WHO guideline on environmentally friendly and less invasive oral health care for preventing and managing dental caries

UN environment programme

World Health Organization

WHO guideline on environmentally friendly and less invasive oral health care for preventing and managing dental caries

UN environment programme

World Health Organization

WHO guideline on environmentally friendly and less invasive oral health care for preventing and managing dental caries

ISBN 978-92-4-011694-8 (electronic version)
ISBN 978-92-4-011695-5 (print version)

Suggested citation. WHO guideline on environmentally friendly and less invasive oral health care for preventing and managing dental caries. Geneva: World Health Organization; 2025. Licence: CC BY-NC-SA 3.0 IGO.

Cataloguing-in-Publication (CIP) data. CIP data are available at https://iris.who.int/.

Design and layout: blossom.it

Content

Abbreviations

BPA	Bisphenol A
CI	Confidence Interval
CoI	Conflict of Interest
DoI	Declaration of Interests
ERG	External Review Group
GDG	Guideline Development Group
GEF	Global Environment Facility
GRADE	Grading of Recommendations Assessment, Development and Evaluation
IPC	Infection Prevention and Control
LCA	Life Cycle Assessment
LED	Light-emitting Diode
NCD	Noncommunicable Disease
PICO	Population, Intervention, Comparator and Outcome
PROSPERO	International Prospective Register of Systematic Reviews
SDGs	Sustainable Development Goals
TDI	Tolerable Daily Intake
UNEP	United Nations Environment Programme
UNICEF	United Nations Children’s Fund
WASH	Water, Sanitation and Hygiene
WHO	World Health Organization

Acknowledgments

This guideline was produced by the Department of Noncommunicable Diseases (NCDs), Rehabilitation and Disability (NCD), Universal Health Coverage/ Communicable and Noncommunicable Diseases division of the World Health Organization (WHO), Geneva, Switzerland (WHO headquarters), under the general guidance of Guy Fones, NCD Department, Acting Director, and under the lead of Benoit Varenne, Dental Officer, Oral Health Programme, NCD Department.

Oversight was provided by the **WHO–United Nations Environment Programme (UNEP) Steering Committee**, which included Benoit Varenne, Nicole Rendell, Yuriko Harada, Eduardo Bernabé, Gabriela Katia Sardon Panta, Lesley Onyon, Megha Rathi, Margaret Montgomery, Richard Brown (WHO headquarters); Yuka Makino and Christine Nkerifac (WHO Regional Office for Africa); Carolina Hommes (WHO Regional Office for the Americas); Nalika Gunawardena (WHO Regional Office for South-East Asia); Samar Elkefy (WHO Regional Office for the Eastern Mediterranean), Elena Tsoy and Irina Zastenskaya (WHO Regional Office for Europe); Sangeeta Singh (WHO Regional Office for the Western Pacific); Sushera Bunluesin (WHO Country Office, Thailand); Mady Ba (WHO Country Office, Senegal); Kenneth Davis, Imelda Dossou Etui and Grace Halla (United Nations Environment Programme – UNEP); Eisaku Toda (Minamata Convention on Mercury Secretariat).

WHO extends its sincere appreciation to WHO consultants, Eduardo Bernabé (Queen Mary University of London, United Kingdom of Great Britain and Northern Ireland) and Gabriela Katia Sardon Panta for their editorial leadership and technical writing expertise throughout the development of the report. WHO also gratefully acknowledges Katia Jedeon (Université Paris Cité, France) for her valuable support in reviewing and providing inputs throughout the various stages of the report's development.

The **Guideline Development Group (GDG)** comprised international experts with diverse backgrounds in clinical dentistry, public health, biomaterials and environmental health. WHO sincerely thanks Alice Baras (Ecoresponsabilité Promotion Santé, France), Carlos Alberto Feldens (Universidade Federal do Rio Grande do Sul, Brazil), Edward Lo (University of Hong Kong, Hong Kong Special Administrative Region, China); Ellen Bruzell (Nordic Institute of Dental Materials, Norway), Florian Schulze (European Network for Environmental Medicine, Germany), Homa Kashani (University of Social Welfare and Rehabilitation Sciences, the Islamic Republic of Iran), Richard Niederman (WHO Collaborating Centre, New York University, the United States of America), Rico Euripidou (Groundwork, South Africa), Ritu Duggal (WHO Collaborating Centre, All India Institute of Medical Sciences, India), Waranun Buajeeb (WHO Collaborating Centre, Mahidol University, Thailand).

Special advisers to the **Guideline Development Group** included Adriana Otheguy (Ministerio de Salud Pública, Uruguay), Aristomenis Syngelakis (Ministry of Health, Greece), Fauziah Binti Ahmad and Noormi Othman (Ministry of Health, Malaysia), Mane Codou Badiane (Ministère de la Santé, Senegal), Rami Ahmad Assad (Ministry of Public Health, Qatar).

WHO gratefully acknowledges the members of the **External Review Group**, who provided independent review and constructive feedback to strengthen the clarity, scientific quality and practical relevance of the guideline. The group included Ali Kazemian (Mashhad University of Medical Sciences, the Islamic Republic of Iran), Janet Clarkson and Tanya Walsh (Cochrane Oral Health Group, University of Manchester, the United Kingdom), Murray Thomson (University of Otago, New Zealand), Nigel Pitts (King's College London, the United Kingdom), Nilantha Ratnayake (National Institute of Oral Health, Sri Lanka), Roberto Ruggiero Braga (Universidade de São Paulo, Brazil), Satoshi Imazato (International Association of Dental, Oral and Craniofacial Research, University of Osaka, Japan), Sudeshni Naidoo (WHO Collaborating Centre, University of the Western Cape, South Africa).

WHO also appreciates the contributions of **subject matter experts** who provided additional technical input during the guideline development process: Julian Fisher (University of Pennsylvania, the United States of America), Nicolas Martin (University of Sheffield, the United Kingdom), Raman Preet (Umeå University, Sweden).

WHO gratefully acknowledges the valuable inputs made by Jennifer De France (WHO Water, Sanitation

and Hygiene Unit), Meera Thapa Upadhyay and Wilson Milton Were (WHO Department of Maternal, Newborn, Child and Adolescent Health). WHO also recognizes the many individuals and organizations that contributed to the development of this guideline.

Special thanks are extended to the international **systematic research team**, led by Katia Jedeon (Université Paris Cité, France), and to all contributors to the evidence synthesis and the Grading of Recommendations Assessment, Development and Evaluation (GRADE).

The team was composed of Ana Ribeiro and Olivia Kérourédan (University School of Dentistry, Bordeaux, France); André Porporatti, Diluxe Mutale, Pierre Colon, Caroline Mocquot, Claire-Adeline Dantagnan and Sylvie Babajko (Université Paris Cité, France); Angela Graciela Deliga Schroder (Tuiuti University of Paraná, Brazil); Ayako Washio (Kyushu Dental University, Japan); Avijit Banerjee (King's College London, United Kingdom); Bartosz Walendzik and Roman Ardan (Koszalin University of Technology, Poland); Claudia Salerno and Guglielmo Campus (University of Bern, Switzerland); Denise Corridore, Livia Ottolenghi and Marta Mazur (Sapienza University of Rome, Italy); Maciej Jedlinski (Pomeranian Medical University, Szczecin, Poland); Sophie Doméjean (Clermont-Ferrand, France); and Tran Thu Thuy (University of Medicine and Pharmacy, Ho Chi Minh City, Viet Nam).

The application of the GRADE approach was led by André Porporatti (Université Paris Cité, France). Katia Jedeon and Eduardo Bernabé supported the GDG in interpreting the GRADE summary profiles.

This guideline was developed as part of the project Accelerate implementation of dental amalgam provisions and strengthen country capacities in the environmental sound management of associated wastes under the Minamata Convention. The project was funded by the Global Environment Facility (GEF), implemented by UNEP and executed by WHO with targeted technical assistance by the UNEP Global Mercury Partnership.

WHO gratefully acknowledges the financial support of the GEF, which made this work possible.

Executive summary

Background

Dental caries is a major public health problem affecting all age groups. It often begins in early childhood and increases across the life course. Although largely preventable and treatable at an early stage, dental caries affects 2.7 billion people worldwide, with a disproportionate impact on marginalized populations that have limited access to essential oral health care services *(1)*. Dental amalgam has been used for decades to restore teeth affected by dental caries. It contains mercury, about 50% by weight, chemically bonded to other metallic elements such as silver and tin. Mercury is a highly toxic heavy metal that poses a global threat to human health and the environment.

The Minamata Convention on Mercury, a global treaty in force since 2017, seeks to protect human health and the environment from anthropogenic emissions and releases of mercury. The World Health Organization (WHO), mandated by Member States through World Health Assembly resolutions, supports countries in implementing the Minamata Convention, promoting oral health and mercury-free dental practices, and ensuring access to essential oral health care. In collaboration with the United Nations Environment Programme (UNEP), WHO is executing a project to phase down the use of dental amalgam and to manage associated waste in line with the provisions of the Minamata Convention.

Rationale and objective

As mercury is harmful to both human health and the environment, there is a need for strong evidence-based guidance on the use of alternative materials that are free from mercury and effective in the management of dental caries. This guideline provides recommendations on safe, less invasive and environmentally friendly oral health care for preventing and managing dental caries using mercury-free dental products.

The mandate for WHO to develop such guidance comes directly from World Health Assembly resolution WHA74.5 on oral health *(2)*. In addition, both the Minamata Convention on Mercury and the WHO Global Strategy and Action Plan on Oral Health 2023–2030 call for phasing down the use of dental amalgam, which requires sufficient uptake of alternative materials to manage dental caries.

Scope and target audience

The scope of this guideline is to identify and promote mercury-free dental products, including those that can be considered direct alternatives to dental amalgam, for preventing and managing dental caries.

This guideline is intended for governments, intergovernmental organizations, non-State actors, oral health professional organizations, ministries of health and environment, health authorities, public health policymakers, health programme managers, nongovernmental organizations, industry, oral health professionals and health workers.

Methods

These recommendations in this guideline are based on the most current, high-quality scientific evidence. They were formulated using processes and methods that meet the highest international standards for guideline development, as outlined in the *WHO handbook for guideline development (3)*. Oversight of the development process was provided by the WHO Oral Health Programme, with support from a dedicated WHO–UNEP Steering Committee.

A Guideline Development Group (GDG), composed of independent international experts with diverse expertise and perspectives, was convened to identify key questions, review the evidence and formulate recommendations. The evidence base was drawn from systematic reviews, both existing and newly commissioned, on the clinical effectiveness, cost-effectiveness, toxicity and environmental impact of mercury-free dental products for preventing and managing dental caries.

The GDG assessed this evidence and developed recommendations using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach to determine the certainty of the evidence. In addition, the group considered other factors, including whether the

balance of benefits to harms was sensitive to variability in patient values and preferences; the relative costs; resource use and cost-effectiveness; the acceptability and feasibility of interventions in the intended populations and settings; and anticipated impacts on equity of access and outcomes.

Recommendations and best-practice statements

This WHO guideline is grounded in the guiding principles of prioritizing preventive strategies, promoting minimally invasive interventions, fostering open communication between patients and oral health care professionals, and the precautionary principle.

This guideline includes eight recommendations and two best-practice statements. Clinical recommendations are grouped according to their primary indication: prevention of dental caries, nonrestorative interventions for managing dental caries, and direct restorations (excluding indirect restorations and advanced caries stages). Two additional recommendations and two best-practice statements address risk mitigation among clinical teams and patients.

Each recommendation and best-practice statement is accompanied by remarks to support interpretation. The guideline also summarizes the GDG discussions and the rationale behind each decision. Finally, it highlights important knowledge gaps that require further investigation through primary research.

