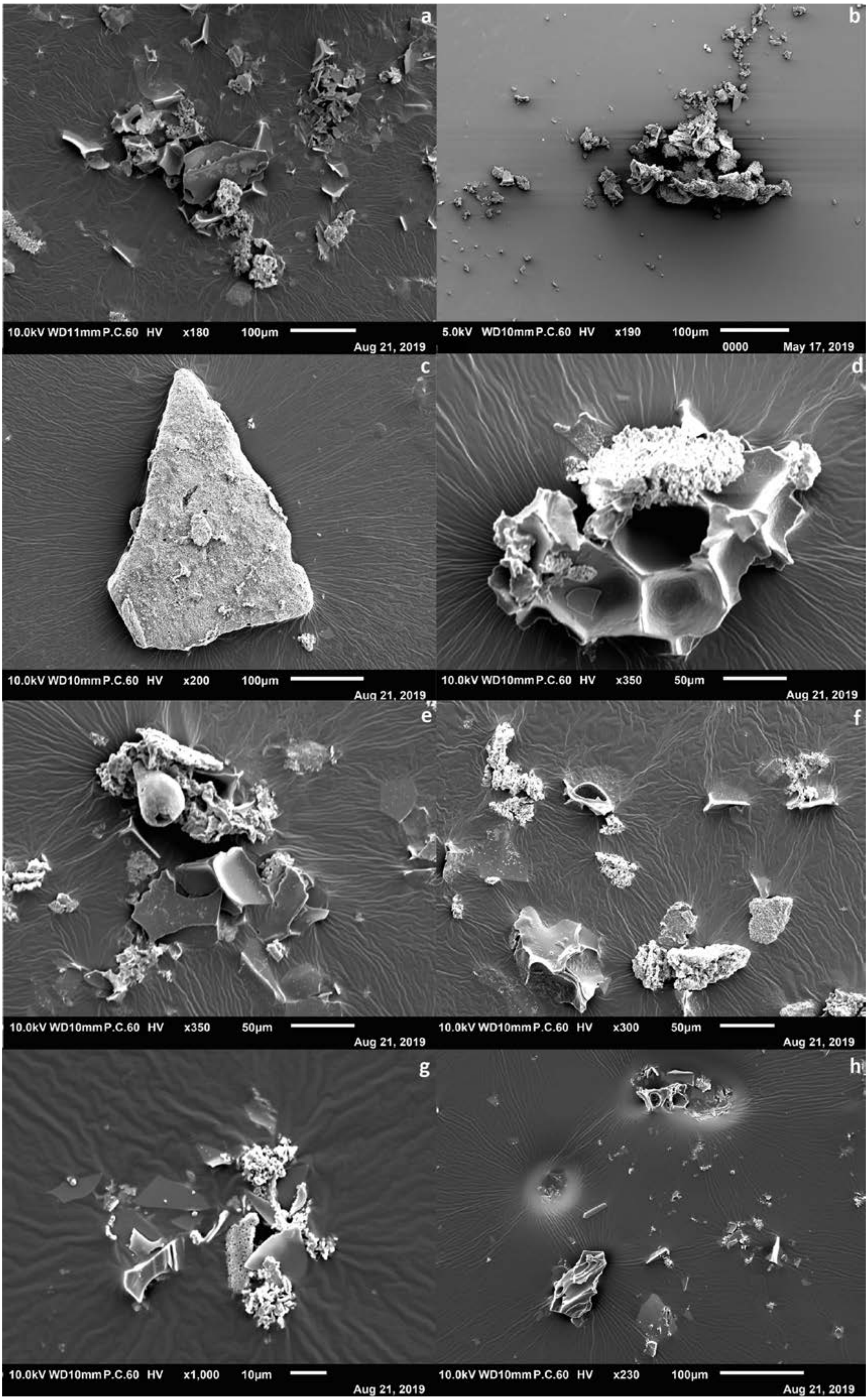


Figure 4.6. SEM images of particles found in the dental wastewater streams from DP1 obtained with the JEOL JSM-IT200 InTouchScope SEM.