Summary of recommendations

RECOMMENDATIONS FOR CLINICAL PRACTICE

Clinical interventions to prevent dental caries	**Recommendation 1: strong, moderate certainty of evidence. New** WHO recommends the use of fluoride varnish (5% sodium fluoride) applied twice a year as a population-wide preventive intervention against dental caries in both primary and permanent teeth. **Recommendation 2: conditional, low certainty of evidence. New** WHO suggests the use of silver diamine fluoride (38% concentration), applied twice a year, as a population-wide preventive intervention against dental caries in both primary and permanent teeth. **Recommendation 3: strong, moderate certainty of evidence. New** WHO recommends the use of pit and fissure sealants as an intervention to prevent dental caries in the first permanent molars of children at high risk of caries.
Clinical interventions to manage dental caries: nonrestorative treatments	**Recommendation 4: strong, moderate certainty of evidence. New** WHO recommends the use of fluoride varnish (5% sodium fluoride) as a noninvasive treatment option for managing initial (non-cavitated) carious lesions in primary and permanent teeth. **Recommendation 5: strong, moderate certainty of evidence. New** WHO recommends the use of silver diamine fluoride (38% concentration), applied twice a year as a non-invasive treatment option for managing cavitated carious lesions without pulp involvement in primary teeth and cavitated carious lesions without pulp involvement on the root surfaces of permanent teeth.
Clinical interventions to manage dental caries: restorative treatments	**Recommendation 6: conditional, low certainty of evidence. New** WHO suggests the use of glass ionomer cements and resin-based composites as direct restorative materials for the treatment of dental caries.

RECOMMENDATIONS AND BEST-PRACTICE STATEMENTS FOR RISK MITIGATION AMONG CLINICAL TEAMS AND PATIENTS

Oral health care for vulnerable populations	**Recommendation 7: conditional, very low certainty of evidence. New** WHO suggests limiting the use of resin-based fissure sealants and composites containing bisphenol A (BPA) derivatives in children, adolescents, pregnant or breastfeeding women, as these groups are more susceptible to potential endocrine effects. **Recommendation 8: conditional, low certainty of evidence. New** WHO suggests exercising caution when using resin-based composites, including fissure sealants and restorations, in individuals with allergic conditions, as the monomers present in these products may cause sensitization.
Safe handling and application of resin-based composites	**Best-practice statement 1** Follow occupational safety protocols for the proper handling of resin-based composites to reduce risks for oral health care professionals and patients. **Best-practice statement 2** Ensure effective isolation and thorough curing with appropriate light sources, and proper surface finishing or polishing techniques to minimize exposure to unpolymerized monomers during the application of resin-based composites.

1. Introduction

The World Health Organization (WHO) defines oral health as the state of the mouth, teeth and orofacial structures that enables individuals to perform essential functions, such as eating, breathing and speaking, and encompasses psychosocial dimensions, such as self-confidence, well-being and the ability to socialize and work without pain, discomfort and embarrassment (*4*). Dental caries is a major public health problem worldwide. The disease affects all age groups, with onset in early childhood and increasing prevalence across the life course. Although largely preventable and treatable in its early stages, dental caries contributes substantially to the economic burden globally, particularly among underserved and vulnerable populations with limited access to essential oral health care services (*5*). For more than 175 years, dental amalgam – which contains approximately 50% mercury by weight, chemically combined with other metallic elements such as silver and tin – has been widely used as a restorative material to fill cavities caused by dental caries.

Mercury (Hg) is a highly toxic heavy metal that poses a global threat to human health, and more broadly, to the health of ecosystems (*6, 7*). Mercury pollution occurs in three main forms: elemental (metallic), organic (primarily methylmercury) and inorganic compounds (such as those found in amalgam restorations). All forms have toxic effects on the nervous, digestive and immune systems, as well as on the lungs, kidneys, skin and eyes, depending on the type of mercury, the dose and duration of exposure. Once released into the environment, mercury can travel long distances through the atmosphere, persist in ecosystems and bioaccumulate in the food chain, particularly in fish, seafood and humans (*8, 9*).

Outside occupational settings (such as artisanal and small-scale gold mining and oral health care), human exposure to mercury occurs primarily through the consumption of contaminated seafood and through contact with mercury-containing products, including dental amalgam, certain pesticides, damaged mercury-containing products such as thermometers, fluorescent light bulbs, batteries and skin-lightening products (*10*). Dental amalgam is a direct restoration material commonly used to restore decayed teeth. The placement and removal of dental amalgam restorations expose patients and oral health care professionals to low levels of mercury vapour. Moreover, dental amalgam restorations may continuously release very small amounts of mercury vapour, especially during toothbrushing, chewing, eating hot foods and liquids, and teeth grinding (*11, 12*). Mercury from dental amalgam can enter the natural environment through several pathways, polluting air (via emissions from dental clinics, crematoria and sewage sludge incineration), water (through releases from dental clinics and household waste), and soil (through disposal in landfills, burials and the use of contaminated fertilizer) (*13*).

The Minamata Convention on Mercury, a global treaty to protect human health and the environment from emissions and releases of mercury and its compounds resulting from human activity, entered into force on 16 August 2017. It initially required Parties to phase down the use of dental amalgam by implementing at least two of nine recommended measures listed in Annex A, Part II, of the Minamata Convention on Mercury. In 2022, at its fourth meeting (COP4), the Conference of the Parties restricted the use of dental amalgam in primary teeth, in children under 15 years of age and for pregnant or breastfeeding women, except when deemed strictly necessary by an oral health care professional. COP4 also prohibited the use of mercury in bulk form by oral health care professionals. In 2023 at its fifth meeting (COP5), the Conference of the Parties adopted a new mandatory measure requiring Parties that have not yet phased out dental amalgam to submit to the Secretariat, every four years, a national action plan or a report, based on available information, detailing progress achieved or under way in phasing down or phasing out dental amalgam (*14*).

WHO is mandated by its Member States, through two World Health Assembly resolutions (WHA67.11 and WHA74.5), to support countries in implementing the Minamata Convention on Mercury. In accordance with the resolution on oral health (WHA74.5), WHO was requested to provide technical guidance on environment-friendly and less invasive oral health care to assist countries in implementing the Convention, including supporting prevention programmes (*2*).

The Global Oral Health Action Plan 2023–2030 has set one global oral health target and a range of actions to progressively reduce, or, where appropriate eliminate, the use of dental amalgam (*2*). Phasing down the use of dental amalgam must be supported by creating an enabling environment for mercury-free dental products and by ensuring access to essential oral health care (*15*). This is reinforced by WHO's ongoing work to mobilize political action towards universal health coverage for oral health. This work is based on guiding principles that include a public health approach to oral health, focusing on the prevention of dental caries and health promotion, thereby minimizing the need for dental restorations, in line with the first measure of Annex A, Part II, of the Minamata Convention (*14*).

In collaboration with the United Nations Environment Programme (UNEP), WHO is implementing a Global Environment Facility (GEF)-funded project entitled *Accelerating the implementation of dental amalgam provisions and strengthening countries' capacity for the environmentally sound management of associated waste under the Minamata Convention* (GEF7 Phasing Down Dental Amalgam project). The project takes advantage of relevant opportunities to disseminate the findings and make recommendations to phase down dental amalgam use and manage the associated waste in an environmentally sound manner. This guideline has been developed as a key output of the project.

1.1 Rationale

The high prevalence of untreated dental caries and the widespread social inequalities in dental caries within and between countries highlight the need for accessible strategies to prevent and treat the disease (*1*). Reducing the consumption of free sugars and toothbrushing with fluoridated toothpaste are effective strategies for preventing dental caries across the life course in the general population. Nonrestorative strategies include the application of topical fluorides and fissure sealants, while restorative strategies include the placement of glass ionomer cements, resin-based composites and compomers (*4*).

Moving away from mercury in oral health care supports wider environmental and public health objectives by reducing mercury pollution and the associated risks. This shift also supports the implementation of the Minamata Convention on Mercury and the Global Oral Health Action Plan 2023–2030, which call for the progressive reduction, and, where appropriate, elimination of dental amalgam use. To support this transition, it is essential to strengthen the evidence on the characteristics of mercury-free dental products and their selection and use to prevent and manage dental caries. In addition, a better understanding of their potential risks to human health and the environment will help inform decisions on safer and more sustainable practices.

Advice is therefore needed to ensure that the transition to mercury-free dental products does not compromise the quality of essential oral health care and that it safeguards the health of humans, animals and the environment.

1.2 Purpose

This guideline presents current knowledge and offers guidance on safe, minimally invasive oral health care that minimizes the impact on the natural environment. It focuses on the prevention and management of dental caries using mercury-free dental products. The guideline is aligned with the Minamata Convention, which calls for the reduction and, where feasible, elimination of mercury pollution worldwide. It does not include or compare products containing mercury-based dental amalgam, as these are not considered environmentally sustainable and their use requires extensive removal of tooth tissue. The objectives of this guideline are to:

- present the best available evidence on the clinical effectiveness, cost-effectiveness and safety (toxicological and ecotoxicological effects) of mercury-free dental products used in the prevention and management of dental caries;
- provide evidence-based recommendations for the selection and use of mercury-free dental products for preventing and managing dental caries, with emphasis on minimal intervention procedures and environmental sustainability;
- identify the roles, contributions and responsibilities of relevant stakeholders, including industry, in

supply chain management (materials sourcing, manufacturing and distribution) and in supporting oral health care through the use of environmentally sustainable materials;

- share best practices in the management of dental waste, including materials used and replaced in oral health care facilities;
- share cost-effective interventions to promote oral health and prevent dental caries in health care facilities and key settings; and
- share best practices to reduce the environmental impact of mercury-free dental products.

1.3 Scope

This guideline builds on the 2009 WHO report on the future use of materials for dental restoration, which recognized the potential of mercury-free alternatives such as glass ionomer cements and resin-based composites for the treatment of dental caries (*16*). Reflecting continuing progress, fluoride toothpaste, glass ionomer cements and 38% silver diamine fluoride were added to the WHO Model List of Essential Medicines in 2021, followed in 2023 by the inclusion of other topical fluorides (varnishes, gels and mouthrinses) and resin-based composites for use as fissure sealants and restorations (*17, 18*). In addition, WHO has developed briefing notes on preventing and managing dental caries that emphasize mercury-free products and minimal interventions (*4*). WHO is also preparing its first set of cost-effective oral health interventions (*19*). These developments reflect a broader shift towards evidence-based, preventive and minimally invasive approaches.

This guideline addresses the safe, effective, affordable and environmentally sustainable use of mercury-free dental products for the prevention and management of dental caries. It is relevant to policy-makers responsible for health promotion, to health care workers providing preventive and restorative care for dental caries, and to people of all ages receiving essential oral health care.

The key questions that informed the evidence synthesis for the guideline recommendations are outlined in section 2.1. They are organized under three headings, corresponding to the types of interventions discussed in section 4 of this document:

- interventions for the prevention of dental caries;
- nonrestorative interventions for the management of dental caries; and
- direct restorations for the management of dental caries.

This guideline excludes interventions for managing dental caries through indirect restorations (such as inlays, onlays and crowns) and for advanced stages of caries with pulp involvement. These exclusions are deliberate, as such clinical situations usually require specialized approaches and fall beyond the practical scope and target population of a primary care guideline.

1.4 Target audience

This document is intended to provide recommendations to governments, intergovernmental organizations, non-State actors and other stakeholders involved in planning and delivery of interventions to prevent and manage dental caries in individuals and populations.

Stakeholders include oral health professional associations, ministries of health and environment, government entities, health authorities, public health policy-makers, health programme managers, nongovernmental organizations, the private sector, oral health professionals and other health workers.

2. Methods

The WHO Oral Health Programme led the development of this guideline in accordance with WHO methodology for the development of guidelines and normative products (*3, 20*). A Steering Committee was established with representation from WHO staff at headquarters, regional and country offices, as well as from the United Nations Environment Programme (UNEP), including staff from the Secretariat of the Minamata Convention on Mercury. The Steering Committee appointed the members of the Guideline Development Group (GDG) and the External Review Group (ERG). The GDG consisted of 10 members, reflecting gender and geographical balance, and included expertise in clinical practice, biomaterials, public health and environmental science. Five chief dental officers participated in GDG meetings as special advisers, sharing country experience and ensuring that recommendations were realistic and implementable in diverse contexts. Implementation considerations were further enriched by contributions from selected experts in relevant fields, who were also appointed by the Steering Committee.

The draft guideline was reviewed by the ERG, consisting of nine external reviewers with diverse backgrounds relevant to the topic. They provided feedback on clarity, completeness, scientific evidence and practical relevance. Inputs from the ERG were incorporated into the draft, which was subsequently reviewed by the Steering Committee before finalization.

Full details of the composition of the Steering Committee, GDG and ERG are available in annexes 1–3. Declaration of interest forms were collected from all contributors and assessed by the WHO Secretariat in accordance with established procedures for the management of conflicts of interest (see annex 4).

2.1 Research questions of interest

The scope of the guideline was established by mapping existing systematic reviews and relevant reports from national and international organizations on the safety of mercury-free dental products for preventing and managing dental caries. The GDG reviewed the scope and agreed on the following five key questions:

1. What is the clinical effectiveness (for example, longevity and annual failure rate, or equivalent measures) and cost-effectiveness of mercury-free dental products for preventing and managing dental caries?

2. What is the cytotoxicity and biocompatibility of mercury-free dental products or their components (such as monomers and nanoparticles)?

3. To what extent are the components of mercury-free dental products (such as residual monomers and nanoparticles) released into the oral environment (through residual release or intraoral degradation)?

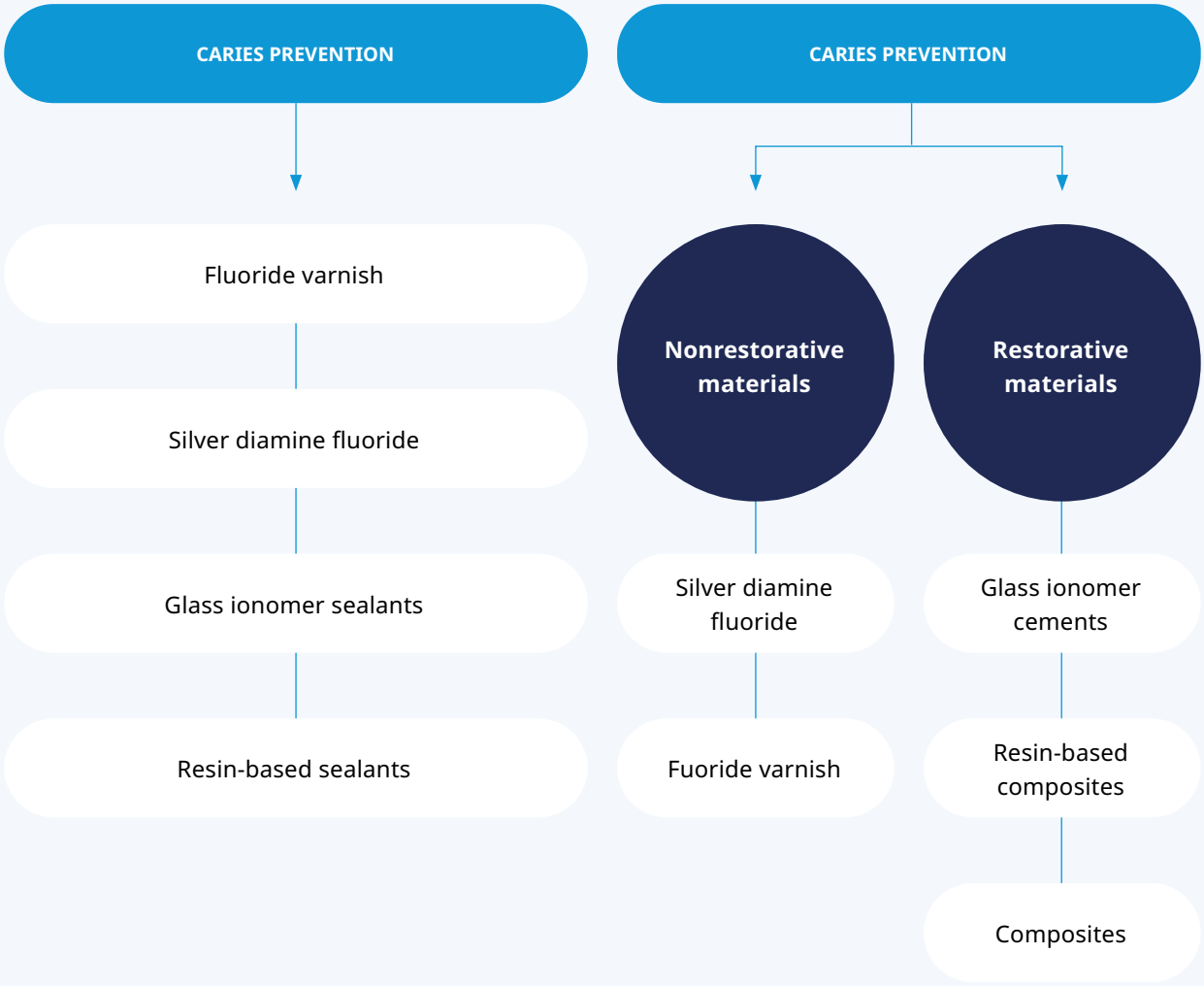
4. What are the health effects (for example, on organs, systems, physical and psychosocial functions) of mercury-free products on patients and health workers?

5. What are the environmental effects (for example, on water, air, soil and wildlife) associated with the manufacture, distribution, clinical use and waste management of mercury-free dental products?

The above key questions addressed four topic areas: clinical effectiveness (question 1), cost-effectiveness (question 1), toxicological effects (questions 2–4) and environmental impact (question 5) of mercury-free dental products for preventing and managing dental caries. Each review focused on the following professionally administered dental products: fluoride varnish, glass ionomer fissure sealants, resin-based fissure sealants, silver diamine fluoride, glass ionomer cements, resin-based composites and compomers (see Figure 1).

The use of glass ionomer and resin-based sealants for the nonrestorative management of non-cavitated carious lesions was not considered in this guideline.

Fig. 1. Mercury-free dental products assessed for preventing and managing dental caries in this guideline



The Steering Committee commissioned a systematic review team to identify and synthesize the best available evidence to address each review question. The team registered the five review protocols in the International Prospective Register of Systematic Reviews (PROSPERO) before the searches were carried out. The five review questions in population, intervention, control and outcomes (PICO) format are presented in annex 5. These five systematic reviews *(21-25)* are currently undergoing journal submission and are therefore cited as forthcoming publications in the reference list.

The team first identified and assessed existing systematic reviews. When these were recent and demonstrated a low risk of bias, they were used to summarize the evidence for recommendations and were cited accordingly. When systematic reviews were unavailable, outdated, at high risk of bias or presented conflicting evidence, a new review of primary studies was conducted. When existing systematic reviews were utilized, they were cited accordingly. Otherwise, the text indicated that a newly commissioned systematic review was conducted.

2.2 Going from evidence to recommendations

The GDG formulated the recommendations based on the quality of the available evidence. The overall certainty of the evidence for each key question was assessed using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach (*26*).

Using GRADE, the certainty of evidence was categorized into four levels (see Table 1). These levels could be downgraded due to risk of bias, inconsistency, imprecision, indirectness or publication bias, or upgraded when there was a large magnitude of effect, a dose–response gradient or when plausible residual confounding would reduce but not eliminate a demonstrated effect.

Table 1. The four GRADE levels of quality of evidence

QUALITY OF EVIDENCE	DESCRIPTION
High	We are very confident that the true effect is likely to be close to the effect estimate.
Moderate	We are moderately confident that the true effect is likely to be close to the effect estimate, but there is a possibility that it is substantially different.
Low	Our confidence in the effect estimate is limited: The true effect may be substantially different from the effect estimate.
Very low	We have very little confidence in the effect estimate: The true effect is likely to be substantially different from the effect estimate.

The GDG formulated evidence-informed, practical and actionable recommendations by judging whether the desirable effects outweighed any potential undesirable effects. Other factors considered included:

- whether the balance of benefits to harms was sensitive to variability in patient values and preferences regarding outcomes;
- costs and resource use, including cost-effectiveness;
- acceptability and feasibility in the intended populations and settings; and
- anticipated positive impacts on equity of access and outcomes (*27*) (see Table 2).

The recommendations are presented in section 4 of the document.

The GDG also formulated best practice statements, which reflect clinical norms considered self-evident and critical for practice. They are supported by high-certainty indirect evidence or strong consensus and are not formally rated for evidence quality (*28*).

Table 2. WHO-INTEGRATE evidence-to-decision framework criteria *(22)*

CRITERION	DEFINITION
Balance of health benefits and harms	Weighs the positive health outcomes of an intervention against any adverse effects or harms.
Human rights and sociocultural acceptability	Evaluates the alignment of the intervention with universal human rights standards and sociocultural appropriateness.
Health equity, equality and non-discrimination	Assesses how the intervention impacts disparities in access or outcomes.
Societal implications	Considers the broader social and environmental consequences of the intervention.
Financial and economic considerations	Reviews the costs of the intervention and its broader economic impact.
Feasibility and health system considerations	Examines the practicality of implementing the intervention within a health system.

* Quality of evidence is a meta-criterion that assesses the quality of the evidence supporting each of the six substantive criteria.

The guideline also provides a range of policy options and strategies to support implementation of the recommendations. These elements were not drawn directly from the systematic reviews but were developed through discussions with the GDG and expert input from external specialists. These are presented in section 5 of the document.

The ERG provided feedback on the draft guideline after it had been developed and revised by the Steering Committee and the GDG. It was not within the ERG's remit to change the recommendations formulated by the GDG. The Steering Committee revised the draft guideline based on the ERG's feedback.

3. Guiding principles

All recommendations and best practice statements in this guideline are informed by guiding principles that reflect the position of WHO, other United Nations agencies and the GDG on promoting mercury-free dental products for preventing and managing dental caries in accordance with the provisions of the Minamata Convention on Mercury.

These guiding principles are:

- **Prevention first.** The best way to minimize the environmental impact of oral health care is to reduce the need for treatment of preventable oral diseases. Strategies to promote oral health and prevent oral diseases provide greater benefits than restorative approaches in terms of health, economic and environmental benefits, as they reduce the prevalence of dental caries and the need for resource-intensive restorative treatment.

- **Sugar reduction and fluoride use.** Reducing the consumption of free sugars and ensuring the optimal use of fluoride are fundamental pillars of caries prevention in the general population. Policies and interventions that lower sugar intake and promote the optimal delivery of fluoride can decrease the incidence of dental caries and reduce the future need for dental restorations.

- **Early and minimally invasive care.** In addition to prevention, early detection and non-invasive or minimally invasive interventions help preserve tooth structure, prevent disease progression and substantially reduce the need for more complex treatment.

- **Shared decision-making.** Open communication between patients and oral health professionals is essential for shared decision-making and patient-centred care. This includes discussing the advantages and disadvantages of mercury-free dental products and ensuring that patients are fully informed before giving consent.

- **Precautionary principle.** The guideline applies the precautionary principle to ensure that safety and environmental responsibility are prioritized, particularly when scientific evidence is uncertain or incomplete.