Figure 4.7. The four resin composite dental filling materials after light polymerisation, from left to right: Ceram.X, manufactured by Dentsply Sirona; SDR flow+, manufactured by Dentsply Sirona; Filtek, manufactured by 3M; and Herculite XRV, manufactured by Kerr Dental.

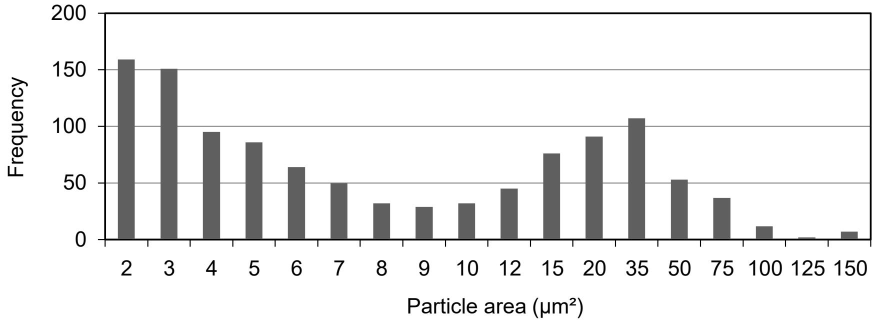


Figure 4.8. Size distribution of particles detected during efficacy testing of the amalgam separator using four commonly used MFDRMs: Ceram.X, SDR flow+, Filtek and Herculite XRV.

The immobilisation percentage shows that for DP1 the immobilisation of 100% of *D. magna* ranged from a concentration of 1% to 4% DWW/L, for DP2 it ranged from 0.1% to 0.2% DWW/L and for DP3 it ranged from 0.04% to 0.1% DWW/L (Table 4.2). Three of the samples from DP1 did not reach a 100% immobilisation end point.

Estimated and calculated EC_{50} values were found to match closely in most cases (Table 4.2). Calculated EC_{50} values were obtained by processing in GraphPad Prism (version 8.2.1), which highlighted that the data were inconclusive when a best fit that included the values of all parameters could not be achieved; hence, 95% CIs were very wide or unavailable. The EC_{50} values for DP1 ranged from as low as 0.01% to as high as 6.69% DWW/L. EC_{50} values for DP2 ranged from 0.01% to 0.04% DWW/L and DP3 showed an EC_{50} value of 0.01% DWW/L.

4.3 Results for Objective 5

Conduct a comprehensive review of the literature with respect to the occupational and health challenges arising from the use of MFDRMs

The information retrieved from the literature on MFDRMs, their toxicity, and their occupational health and environmental impacts in the dental surgery is presented in this section. In addition to the papers retrieved (Figure 4.9), the reports by the EU's SCENIHR (2015) and the World Health Organization and the Food and Agriculture Organization of the United Nations (WHO and FAO, 2011) were guiding resources.

4.3.1 Toxicity

Dental polymer materials based on methacrylate are used in MFDRMs, and only retrospective case reviews

Table 4.2. Results of ecotoxicity testing of wastewater samples from three dental practices (DP1, DP2 and DP3), showing percentage immobilisation of *D. magna* after 48 hours, calculated and estimated EC_{50} values and 95% CIs

Conc. (% DWW/L medium)	DP1 samples							DP2 samples			DP3 samples	
	1	2	3	4	5	6	7	1	2	3	1	2
0	0	0	0	0	0	0	0	0	0	0	0	0
0.01	0	0	0	5	0	0	0	10	0	0	50	55
0.02	5	0	0	0	0	0	0	10	0	0	N/A	75
0.04	5	0	0	0	0	0	5	60	0	75	100	90
0.1	15	0	0	0	0	20	10	100	65	85	100	100
0.2	0	15	0	0	0	30	0	100	100	100	N/A	100
0.5	35	85	20	0	0	10	N/A	100	100	100	100	100
1	85	100	100	0	10	0	100	N/A	100	100	100	100
2	0	100	100	0	20	40	100	N/A	100	100	N/A	N/A
4	0	100	100	N/A	10	100	100	N/A	100	100	100	N/A
Estimated EC_{50} (48 h)	N/A	0.028	0.55	0.02	0.96	2.08	0.55	0.04	0.09	0.04	0.01	0.01
Calculated EC_{50} (48 h)	N/A	0.28	0.42	0.01[a]	6.69	2.04[a]	0.44	0.04[a]	0.01[a]	0.04	0.01	0.01
95% CI	N/A	0.26–0.31	N/A	Very wide	N/A	1.98–17.86	N/A	N/A	N/A	N/A	0.007–0.01	0.002–0.02