4. Recommendations and best practice statements on the use of mercury-free dental products to prevent and manage dental caries

4.1 Recommendations for clinical practice

4.1.1 Clinical interventions to prevent dental caries

RECOMMENDATION 1

WHO recommends the use of fluoride varnish (5% sodium fluoride) applied twice a year, as a population-wide preventive intervention against dental caries in both primary and permanent teeth.

STRONG RECOMMENDATION, MODERATE CERTAINTY OF EVIDENCE

Remarks

- The optimal application frequency of fluoride varnish for caries prevention is twice a year. A biannual application protocol is the most commonly used in studies and is also the application frequency specified by manufacturers.
- Fluoride varnish can be routinely used in the general population, particularly among children and older adults, not only among those at high risk of caries.

Summary of evidence

This recommendation is based on evidence concerning the clinical effectiveness, cost-effectiveness, toxicity and environmental impact of fluoride varnish. The commissioned review identified 10 systematic reviews that addressed its clinical effectiveness and cost-effectiveness which were cited directly. For toxicity and environmental impact, no systematic reviews were available; therefore findings from primary studies were synthesized narratively.

Clinical effectiveness of fluoride varnish
Systematic reviews found that compared with no intervention, fluoride varnish prevents:

- caries in primary teeth (10 studies; preventive fraction 37% after 3 years; 95% confidence interval [CI]: 24–51%; moderate-certainty evidence) (*29*);
- coronal caries in permanent teeth (14 studies; preventive fraction 43% after 3 years; 95% CI: 30–57%; moderate-certainty evidence) (*29*); and
- root caries (one study; mean root caries increment per adult was 0.67 surfaces lower after 2–4 years; 95% CI: –1.22 to –0.12; moderate-certainty evidence) (*30*).

Regarding application frequency, a systematic review found that applying fluoride varnish twice a year was more effective than a single annual application in preventing early childhood caries (one study; mean caries increment per child was 3.57 primary tooth surfaces lower after one year; 95% CI: –7.73 to 0.58; moderate certainty) (*31*). Almost all studies applied fluoride varnish twice a year (*29, 30*).

When compared with other caries-preventive interventions, the evidence was uncertain as to whether fluoride varnish or silver diamine fluoride was more effective in preventing dental caries in primary teeth (low certainty) and in preventing coronal or root caries in permanent teeth (very low certainty) (*32*). It was also uncertain whether fluoride

varnish or fissure sealants (resin-based or glass ionomer based) were more effective in preventing dental caries in permanent teeth (very low certainty) (*33, 34*). No evidence was found comparing fluoride varnish with fissure sealants for preventing dental caries in primary teeth (*35*).

Cost-effectiveness of fluoride varnish
Two systematic reviews reported mixed findings on the cost-effectiveness of targeted preschool or primary school fluoride varnish programmes delivered by oral health professionals or other primary health care workers *(36, 37)*.Another review suggested that fluoride varnish could be cost-effective, particularly when targeted to children at high risk of dental caries (*38*).

When compared with other caries-preventive interventions, evidence suggests that fluoride varnish may achieve similar outcomes to fissure sealants but at lower cost (*33*).

Toxicity of fluoride varnish
A systematic review found no treatment-related adverse events in fluoride varnish clinical trials, although few studies collected information concerning possible adverse effects (*29*). The commissioned review reported that fluoride levels in urine and plasma increase within six hours of application but remain within safe limits (*39, 40*). Reported adverse reactions are rare and generally mild, such as swelling, burning, itching, soreness or rash (*41*). Allergic reactions may occur in individuals sensitive to ingredients such as colophony (*42*). Mild dental fluorosis (mottling of enamel) can result from early, excessive fluoride exposure from multiple sources (*43*).

Environmental impact of fluoride varnish
The commissioned review found that fluoride varnish had a very low carbon footprint, though this is context-dependent and largely influenced by travel and single-use materials. A life cycle assessment (LCA) indicated that the most sustainable approach is to apply fluoride varnish during an existing dental visit, when the child is already in the chair for another appointment. Delivery in schools was the next most sustainable option. By contrast, scheduling separate dental appointments solely for fluoride varnish application resulted in higher environmental impact (*44, 45*).

Evidence-to-decision considerations

The guideline development group (GDG) concluded that there is moderate-certainty evidence that fluoride varnish prevents dental caries in both primary and permanent teeth compared with no intervention. Evidence also supports twice-yearly application. However, certainty was low when comparing fluoride varnish with other preventive interventions such as silver diamine fluoride or fissure sealants. Overall, the balance of benefits versus harms favoured the use of fluoride varnish, particularly among children and older adults.

Fluoride varnish is widely accepted by patients and communities (*46*) and is included in WHO's Model List of Essential Medicines (*18*). It can be used across diverse settings—including urban, rural and remote areas—and among vulnerable populations. Its ease of application and minimal training requirements support equitable access, including for children with special needs and for use in low-resource settings. Low cost and minimal resource requirements make fluoride varnish feasible for large-scale public health programmes. It can also be integrated into existing health and school systems and applied by a range of trained personnel, including community health workers and nurses.

RECOMMENDATION 2

WHO suggests the use of silver diamine fluoride (38% concentration), applied twice a year, as a population-wide preventive intervention against dental caries in both primary and permanent teeth.

CONDITIONAL RECOMMENDATION, LOW CERTAINTY OF EVIDENCE

Remarks

- Evidence on the optimal frequency and concentration of silver diamine fluoride is limited. Most studies, however, have used a biannual application of a 38% concentration, consistent with current manufacturer specifications. Providers should also be aware of contraindications, such as allergies to silver or fluoride.

- Silver diamine fluoride can be used routinely in the general population, particularly among children and older adults, and is not restricted to individuals at high risk of caries.

Summary of evidence

This recommendation draws on evidence about the clinical effectiveness, cost-effectiveness, toxicity and environmental impact of silver diamine fluoride. The commissioned review identified one systematic review addressing clinical effectiveness, which was directly cited. For cost-effectiveness, toxicity and environmental impact, no systematic reviews were available; therefore, findings from primary studies were synthesized narratively.

Clinical effectiveness of silver diamine fluoride
A systematic review found that, compared with no intervention, the effect of silver diamine fluoride in preventing dental caries in primary and permanent teeth is uncertain (very low and low certainty, respectively). However, evidence indicates that it prevents root caries in adults (three studies; mean caries increment was 0.79 surfaces lower after 2–3 years, 95% CI: –1.40 to –0.17, moderate certainty) (*32*). Given the limited evidence available, no conclusions could be drawn about different approaches to applying silver diamine fluoride (e.g. frequency or interval of application, concentration, or duration) (*32*).

When compared with other caries-preventive interventions, it was uncertain whether silver diamine fluoride or fluoride varnish was more effective in preventing dental caries in primary teeth (low certainty evidence) or in preventing coronal or root caries in permanent teeth (very low certainty) (*32*). It was also uncertain whether silver diamine fluoride or resin-based fissure sealants were more effective in preventing dental caries in permanent teeth (very low certainty evidence) (*32*). No evidence was identified comparing silver diamine fluoride with resin-based sealants for preventing dental caries in primary teeth or comparing with glass ionomer sealants for preventing dental caries in either primary or permanent teeth (*32*).

Cost-effectiveness of silver diamine fluoride
The commissioned review found no any primary studies evaluating the cost-effectiveness of silver diamine fluoride for caries prevention.

Toxicity of silver diamine fluoride
No severe adverse events related to the application of silver diamine fluoride have been reported in clinical trials (*32, 47*). Biomonitoring studies showed that urinary fluoride and silver ion concentrations rose in the first few hours after application but returned to baseline within 24 hours. The substantial excretion of these ions in urine indicates minimal systemic absorption (*48–50*). Tooth pain or gingival irritation (for example, white mucosal lesions, gum swelling, or gum bleaching) has rarely been reported, and these effects generally resolve within a few days. Such reactions are usually linked to insufficient compliance with application protocols, for example, spill-over from the treated dental cavity (*51*).

The most common side effect reported is transient black staining of arrested dentine caries lesions (*47*). Application of potassium iodide immediately after silver diamine fluoride can reduce staining; however, it remains uncertain whether potassium iodide use affects the caries-arresting efficacy of silver diamine fluoride (*52*).

Environmental impact of silver diamine fluoride
The commissioned review did not identify any data on the environmental impacts of silver diamine fluoride.

Evidence-to-decision considerations

The GDG noted that most evidence on the clinical effectiveness of silver diamine fluoride for caries prevention was of low certainty. However, the GDG judged that, given the moderate-quality evidence supporting silver diamine fluoride's effectiveness in preventing root caries (*32*), it was reasonable to anticipate similar preventive effects on coronal caries in primary and permanent teeth. The GDG therefore issued a conditional recommendation. Although most evidence is derived from studies involving children and older adults, the GDG considered silver diamine fluoride suitable for use across age groups.

Silver diamine fluoride is generally well accepted by patients and communities (*53*). However, the GDG noted concerns about its limited availability, as it remains inaccessible in many countries. The inclusion of silver diamine fluoride in the WHO Model List of Essential Medicines can help improve its availability worldwide (*18*).

Silver diamine fluoride is well suited for use in diverse settings, including urban, rural and remote communities, as well as among vulnerable populations. Its simple application and minimal training requirements help promote equitable access, making it particularly beneficial for children with special needs and for populations in low-resource settings. Its low cost and minimal resource needs make it a practical option for public health programmes. Silver diamine fluoride can be readily integrated into existing health and school systems and administered by trained personnel, including community health workers and nurses.

RECOMMENDATION 3

WHO recommends the use of pit and fissure sealants as an intervention to prevent dental caries in the first permanent molars of children at high risk of caries.

STRONG RECOMMENDATION, MODERATE CERTAINTY OF EVIDENCE

Remarks

- Both glass ionomer sealants and resin-based sealants for pits and fissures are most effective when targeted to children at high risk of dental caries.

- Identifying children at high risk of caries requires oral health professionals to assess the most relevant combination of social, behavioural, medical and clinical factors that increase the likelihood of developing dental caries within a defined period.

Summary of evidence

This recommendation draws on evidence about the clinical effectiveness, cost-effectiveness, toxicity and environmental impact of fissure sealants (glass ionomer-based and resin-based). The commissioned review identified seven systematic reviews addressing clinical effectiveness, which were directly cited. However, for cost-effectiveness, toxicity and environmental impact, no existing reviews were available; therefore, findings from primary studies were synthesized narratively.

This section summarizes evidence on the clinical effectiveness and cost-effectiveness of fissure sealants. Evidence on their toxicity and environmental impact is summarized under recommendation 6 in section 4.1.3.

Clinical effectiveness of fissure sealants

A systematic review found that resin-based sealants prevent caries in permanent first molars compared with no intervention (seven studies). The odds of incident caries in first molars were 88% lower after two years (95% CI: 81–92%; moderate certainty) (*54*). However, it is uncertain whether resin-based sealants prevent caries in primary molars (*55*).

For glass ionomer sealants, several systematic reviews found the evidence for caries prevention in any dentition to be uncertain (low certainty) (*54–56*). It was also uncertain whether glass ionomer sealants or resin-based sealants were more effective in preventing caries in primary molars (low certainty) (*57*) or in permanent molars (very low certainty) (*54*). Similarly, the evidence was uncertain as to whether auto-polymerized (self-cured) or light-polymerized (light-cured) resin-based sealants were more effective in preventing caries in primary teeth (low certainty) or permanent teeth (no evidence) (*57*).

Compared with other caries-preventive interventions, the evidence was uncertain as to whether fissure sealants (resin-based or glass ionomer based) or fluoride varnish were more effective in preventing dental caries in permanent teeth (very low certainty) (*33, 34*). No evidence was found comparing fissure sealants versus fluoride varnish to prevent dental caries in primary teeth or root caries.

Similarly, the evidence was uncertain as to whether resin-based sealants or silver diamine fluoride were more effective in preventing dental caries in permanent teeth (very low certainty) (*32*). No evidence was found comparing resin-based sealants with silver diamine fluoride for prevention of caries in primary teeth, or comparing glass ionomer sealants with silver diamine fluoride for the prevention of caries in either primary or permanent teeth (*32*).

Cost-effectiveness of fissure sealants
The commissioned review found inconsistent results for the cost-effectiveness of targeted school-based fissure sealant programmes, even when comparing sealant application based on caries risk with no intervention (*36*). Evidence also suggests that fissure sealants may achieve similar outcomes to fluoride varnish, but at higher cost (*33*).

Evidence-to-decision considerations

The GDG observed moderate-certainty evidence supporting the preventive effect of fissure sealants, specifically for first permanent molars in children. However, evidence comparing different types of sealants, as well as their effectiveness relative to other caries-preventive interventions, was of low certainty.

Fissure sealants are generally well accepted by patients and communities (*45, 58*), and they are now included in the WHO Model List of Essential Medicines (*18*). The GDG also noted that fluoride varnish may achieve similar outcomes to fissure sealants but at lower cost (*33*), likely because:

- fluoride varnish can prevent caries on multiple tooth surfaces (not only occlusal) with a single application; and
- it can be applied outside traditional clinic settings, such as schools or community programmes, and can be administered by mid-level oral health professionals and other primary health care workers (*59*).

The cost-effectiveness of fissure sealants may depend on several factors, including the type of sealant (resin-based versus glass ionomer-based), the delivery setting (school versus clinic), programme coverage (whole population versus targeted population) and the method used to identify children at high risk of caries (*60*). The GDG therefore considered fissure sealants to be most useful among children at higher risk of caries.

4.1.2 Clinical interventions to manage dental caries: nonrestorative treatments

RECOMMENDATION 4

WHO recommends the use of fluoride varnish (5% sodium fluoride), as a non-invasive treatment option for managing initial (non-cavitated) carious lesions in primary and permanent teeth.

STRONG RECOMMENDATION, MODERATE CERTAINTY OF EVIDENCE

Remarks

Evidence regarding the optimal frequency of fluoride varnish application as a non-invasive approach for managing non-cavitated carious lesions is limited. Recall intervals may need to be tailored to individual patient risk factors, typically ranging from 3 to 6 months.

Summary of evidence

This recommendation was informed by evidence on the clinical effectiveness, cost-effectiveness, toxicity and environmental impact of fluoride varnish. This section summarizes evidence on the clinical effectiveness and cost-effectiveness of fluoride varnish for the management of non-cavitated carious lesions. Evidence on its toxicity and environmental impact is presented in section 4.1.1.

Clinical effectiveness of fluoride varnish
A network meta-analysis (*61*) showed that fluoride varnish was effective in reversing non-cavitated carious lesions on coronal surfaces compared with no intervention. In one study, the incidence of caries reversal was 2.15 times higher after 9 to 12 months (95% CI: 1.80–2.57; moderate certainty). Effectiveness was particularly evident on occlusal surfaces: one study reported a 1.97-fold higher incidence of reversal after 8 to 12 months (95% CI: 1.63–2.40; moderate certainty).

Evidence was weaker for proximal (very low certainty) and facial or lingual surfaces (low certainty). The effectiveness of fluoride varnish for non-cavitated or cavitated root caries in permanent teeth remains uncertain (very low certainty) (*61*). The optimal frequency of fluoride varnish application for reversing non-cavitated carious lesions is also uncertain, although studies have used intervals of 3 to 6 months (*61*).

Compared to other interventions, it is uncertain whether fluoride varnish or silver diamine fluoride is more effective for arresting cavitated caries in primary teeth (low certainty) or cavitated caries in permanent teeth (very low certainty) (*32, 61*).

Cost-effectiveness of fluoride varnish
The commissioned review for this guideline found no data on the cost-effectiveness of fluoride varnish as a nonrestorative treatment for dental caries.

Evidence-to-decision considerations

The GDG acknowledged the moderate-certainty evidence supporting the effectiveness of fluoride varnish for the management of non-cavitated carious lesions. They noted that the evidence is particularly robust for occlusal surfaces, while data for other tooth surfaces are less conclusive. The GDG also highlighted practical considerations, such as the potential need for more frequent follow-up appointments to monitor progress and reapply the varnish, given that the optimal application frequency remains uncertain. This requirement for regular recall visits may pose challenges for certain populations, especially those residing in remote or geographically dispersed areas, where access to oral health care is limited.

As a result, the GDG concluded that fluoride varnish, as a nonrestorative treatment, is better suited for clinical settings where consistent follow-up can be reliably maintained, rather than as a primary intervention in large-scale public health programs. They stressed the critical importance of clear and open communication with patients and caregivers regarding the benefits, limitations, and ongoing care requirements of this approach. However, in settings where access barriers are minimal and follow-up is assured, fluoride varnish is a viable option for the nonrestorative management of non-cavitated carious lesions.

RECOMMENDATION 5

WHO recommends the use of silver diamine fluoride (38% concentration), applied twice a year, as a non-invasive treatment option for managing cavitated carious lesions without pulp involvement in primary teeth and cavitated carious lesions without pulp involvement on the root surfaces of permanent teeth.

STRONG RECOMMENDATION, MODERATE CERTAINTY OF EVIDENCE

Remarks

- Evidence on the optimal frequency and concentration of silver diamine fluoride application is limited. Most studies, however, have used a biannual application protocol with 38% silver diamine fluoride.

- Oral health care professionals should carefully select cases, excluding teeth with signs of pulpal inflammation, periapical pathology or reported spontaneous pain. They should also be aware of contraindications, including allergies to silver or fluoride.

Summary of evidence

These recommendations are informed by evidence regarding the clinical effectiveness, cost-effectiveness, toxicity and environmental impact of silver diamine fluoride. This section summarizes the clinical and cost-effectiveness evidence for the management of cavitated carious lesions. Evidence on the toxicity and environmental impact of silver diamine fluoride is summarized in section 4.1.1.

Clinical effectiveness of silver diamine fluoride
A systematic review published in 2024 found uncertainty about whether silver diamine fluoride arrests cavitated caries in primary teeth (two studies; mean number of arrested surfaces 0.86 higher; 95% CI: 0.39–1.33; low certainty) or cavitated coronal caries in permanent teeth (one study; mean number of arrested surfaces was 0.20 higher; 95% CI: 0.00–0.40; very low certainty) compared with no intervention (*32*). Its effect on arresting or reversing root caries is also very uncertain (one study, mean number of arrested surfaces 0.24 higher; 95% CI: 0.12–0.36; very low certainty) (*32*).

The commissioned review for this guideline found moderate certainty of evidence showing that silver diamine fluoride had a favourable effect on arresting dental caries in primary teeth (one study; probability of arrested carious lesions was 24 times higher after 14–21 days; log risk ratio = 3.18; 95% CI: 1.24–5.13; Web Annex B, Table 2.3) and on arresting root caries in permanent teeth (two studies; probability of arrested carious lesions two times higher after 2.5 years; log risk ratio = 0.71; 95% CI: 0.36–1.06; Web Annex B, Table 2.3). No evidence of caries arrest in permanent teeth was identified.

Evidence was initially rated as high, given reliance on data from randomized controlled trials, but was downgraded to moderate owing to risk of bias in some studies. These results should be treated with caution given the small number of studies.

The commissioned review also found low certainty evidence indicating that higher concentrations (38% versus 12%) and more frequent applications (twice or four times a year versus once a year) of silver diamine fluoride were more effective in arresting carious lesions (Web Annex B, Table 2.1).

It is uncertain whether silver diamine fluoride or fluoride varnish is more effective in arresting cavitated caries in primary teeth (low certainty) or cavitated caries or permanent teeth (very low certainty) (*32, 61*). The commissioned review also found low certainty evidence when comparing the effectiveness of silver diamine fluoride and fluoride varnish for caries arrest (Web Annex B, Table 2.2).

Cost-effectiveness of silver diamine fluoride
The commissioned review found evidence from simulation studies suggesting that silver diamine fluoride may be cost-effective for managing dental caries in young children (*62*), in children (*63*) and for root caries in older adults (*64*), particularly in resource-limited settings. Studies highlighted its simplicity, low cost and ability to reduce the need for more invasive treatments (*65*).

In addition, the application of 38% silver diamine fluoride twice a year has been included in the forthcoming WHO menu of cost-effective interventions for oral health for the prevention and management of dental caries. A recent model-based economic evaluation showed that silver diamine fluoride was cost-effective in most situations, except for caries control in children with low caries activity (*66*).

Evidence-to-decision considerations

The GDG acknowledged that the overall certainty of evidence on the clinical effectiveness of silver diamine fluoride was low and moderate, as reflected in the existing commissioned systematic review (low certainty) and in the newly commissioned review (moderate certainty). Both reviews indicated that the quality of evidence was relatively stronger in specific contexts, namely for arresting dental caries in primary teeth and for managing root caries lesions in older adults.

The GDG considered this gradient in evidence certainty when formulating the recommendation. Although the certainty of evidence was low to moderate, the GDG agreed on a strong

recommendation because the balance of benefits and harms, as well as equity considerations, feasibility and acceptability, clearly favoured the use of silver diamine fluoride.

The GDG concluded that the potential harms of not intervening, such as increased risk of caries progression and the need for more complex treatment, far outweigh the uncertain risks associated with silver diamine fluoride. By arresting dental caries lesions early and preventing further deterioration, silver diamine fluoride can reduce the need for invasive procedures and extensive restorative care, thereby optimizing the use of health resources.

In addition, silver diamine fluoride is likely to offer significant equity gains, particularly in resource-limited settings where the burden of dental caries is high. It may be especially beneficial in community health settings and for individuals with limited access to oral health care services, such as those in rural, remote or in socioeconomically disadvantaged populations. Silver diamine fluoride can be applied by health workers after appropriate training, thereby increasing access to care.

Silver diamine fluoride is feasible to implement in most settings. Its application does not require removal of sound tooth tissue, drilling or anaesthesia, making it minimally invasive and suitable for patients who may not tolerate conventional dental procedures. Its simplicity and speed of application make it particularly useful for young children, older adults and people with behavioural or medical management challenges. The GDG judged that its practical advantages and potential to improve access to care present a compelling case for its use, especially when conventional treatments are not feasible or available.

Silver diamine fluoride can stain carious lesions after application, which may be a concern, particularly for visible front teeth. This could reduce its acceptability among patients and clinical teams. However, silver diamine fluoride is generally well accepted among patients (*53*) and concerns about the staining of carious lesions and oral mucosa do not appear to affect quality of life (*51*).

The GDG emphasized the importance of patient-centred care and shared decision-making. Patients should be informed about the potential for black staining of treated lesions with silver diamine fluoride, and informed consent should be obtained before its application. Oral health professionals should follow a standardized application protocol, including isolation, plaque removal and protection of surrounding tissues (*67, 68*).

4.1.3 Clinical interventions to manage dental caries: restorative treatments

RECOMMENDATION 6

WHO suggests the use of glass ionomer cements and resin-based composites as direct restorative materials for the treatment of dental caries.

CONDITIONAL RECOMMENDATION, LOW CERTAINTY EVIDENCE

Remarks

- The choice of restorative material should be based on a detailed assessment of dental, oral and patient-related factors.
- Compomers were included in the evidence synthesis for these recommendations, but evidence on their clinical effectiveness was limited.
- Alkasites, a relatively new subcategory of resin-based composites, were also included in the evidence synthesis, however, no studies have directly evaluated the clinical effectiveness of this material.

Summary of evidence

This recommendation is based on evidence regarding the clinical effectiveness, cost-effectiveness, toxicity and environmental impact of glass ionomer cements, resin-based composites and compomers. The commissioned review identified four systematic reviews on the clinical effectiveness of these mercury-free dental products, which were cited.