Tested in accordance with OECD 202 standard methods.

[a]Data were flagged by the software as inconclusive.

N/A, not available.

Figure 4.9. Flow diagram showing the databases searched and the number of articles retrieved.

have indicated contact dermatitis and occupational asthma in dental personnel (Lindström *et al.*, 2002; Walters *et al.*, 2017).

Concern exists that incomplete polymerisation of dental composites may give rise to degradation products in the mouth, which could then be metabolised by different enzymes such as esterases. The implications of such activities and pathways are still under examination, with improvements being incorporated in new materials as they are developed (Gupta *et al.*, 2012, MacAulay *et al.*, 2017). The SCENIHR report and the joint WHO and FAO report concluded that the risk posed by the BPA content of dental resinous materials was negligible (SCENIHR, 2015; WHO and FAO, 2011). SCENIHR (2015) also noted that, just as in the case of mercury, genetic polymorphisms may affect the toxicokinetics of some constituents of these alternative materials. Genes involved in the reaction to mercury are also involved in cellular reactions to resin monomers, and therefore genetic variability is relevant for resin-based materials. To date, the available epidemiological studies do not provide sufficiently consistent outcomes to enable conclusions to be drawn on possible human health effects. These aspects need further investigation in properly conducted studies using a wide dose range of BPA (SCENIHR, 2015).

4.3.2 Inhalation effects

The filler content in some RCs, which are often polished after placement in the oral cavity, is in the nanoparticle scale range. Research findings have raised the possibility of respirable dust being produced and have emphasised the need to carry out any necessary polishing with water and with adequate ventilation (Schmalz *et al.*, 2018; Van Landuyt *et al.*, 2012). Studies in which the presence of organic matter from RCs suspended in the atmosphere was measured have indicated its presence but at levels considerably below the acceptable limit (Marquardt *et al.*, 2009; Nilsen *et al.*, 2019). Methacrylate derivatives also have the potential to be respiratory sensitisers and to cause asthma (Walters *et al.*, 2017). These findings demonstrate how important it is that dentists wear personal protective equipment and work within health and safety legislation (Government of Ireland, 2005).

4.3.3 Dermal effects

Contact dermatitis has been demonstrated in an individual when uncured bonding agent (unfilled resin) permeated through nitrile gloves. The uncured bonding agent was placed on the non-dominant gloved hand to increase the wettability of the RC dental material during application (Sananez *et al.*, 2020). Our search of the literature identified a significant number of *in vitro* studies and clinical studies of small sample sizes, each hypothesising a potential risk of contact dermatitis with MFDRMs – both dental resins and fillers – but none providing consistent evidence.

Examination of the MSDSs provides important information on the chemicals present, hazards and appropriate handling of dental materials. However, many of the mercury-free dental filling materials may have substances present that are not disclosed. This may be because of their integral role in the efficacy of the dental material or because they constitute < 1% of the mercury-free dental filling material and there is no requirement to record their presence. This is changing following the introduction of the EU regulation on medical devices (EU 2017/745), however.

4.3.4 No change in adverse events

Since 1993 dentists, dental hygienists and physicians in Norway have reported all types of adverse reactions (not limited to serious events) to dental materials to the Adverse Reaction Unit (NORCE). From 1993 to the end of 2013, more than 2100 reports were received. In 2013, 28% of the reports related to composites and cements. According to NORCE, this ratio had remained relatively stable over the years following the country's phasedown (2008) to phaseout (December 2010) of dental amalgam-containing products (NORCE, 2020). This meant that, although there was an increase in the use of MFDRMs, there was no increase in the number of adverse events reported for such materials.