For cost-effectiveness and environmental impact, no relevant reviews were available: therefore, findings from primary studies were synthesized narratively. In the case of toxicity, existing reviews did not address all required outcomes, so additional findings from primary studies were also synthesized narratively.

Clinical effectiveness of glass ionomer cements, resin-based composites and compomers

For anterior permanent teeth, a systematic review reported that the median success rate of resin-based composites was 95% after 10 years for Class III restorations and 90% for Class IV restorations (low certainty). In addition, hybrid composites performed better than microfilled composites and glass ionomer cements (low certainty) (*69*).

For posterior permanent teeth, a systematic review found that the mean survival rate of resin-based composites was 95–97% after four years, decreasing to 85–90% after 10 years, with no differences between hybrid, microhybrid and nanohybrid composites (low certainty) (*70*). Another systematic review found that bulk-fill composites performed as well as incrementally placed resin-based composites for at least five years (very low certainty) (*71*). No evidence was available on the long-term effectiveness of bulk-fill composites (*71*).

A further systematic review reported that the longevity of compomers and glass ionomer cements was inferior to that of resin-based composites. The mean survival rate was 87% after four years for both compomers and glass ionomer cements, and 80% after six years for glass ionomer cements (very low certainty) (*70*).

Another systematic review compared absolute risk differences in restoration failure, secondary caries and restoration loss between different mercury-free dental products used as direct restorations, according to dentition and restoration class (*72*).

In primary teeth, it was uncertain whether using conventional glass ionomer cements for Class I restorations was more effective than macrofilled resin-based composites or compomers (low certainty evidence). No evidence was found for other mercury-free dental products.

For Class II restorations, conventional glass ionomer cements were less effective than hybrid resin-modified glass ionomer cements (two studies; absolute risk of restoration loss 9% higher in the glass ionomer cement group; 95% CI: 2–16% after 12–24 months; moderate certainty) and hybrid resin-based composites (one study; absolute risk of restoration loss 14% higher in the glass ionomer cement group; 95% CI: 3–25% after 36 months; moderate certainty). Beyond this, it was uncertain whether glass ionomer cements were more effective than compomers, hybrid resin-based composites, macrofilled resin-based composites or nanofilled resin-based composites (low certainty).

It was also very uncertain whether resin-modified glass ionomer cements or hybrid resin-based composites were more effective for Class II restorations in primary teeth (*72*). Of note, macrofilled resin-based composites are no longer used in clinical practice.

In permanent teeth, it was uncertain whether conventional glass ionomer cements, hybrid resin-based composites, resin-modified glass ionomer cements, nanofilled resin-based composites or compomers was more effective for Class I restorations (low certainty).

For Class II restorations, it was uncertain whether conventional glass ionomer cements, resin-modified glass ionomer cements or hybrid resin-based composites were more effective (low certainty). No evidence was available comparing other mercury-free dental products.

When considering Class I and II restorations together, it was uncertain whether hybrid resin-based composites were more effective than macrofilled resin-based composites (very low certainty) or whether resin-modified glass ionomer cements were more effective than conventional glass ionomer cements (low certainty). No evidence was found comparing other mercury-free dental products.

For Class V restorations, it was very uncertain whether glass ionomer cements or hybrid resin-based composites were more effective (very low certainty). It was also uncertain which of resin-modified glass ionomer cements, hybrid resin-based composites or conventional glass ionomer cements was more effective for root surface restorations (*72*).

Cost-effectiveness of glass ionomer cements, resin-based composites and compomers

The commissioned review identified modelling studies indicating that glass ionomer cements had lower upfront costs. However, these savings were sometimes offset by their lower longevity. Similarly, the initial savings from bulk-fill resin-based composites and glass ionomer cements compared with incrementally placed resin-based composites are likely to be outweighed by their lower longevity and the associated costs of retreatment (*73*).

In addition, both glass ionomer cements and resin-based composites can be repaired, which can increase the longevity of the restoration and the tooth, and potentially reduce costs (*74*). Repairing partially defective restorations, rather than replacing them, is also likely to preserve teeth longer than full replacement. Evidence indicates that repairing resin-based composite restorations is a cost-effective method (*75*).

Toxicity of glass ionomer cements, resin-based composites and compomers

For glass ionomer cements, evidence from clinical trials is limited, as none have specifically measured adverse events (*55, 76*). Although intraoral fluoride release from glass ionomer cements has been well-studied (*77*), clinical studies have not monitored possible systemic exposure to other constituents (e.g. aluminium, polyacrylic acid) through biological sample analysis.

Glass ionomer cements may cause mild, localized side effects such as pulp irritation (particularly in deep cavities with little remaining dentine due to acidic setting reactions) and transient postoperative sensitivity. Allergic reactions are very rare but have been reported, mainly with resin-modified glass ionomer cements containing methacrylates (*11, 12*).

The potential toxicity of resin-based composites is associated with the release of unreacted monomers or polymer degradation over time, which can release leachable components (*78, 79*). The monomer systems of most current resin-based composites contain bisphenol-A-glycidyl methacrylate (Bis-GMA) or derivatives (Bis-DMA, Bis-EMA, BADGE, PBPA).

Bisphenol A (BPA) is recognized by the European Chemicals Agency as a substance of very high concern because of its endocrine-disrupting and reproductive toxic properties (*80*). Although BPA is not directly used in the production of resin-based composites, it is used in the synthesis of monomers commonly found in these materials, such as Bis-GMA, Bis-EMA, Bis-DMA, and BADGE. Residual BPA from the synthesis process may remain as a contaminant in resin-based products, including resin-based composites, resin-based fissure sealants and resin-modified glass ionomer cements.

Trace levels of residual BPA may also leach from freshly polymerized resin-based composites (sealants and restorations) and from degradation of the polymer matrix over time (*81-85*).

The monomers in resin-based composites, whether BPA derivatives or non-BPA derivatives, can cause rare adverse events among oral health professionals and patients. Reported allergic reactions can range from contact dermatitis and conjunctivitis to burning mouth syndrome and persistent oral lesions (*79, 86*). Respiratory conditions, including nasal irritation, cough, asthma, dyspnoea and chronic bronchitis, have also been reported, particularly among those handling methacrylate-based materials on a daily basis (*86*).

Extended patch testing has revealed delayed allergic responses, especially to monomers in resin-based composites. The risk increases with prolonged exposure, suggesting a dose–response relationship. Atopic individuals appear to be more vulnerable to respiratory and dermatological effects (*79, 86*).

In addition to the monomers present in resin-based composites, micro- and nanoparticles are generated during the grinding, polishing or removal of restorations (*87*). There are growing concerns on the health harms of micro- and nanoparticles, particularly plastic particles (*88, 89*). In oral health care settings, micro- and nanoparticles can enter the body through inhalation or ingestion.

Risk assessment based on worst-case mass calculations indicates that the additional risk of exposure to nanoparticles for patients and oral health professionals is low (*90*). However, there are few studies on the long-term health effects of nanoparticles. Research is ongoing to understand the body's ability to eliminate nanoparticles and prevent their accumulation in tissues (*91*). The available evidence is limited, particularly on the effects of nanoparticles in dental materials on vulnerable patient groups, such as people with asthma or chronic obstructive pulmonary disease (*90*).

Environmental impact of glass ionomer cements, resin-based composites and compomers

Life cycle assessments have shown that glass ionomer cements are more sustainable than resin-based composites, as indicated by their lower carbon footprint from the extraction of natural resources to the factory gate (before distribution to the customer) (*92*) and from procurement to use on patients (*93*).

One consideration is that glass ionomer cements have lower durability and may require more frequent replacement. This could partially offset their environmental advantages if improvements in material longevity are not achieved.

The potential environmental pollution caused by resin-based composites reflects the life cycle of these mercury-free dental products. Resin-based composites are produced industrially, and the waste from the manufacturing process is typically sent to landfill. Landfill leachate can react with resin-based composites, allowing the release of their components, including BPA. However, the evidence for this release pathway is not clear (*94*).

The release of chemicals into the environment can also occur during clinical application (*95*). This includes the constituent monomers and micro- and nanoparticles from resin-based composites (*96*). When these products are polished after light curing or removed from teeth, micro- and nanoparticles are released into wastewater (*97*). Leached monomers are also released into wastewater and sewage via human excreta after dental procedures involving resin-based composites (*96*). These waste products eventually reach the natural environment. Studies have shown harmful effects of wastewater streams from dental practices on marine life (*98*).

Expired resin-based composites from oral health services, together with unused excess material in discarded capsules and syringes, are managed differently across countries. There are no institutional guidelines on this matter, and it remains unclear how countries are handling this type of waste.

Uncontrolled disposal of hazardous waste carries a greater risk for environmental harm.

Incineration of resin-based composites results in the release of significantly lower concentrations of monomers, elements and ions than landfill disposal (*94*). Degradation products are also likely to be released into the air and groundwater following cremation or burial of cadavers with resin-based composite restorations (*96*).

Evidence-to-decision considerations

The GDG noted that mercury-free direct restorative materials have improved over time in terms of biocompatibility, durability, tooth colour matching and ease of handling. However, no single material is suitable for all clinical situations. It is therefore necessary to have a range of materials, with different options indicated in different circumstances.

Both glass ionomer cements and resin-based composites are now included in the WHO Model List of Essential Medicines for use as fissure sealants or restorations (*18*). Despite numerous reviews on the clinical performance of mercury-free restorative materials, the GDG noted that the overall quality of evidence remains low, supporting a conditional recommendation only.

The selection of restorative materials requires a comprehensive evaluation of dental, oral and patient-related factors. Dental factors include the type of tooth, cavity classification and extent of restoration required. Oral factors involve patients' caries risk and related risk factors. Patient-related factors include systemic conditions and likely adherence to post-treatment care instructions (*99*).

It is therefore essential that the choice of dental material is based on shared decision-making between oral health professionals and patients, as well as on local guidelines and protocols. The availability of direct restorative materials should also be considered, particularly in resource-limited settings.

Dental restorative materials are classified as medical devices and, like medicines, are intended to alleviate, prevent or cure health conditions. Consequently, some risk of adverse effects is inherent and should be considered acceptable. However, unlike medicines, the full composition of dental restorative materials is not always disclosed, which warrants a slightly lower tolerance for risk than that accepted for pharmaceuticals.

Resin-based composites more closely match the natural colour of teeth and offer greater durability than glass ionomer cements. However, they are technique-sensitive, require additional equipment, and involve longer application times.

Glass ionomer cements, by contrast, release fluoride (reducing caries risk) and are less sensitive to moisture conditions (*100*). However, they are more prone to fracture in high load-bearing areas (posterior teeth) and wear down faster over time than resin-based composites.

Glass ionomer cements may therefore be suitable for non-load-bearing restorations and for children and older adults, while resin-based composites might be preferred when tooth-coloured appearance and high mechanical properties are critical, provided that meticulous technique is applied.

Resin-based composites require qualified staff, such as dentists or dental therapists, working with a fully equipped dental clinic. This involves considerable financial investment and a long lead time. In addition, they often require light-curing units for polymerization, which depend on electricity either directly or indirectly.

Conventional glass ionomer cements may offer cost savings, as they can be placed by trained non-oral health professionals after removal of decayed tooth tissue with hand instruments. However, resin-modified glass ionomer cements also require a light-curing unit. Because conventional glass ionomer cements do not require fixed facilities or electricity, they make restorative care accessible to many people who might otherwise lack access.

The GDG also discussed the potential value of the sandwich restoration technique, in which glass ionomer cement is used to replace lost dentine, followed by placement of resin-based composite to replace lost enamel (*101*). The technique can reduce material costs, shrinkage stress and increase the marginal seal.