4.3.5 Project limitations

This study was limited to three out of five dental amalgam separators currently in use in Ireland. While the efficacy of these amalgam separators is stated to be 95%, according to manufacturer and ISO certification guidelines, the test slurry used to establish this efficacy may not be representative of a typical particle load encountered in dental clinics. This is because particle size distributions differ depending on the individual using the dental equipment, differences in patients’ enamel and filling needs and other environmental factors.

The sampling period was restricted by the short duration of the overall project and consisted of less than 6 months overall. The standardised *D. magna* ecotoxicity test is used as a toxicity bioindicator and is therefore limited in its application to real-world scenarios.

5 Conclusions

This chapter will discuss what the results mean for the practice of dentistry, dental personnel, patients, the public and the environment. It must be acknowledged, however, that this was a small-scale study in which only three amalgam separators were considered.

Research on the impact of dental filling materials on the environment has focused predominantly on the impact of dental amalgam, with little research on the impact of MFDRMs on the environment (UNEP, 2013). Further research in this area must be conducted, especially in terms of nanoparticle release using nanoscale investigations, as well as research into disinfection by-products in wastewater treatment plants and whether trophic transfer of dental material particles occurs, which has already been observed in microplastics research. Recommended areas of research are set out in Chapter 6.

Efficacy testing of the DWW demonstrated that the highest proportion of particles were of sizes between 1.2 and 5 μm^2. Testing demonstrated that the small filler particles associated with MFDRMs passed through the filters on the dental chair and dental amalgam separator. The findings from this small study should be further elaborated using ISO 11143:2008-certified amalgam separators of all types used in dental practices. This is of particular importance in the context of emerging contaminants such as microplastics and nanoparticulate wastes found in the environment (Brar *et al.*, 2010; Froggett *et al.*, 2014; Reijnders, 2009). Ecotoxicity testing conducted with the planktonic crustacean *D. magna* and wastewater streams from all three dental practices demonstrated the deleterious effect of the wastewater on the crustacean, suggesting that more extensive ecotoxicity testing should be considered.

Research on the organic polymers in use and possible sensitising of dental professionals to methacrylate derivatives should be identified and appraised. Audits must be ongoing to ensure that working practices adhere to the Health and Welfare at Work Act 2005 (Government of Ireland, 2005).

Any dental filling material must perform satisfactorily in the mouth, an often challenging environment for the long-term success of dental materials (Stewart and Finer, 2019), but the wider environment and sustainable development must also be considered (United Nations, 2019). Evidence-informed means of primary prevention in dentistry must also be addressed (Ajiboye *et al.*, 2020; Bayne, 2013; Department of Health, 2019a,b). New dental materials are still emerging on the market, and monitoring of the environment, the dental clinic space, personnel, patients and the public must continue.

6 Recommendations

In the light of the conclusions presented in Chapter 5, and based upon the results generated in this project, we have a number of recommendations:

1. The use of amalgam separators (ISO 11143:2008) should continue in dental practices, as they are effective in removing larger particulate waste from DWW streams.
2. With the widespread use of MFDRMs, further research in the area of enhanced capture of micro- and nanoparticulate waste should be considered as a matter of priority.
3. Dental clinics should have a protocol or standard operating procedure for routine and preventative maintenance of installed waste separation equipment.
4. This study focused on particulate matter arising through the use of MFDRMs; chemical components (e.g. uncured monomers, plasticisers) were not characterised or quantified in the present work. However, this study has demonstrated, through ecotoxicity testing and physico-chemical analysis, that DWW is a potentially potent and complex wastewater stream with considerable temporal heterogeneity both within and between dental practices. The nature, extent and concentrations (loadings) of synthetic compounds present in DWW streams, and their spatial and temporal variability, should therefore be addressed in future studies examining the potential health and environmental risks of DWW arising from the use of MFDRMs.
5. As the demand for MFDRMs, their use and constituent components continue to evolve, we suggest, in line with recommendation 4, that channels be developed for regular documentation and reporting of predominant MFDRMs used in dental practice in Ireland.
6. Dental clinics should ensure that health and safety protocols are adopted and all personal protective equipment is appropriately worn.
7. Continued monitoring of occupational exposure to MFDRMs in dental practice (in the Irish context by the Health and Safety Authority) is recommended, as MFDRM constituents continue to evolve along with regulatory drivers, practitioners and patient demands. There is an established trend towards increased incorporation of novel nanoscale particulates and “fillers” within dental practice to fulfil the demand for a wider range of MFDRMs that include “tuneable” materials with enhanced properties in terms of aesthetics, cost and durability.