However, disadvantages include that the procedure is more time-consuming than single-material restorations, and its success depends on appropriate material handling and placement (*102, 103*).

Clinical evidence on the longevity of direct restorations in vulnerable groups is limited. For individuals who are unable to cooperate during dental procedures or maintain adequate oral hygiene, treatments that require longer clinical time and strict moisture control may be difficult to implement.

Glass ionomer cements are simpler and quicker to apply than other restorative materials, as they do not require extensive tooth preparation, specialized equipment or strict moisture control. This makes them particularly suitable for patients who may have difficulty cooperating during dental procedures.

Glass ionomer cements are generally considered less technique-sensitive than resin-based composites (*104*). However, they still require proper handling for optimal results. Fluoride release from glass ionomer cements can prevent new dental caries more effectively than other mercury-free dental products for direct restoration of carious lesions (*105, 106*). However, whether this preventive effect provides additional clinical benefit beyond that achieved through the regular use of topical fluoride, such as fluoride-containing toothpastes, remains uncertain given the widespread availability of these fluoride sources.

The safety profile of glass ionomer cements and lower need for complex procedures make them a preferred option for children and older adults, as they minimize stress and reduce exposure to potentially harmful substances during oral health care. This recommendation may also apply to individuals with high caries risk, behavioural or medical complexities, multiple cavitated carious lesions or limited access to oral health care.

4.2 Recommendations and best-practice statements for risk mitigation among clinical teams and patients

4.2.1 Oral health care for vulnerable populations

RECOMMENDATION 7

WHO suggests limiting the use of resin-based fissure sealants and composites containing bisphenol A (BPA) derivatives in children, adolescents, pregnant or breastfeeding women, as these groups are more susceptible to potential endocrine effects.

CONDITIONAL RECOMMENDATION, VERY LOW CERTAINTY EVIDENCE

Remarks

- Clinical teams may consider other mercury-free dental products, such as silver diamine fluoride, glass ionomer cements or resin-based fissure sealants and composites without BPA derivatives, as suitable alternatives for these patients.
- Dental amalgam should not be considered an alternative.

Summary of evidence

This recommendation is based on evidence concerning the health effects (toxicity) of resin-based composites, which was presented under recommendation 6 in section 4.1.3. This section summarizes evidence from published reviews on the release of BPA from resin-based composites containing BPA derivatives.

BPA-derived monomers are released into the oral environment after placement of resin-based composite restorations (*82, 83*). They may also be present in adhesive systems, resin-modified glass ionomer cements and resin-based sealants, which are commonly used in young children, who are particularly susceptible to BPA exposure (*84*).

BPA is primarily released from resin-based composites due to degradation of the polymer matrix over time or the presence of BPA as a trace contaminant from the synthesis of BPA-derived monomers (*84*). Biomonitoring studies have consistently confirmed transient increases in BPA concentrations in saliva and other body fluids, such as urine, after the application of resin-based composites (sealants and restorations). However, BPA levels typically return to baseline within a few days (*81–84*).

There is a lack of studies investigating the association between BPA exposure from resin-based composites and adverse effects on human health (*82*). Establishing such a link is difficult because of confounding factors, such as dietary BPA, which is the main source of human exposure in some age groups.

The amount of BPA released from resin-based composites is much lower than that from average daily dietary intake in the general population, making it difficult to detect any additional effect. However, potential risks cannot be completely ruled out (*84*).

The overall certainty of the evidence on the leaching of BPA from resin-based composites was rated as very low. This rating reflected several factors: most of the included studies were non-randomized, introducing a high risk of bias; there was considerable heterogeneity in study designs and outcomes, reducing consistency; and the evidence was indirect, as no studies directly assessed health effects.

Evidence-to-decision considerations

BPA can harm human health because it disrupts the endocrine system and alters hormone function. It may also have harmful effects on the reproductive and immune systems (*107, 108*). Most human exposure to BPA occurs through diet, as it is present in a range of materials commonly used in food and beverage packaging (*109, 110*). BPA has been detected in urine samples of children and adults in multinational surveys across Europe (*111, 112*).

It remains a subject of debate whether a threshold dose exists below which exposure to endocrine disruptors poses no risk (*113-115*). Even exposure to very small doses can alter hormonal responses. This is a particularly important consideration for patients at vulnerable stages, notably the perinatal period (from preconception to the child's second birthday), including breastfeeding, infancy and adolescence (*113, 116*).

The endocrine system is considered fully developed at the end of puberty, generally between the ages of 18 and 20 years as hormone levels stabilize and most endocrine glands reach their mature function. Significant changes occur during the large perinatal period and adolescence, owing to the onset of sex hormone production (*117*).

About one third of resin-based composites available on the market in 2023 contained no BPA-derivative monomers (e.g. HEMA, TEGDMA, UDMA) (*118*). The United States Environmental Protection Agency (EPA) and the Food and Drug Administration (FDA) have established an acceptable daily intake of 50 µg/kg of body weight (*119*). By contrast, the European Food Safety Authority (EFSA) has recently lowered the tolerable daily intake (TDI) from 4 µg/kg to 0.2 ng/kg of body weight (*120, 121*). The revised TDI has faced some criticism (*122, 123*).

Although BPA exposure from resin-based composites appears to be low, the long-term health implications remain unclear. This is important as international agencies implement increasingly strict controls on products containing BPA because of continuing concerns about its potential health effects.

Given this evidence, the GDG considered it advisable to exercise caution in the use of resin-based composites, whether as sealants or restorations, in groups at high risk of endocrine dysfunction. The GDG also noted that this recommendation is important to raise awareness among oral health professionals and patients about the potential risks associated with BPA in resin-based composites.

RECOMMENDATION 8

WHO suggests exercising caution when using resin-based composites, including fissure sealants and restorations, in individuals with allergic conditions, as the monomers present in these products may cause sensitization.

CONDITIONAL RECOMMENDATION, LOW-CERTAINTY EVIDENCE

Remarks

- Given the potential sensitizing effects of monomers, individuals with allergic conditions should preferably receive alternative mercury-free dental products to resin-based composites, such as conventional glass ionomer cements, when clinically feasible.

- Dental amalgam should not be considered an alternative.

Summary of evidence

This recommendation is based on evidence regarding the health effects (toxicity) of resin-based composites and compomers, as presented under recommendation 6 in section 4.1.3. This section summarizes evidence from published reviews on allergic reactions to resin-based composites.

Resin-based dental composites can cause allergic reactions in both oral health professionals and patients, but the risk is higher for professionals because they handle the uncured material, which contains more reactive components. In patients, the material is usually in a cured state, reducing the risk of sensitization (*79, 86*). The methacrylate groups present in the monomers of resin-based composites, sealants and resin-modified glass ionomer cements are well-known sensitizers, as confirmed by positive patch tests. Exposure can lead to contact dermatitis, irritation of the oral mucosa, and allergic stomatitis. Respiratory conditions, including nasal irritation, cough, asthma, dyspnoea and chronic bronchitis, have also been reported, particularly among those handling methacrylate-based materials daily (*86*).

Patients who develop allergic contact dermatitis from these monomers often react to several different methacrylate-based monomers during patch testing, even if they have not been exposed to all of them. This suggests that methacrylate-based monomers can cross-react, meaning that sensitization to one acrylic compound can result in allergic responses to others. As a result, individuals who are sensitized are often allergic to multiple related compounds and should avoid exposure to any acrylic monomers (*79*).

Most of the evidence in this area comes from observational studies, including post-marketing surveillance and questionnaire surveys among oral health professionals and patients. The certainty of the evidence was therefore rated as low.

Evidence-to-decision considerations

Elution of the constituent monomers of resin-based composites, sealants and resin-modified glass ionomer cements occurs through diffusion of unpolymerized monomers out of the material. This is of particular concern for individuals with a predisposition to respond immunologically to diverse antigens or allergens.

The GDG recognized that, although the certainty of the available evidence is low, there remains a potential, albeit small, risk of adverse reactions in certain individuals, particularly those with known hypersensitivity or a history of allergic conditions. The recommendation could raise awareness among oral health professionals and patients, potentially reducing the incidence of adverse reactions and associated health care costs.

The GDG emphasized the importance of proactive risk management strategies to safeguard these vulnerable populations. A key aspect of such risk management is the thorough collection of patient history. Oral health care professionals should consistently inquire about previous allergic reactions or sensitivities during clinical assessment. This enables the early identification of individuals who may be at higher risk of sensitization or allergic responses to specific mercury-free dental products. By integrating detailed history-taking into routine practice, oral health professionals can make more informed decisions regarding product use, tailor recommendations to individual patient risk profiles, and reduce the likelihood of adverse outcomes (*124, 125*).

Implementing this recommendation is feasible in most settings, as it primarily requires oral health care professionals' awareness and patient history-taking. However, access to alternative mercury-free restorative materials may vary by setting. It is also important to inform patients about the potential dental consequences of replacing restorations (to remove the cause of the allergic reaction) when discussing treatment options.

4.2.2 Safe handling and application of resin-based composites

BEST PRACTICE STATEMENT 1

Follow occupational safety protocols for the proper handling of resin-based composites to reduce risks for oral health care professionals and patients.

Remarks

- Good ventilation and high-volume suction, together with the use of personal protective equipment (including blue light–attenuating eye protection) and the no-touch technique, can reduce exposure to unpolymerized monomers and other potentially harmful substances released during the handling of mercury-free dental products.

Summary of evidence

This best-practice statement is based on indirect evidence concerning the toxicity, biocompatibility, release of chemical components and health effects on patients and oral health professionals of glass ionomer cements, resin-based composites and compomers, as well as current occupational safety protocols for handling mercury-free dental products. Evidence on the toxicity of these mercury-free dental restorative materials was summarized for recommendation 6 in section 4.1.3. This section summarizes evidence on current occupational safety protocols, which was not suitable for GRADE assessment.

Oral health care facilities with improved ventilation, dental units with water coolants and high-volume suction can reduce the risks of exposure to potentially harmful aerosols and chemical substances for both patients and clinical teams (*126*).

Because of regular exposure to resin-based composites, oral health professionals are considered a risk group. They are advised to use resin-based composites only with adequate protective measures to minimize exposure. Personal protective equipment includes allergen-free gloves, FFP3 masks and blue light-attenuating eye protection (*11, 126*).

Unpolymerized monomers from resin-based composites can penetrate conventional latex or vinyl gloves. For this reason, oral health professionals should avoid any contact with resin-based composites and adhesives, even when wearing gloves. The no-touch technique consists of manipulating resin-based composites using clean, uncontaminated instruments to place and shape the material (*90*). This approach minimizes exposure to unbound monomers and potential allergens, which can diffuse through standard latex gloves and cause allergic reactions such as contact dermatitis among dental personnel.

Resin-based composites require curing, and the light sources used for this purpose may pose an additional risk of adverse effects for both patients and oral health professionals. The risk is low for patients and moderate for oral health care professionals, but the use of appropriate blue light-attenuating eye protection can eliminate the risk (*11*).

Evidence-to-decision considerations

The GDG noted that most of the evidence in this area was indirect and not suitable for GRADE assessment. They therefore agreed that this statement would be more appropriately classified as a best-practice statement rather than a recommendation. The GDG also considered the statement necessary to help minimize potential occupational exposure among oral health professionals while addressing the possible, albeit low, risks to patients.

The GDG noted that mercury-free dental products are chemically complex. They contain a variety of organic substances that can undergo chemical reactions in the dental cavity and adjacent soft tissues during insertion, releasing newly formed compounds (*87*). It should not be assumed that mercury-free dental products cannot cause adverse effects simply because they are available in the market or have some form of certification (*11*). Furthermore, the composition of mercury-free dental products continues to evolve as new formulations are introduced.