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Abbreviations

BPA	Bisphenol A
CI	Confidence interval
DP	Dental practice
DWW	Dental unit wastewater
GIC	Glass ionomer cement
LESS Hg	Looking to Environmental Sustainability and Securing Health goals
MFDRM	Mercury-free dental restorative material
MSDS	Material safety data sheet
PMRC	Polyacid-modified resin composite
RBC	Resin-bonded composite
RC	Resin composite
SCENIHR	Scientific Committee on Emerging and Newly Identified Health Risks
SEM	Scanning electron microscope
TDS	Total dissolved solids
TSS	Total suspended solids

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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Assessment of the Environmental and Health Impacts Arising from Mercury-free Dental Restorative Materials

Authors: Máiréad Harding, Timothy Sullivan, Hannah Binner, Naghmeh Kamali and Martina Hayes

Identifying Pressures

The United Nations Minamata Convention on Mercury is an international regulatory framework that aims to protect human health and the global environment from the harmful effects of mercury. The Convention addresses the use of mercury-containing dental restorative materials (fillings) and their phaseout in dental practice. The Convention has been transposed into legislation in the EU through Regulation (EU) 2017/852 and in Ireland through S.I. No. 533/2018. Dental fillings are used to replace lost tooth tissue. Prior to the Minamata Convention there had already been a downward trend in the use of mercury-containing dental filling materials (amalgam fillings). Controls present in dental practices have minimised the environmental impacts of mercury-containing dental filling materials. Less is known about the newer mercury-free dental restorative materials and their environmental impact. This project was designed to assess potential environmental and health impacts arising from mercury-free dental restorative materials.

Informing Policy

The Minamata Convention has a direct impact on dentistry in Ireland with respect to policy, society and commerce. Since July 2018, amalgam fillings are no longer permitted for use in patients under 15 years of age and in pregnant or breastfeeding women, except when deemed strictly necessary by the dental practitioner based on the patient's specific medical needs. This research was necessary because of the wide-reaching impacts of the Minamata Convention on dentistry and the subsequent move to alternative filling materials. We identified that particles from the filling materials were present in dental wastewater (DWW) streams, the largest being 1.2 to 5 μm^2 in size, suggesting the presence of many small particles in DWW. Ecotoxicity testing of DWW from participating dental practices with the planktonic crustacean *Daphnia magna* demonstrated a deleterious effect on the crustacean. This suggests that more extensive ecotoxicity testing should be undertaken.

Developing Solutions

What was unique in your approach and what solutions or recommendations do you propose?

The research identified that very little literature exists on the environmental and health impacts of mercury-free dental restorative materials. The research did identify small particles from the mercury-free dental restorative materials in DWW. Given the move away from mercury-containing dental filling materials, it will be essential to consider enhanced capture of small particles from DWW as a priority. Further work with respect to the chemical components of mercury-free dental filling materials should be conducted in future studies to comprehend both the inorganic and organic components of mercury-free dental restorative materials and their environmental impacts.

Given the challenges and absence of evidence with respect to dental restorative filling materials, an emphasis on health promotion, prevention and expansion of primary oral healthcare services for the public for all ages should be embraced as part of the solution.

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