Regarding available evidence on health effects, the GDG observed that assessment of mercury-free dental products for biocompatibility has relied heavily on *in vitro* testing. These tests measure outcomes such as reduced cell viability or altered cell morphology following exposure to mercury-free dental products or their chemical components. While such studies indicate possible biological effects, their applicability to real-world clinical scenarios remains uncertain (*78*). Most *in vitro* endpoint assays provide limited insight into actual patient risks.

More direct evidence on the health effects of mercury-free dental products comes from clinical trials (reporting adverse events), biomonitoring studies (measuring chemical exposure levels in human tissues or fluids after dental procedures) and post-marketing surveillance (reporting harmful effects after the dental product has reached the market). In all these studies, an adverse event is recorded where there is a reasonable possibility that it was caused by the intervention.

Finally, the GDG acknowledged potential implementation challenges related to this best-practice statement. Implementing comprehensive safety protocols may require investment in training, equipment (such as advanced ventilation systems or protective barriers) and additional staff time, which could be burdensome, particularly for smaller or resource-limited practices. In low- and middle-income countries, the cost and availability of safety equipment may hinder practical implementation. Additional safety measures may slow down clinical procedures, potentially increasing appointment times and reducing patient flow.

BEST PRACTICE STATEMENT 2

Ensure effective isolation, thorough curing with appropriate light sources, and proper surface finishing or polishing techniques to limit exposure to unpolymerized monomers during the application of resin-based composites.

Remarks

- Current evidence indicates that the greatest risk of BPA exposure from resin-based composites (sealants and restorations) occurs during and immediately after their application. Specific clinical procedures can therefore be implemented to minimize exposure to unpolymerized resin-based composites.

- Maximizing the degree of conversion in resin-based composites can help reduce the leaching of unreacted monomers and potential BPA exposure in the long-term. This can be achieved by following manufacturers' instructions, ensuring proper curing light function to obtain thorough curing of the material, minimizing the distance between the curing light and the restoration, and applying glycerine gel on the final resin layer.

- Additional strategies for dental patients include using rubber dam isolation, cleaning the restoration surface with mild abrasives or pumice, thoroughly washing the surface with an air–water syringe, and asking patients to rinse with water after the procedure.

Summary of evidence

This best-practice statement is based on indirect evidence regarding the toxicity of resin-modified glass ionomer cements, resin-based composites and compomers, as well as on current clinical protocols for risk mitigation. Evidence on toxicity was presented under recommendation 6 in section 4.1.3. The present section summarizes evidence on current clinical protocols for minimizing exposure to unpolymerized resin-based composites, which was not suitable for GRADE assessment.

Because exposure to BPA-derived monomers from resin-based composites is highest during and immediately after placement, several clinical protocols have been suggested in the literature to reduce contact with unpolymerized resin-based composites (*81, 118, 127*). Most of these strategies are already routinely implemented in oral health care settings:

- The use of rubber dam isolation during placement of resin-based composites and fissure sealants can minimize patients' ingestion of unpolymerized monomers.

- The use of curing lights with irradiances of about ≥1,000 mW/cm^2 together with curing times recommended by the manufacturer, contributes to maximizing the degree of conversion and reducing unreacted monomers. The emitted light must also have wavelengths that match those absorbed by the material to initiate polymerization. Bringing the curing light guide tip close to the restoration, and curing from different sides when applicable, will also contribute to curing optimization. There is no need to prolong curing times beyond material manufacturers' recommendations if the required total energy has been delivered.

- Applying the incremental technique, limiting layer thickness to ≤2 mm per increment for conventional resin-based composites and up to 4 mm per increment for bulk-fill resin-based composites, helps ensure complete curing and reduces residual monomer release.

- Unpolymerized BPA-derived monomers are present on the surface of the material due to oxygen inhibition of polymerization. This superficial, non-polymerized layer should be removed during finishing. Using mild abrasives, or pumice with a cotton applicator or prophylaxis cup can reduce the presence of residual unpolymerized BPA-derived monomers remaining on the surface *(81, 127)*. An alternative is to apply glycerine gel for the polimerization of the final resin layer, followed by a second curing step, after covering the restoration with a glycerine film. Glycerine acts as an oxygen barrier, maximizing monomer-to-polymer conversion. Brushing the restoration surface with pumice or using the water/air spray can also eliminate most residual monomers *(81)*.

- Washing the surface of the resin-based composites or fissure sealants with a water/air spray with suction, or alternatively asking patients to rinse with water after curing, can further reduce residual monomer levels *(118)*.

Evidence-to-decision considerations

The GDG noted that trace amounts of residual BPA-derived monomers may leach from freshly placed or incompletely polymerized resin-based composites. Given this potential risk, limiting exposure to unpolymerized monomers is considered a prudent strategy to safeguard both patients and oral health professionals. This approach not only improves the quality and longevity of dental restorations but also aligns with current safety recommendations, even though the certainty of evidence on long-term health effects remains low.

Current research indicates that the highest risk of exposure to unpolymerized BPA-derived monomers from resin-based composites (sealants and restorations) occurs during and immediately after placement. The GDG therefore recommends the adoption of specific clinical procedures to minimize exposure to unpolymerized resin-based composites (*81, 127*). These include thorough polymerization techniques, immediate removal of the oxygen-inhibited layer and the use of rubber dams or high-volume suction during application.

The GDG issued a best-practice statement endorsing these safety measures to raise awareness and clarify expectations among oral health professionals and patients, thereby emphasizing their importance in routine dental care. However, the GDG also recognized that implementing these protocols may require additional resources, training and equipment.

Oral health care facilities in high-income countries are more likely to already adhere to these protocols, whereas resource-limited settings may face significant challenges, including increased costs and logistical complexities. This disparity could exacerbate existing inequalities in access to safe oral health care.

Finally, the GDG also highlighted the importance of ongoing education and training for oral health care professionals, ensuring they remain informed about best practices for minimizing exposure to potentially harmful substances like BPA.

5. Implementation considerations

5.1 Supply chain and market availability

5.1.1 Policies and regulatory frameworks

As of 16 June 2025, 149 Member States had already ratified the Minamata Convention on Mercury. In addition to ratifying and implementing the Minamata Convention to reinforce their commitment to mercury reduction, Member States are encouraged to establish clear national objectives for oral health promotion and oral disease prevention aligned with the Global oral health action plan 2023-2030. Integrating carbon reduction strategies—such as tracking emissions in the oral health sector—could help align mercury-free transitions with broader sustainability goals. The UN Global Plastics Treaty, currently under negotiation, is expected to address the full life cycle of plastics—from extraction to disposal—and to help establish international standards for control and accountability. This treaty complements the Minamata Convention by promoting environmentally responsible practices across the health sector, including oral health care.

Engagement with international suppliers and local distributors could strengthen supply chains. Encouraging sea rather than air shipment could help reduce emissions. Including mercury-free dental products in national formularies and essential medicines lists would likely improve access and affordability.

Public and private insurance and reimbursement schemes should be revised to incentivize the use of mercury-free dental products and support progress towards universal health coverage. To facilitate this transition, public health systems may need to update procurement policies and clinical guidelines to reflect current best practices. Governments can also introduce policy incentives—such as subsidies, tax reductions or preferential procurement criteria—to offset transition costs, reduce material expenses and encourage the adoption of mercury-free products and sustainable practices across both public and private sectors.

Oral health care facilities may require investment in new equipment and supplies, including curing lights, eye protection and specialized instruments tailored to mercury-free procedures. A phased implementation strategy—beginning with the use of glass ionomer cements in community-based settings and expanding to resin-based composites in more advanced facilities—can support gradual capacity building while ensuring continuity of care.

Supply chain robustness and resilience could be strengthened by diversifying suppliers, fostering strong partnerships and investing in inventory systems with real-time tracking and forecasting. Contingency planning and sustainability measures, such as eco-friendly packaging, could further support both resilience and environmental goals.

Finally, investing in research and development can support the creation of cost-effective and clinically effective mercury-free alternatives. Promoting local production could also reduce emissions, enhance self-sufficiency and support the development of climate-resilient products.

5.1.2 Fiscal measures and market-driven demand

Dental manufacturers could be incentivized to develop and supply mercury-free, environmentally friendly products through tax breaks, grants, streamlined approvals and public procurement policies favouring sustainable options. Insurance and reimbursement systems may also be adjusted to support oral health promotion, preventive care, minimally invasive dentistry and mercury-free dental products, thereby stimulating demand. Manufacturers may need to adapt production lines and supply chains to meet rising demand for mercury-free products efficiently. Priorities could include improving and testing mercury-free alternatives while minimizing the environmental impact of sourcing and manufacturing.

To support informed decision-making and regulatory compliance, manufacturers are encouraged to provide comprehensive information on the composition of mercury-free dental products and associated medical devices (e.g., capsules). This

includes clear product labelling and easy access to simplified safety data sheets for all commonly used chemicals in oral health care facilities, ideally made freely available on manufacturers' websites.

In line with practices in the pharmaceutical industry, manufacturers should also be required to disclose the exact composition of their dental products. This transparency enables oral health professionals to communicate effectively with patients, supporting informed consent, and ensures compliance with traceability requirements.

Market dynamics such as economies of scale, supportive insurance policies and reduced import duties could help lower costs and increase uptake. Raising awareness among oral health professionals and patients might further drive acceptance.

Governments, either independently or through public–private partnerships, could support this shift through targeted training, education and updated professional guidelines. As collective demand grows, suppliers are likely to strengthen supply chains and improve product availability.

5.2 Training for oral and other health professionals

5.2.1 Updating oral health educational curricula

At a time when planetary boundaries are being crossed due to industrial human activities (*128*), it is important that all health professionals are trained in planetary health, the consequences of global environmental change on human health, and strategies to reduce the ecological impact of health care. Such training ensures they are prepared to act in an increasingly volatile context shaped by the triple planetary crisis of climate change, biodiversity loss and pollution.

Oral health educational curricula could include the health impacts of ecological degradation and strategies to reduce the environmental footprint of oral health services. In this way, future oral health professionals can understand the broader environmental consequences of providing oral health care, including biodiversity loss caused by pollution and resource extraction (*129*).

Dental education can also support new skill mixes by incorporating relevant public health competencies, such as integrating climate resilience and environmental sustainability. This would help strengthen the implementation of human health-centred, environmentally sustainable and less invasive oral health care (*130*).

Dental schools could emphasize preventive and minimally invasive approaches, accelerating phase-out of dental amalgam training. They could also prepare new cadres to deliver essential oral health care through a primary health approach. Training should also cover the proper handling and disposal of mercury-free materials.

In addition, professionals could be trained to communicate with patients about the benefits, limitations, safety, durability and cost of mercury-free options. Encouraging shared decision-making can empower patients and build trust in the health system.

5.2.2 Address potential training and retraining needs

Oral health professionals in both public and private sectors may benefit from additional training to optimize the use of mercury-free dental products, particularly for the prevention and nonrestorative management of dental caries. This would support a smooth transition while maintaining patient safety and quality of care.

Health systems may need to invest in training oral health professionals on mercury-free products and minimal intervention techniques to ensure affordable, high-quality care. Training should also cover safety protocols such as no-touch placement of resin-based composites and the use of appropriate eye protection. Ongoing professional development should be planned as materials and techniques continue to evolve.

The development of national and local guidelines could help standardize material selection and reduce variability across providers. Safety protocols may also be needed to manage exposure risks during the placement and removal of mercury-free restorations, protecting both health workers and patients while minimizing environmental impact.

5.2.3 Strengthening communication and collaboration

Collaboration across sectors and health disciplines could help ensure a well-distributed, skilled and motivated oral health workforce within interprofessional primary care teams. The basics of oral health promotion and oral disease prevention could be integrated as core competencies for other health professionals such as doctors, nurses and pharmacists.

Health care professionals, particularly in rural or underserved areas, may need to broaden their skills to deliver essential oral health care in low-resource settings. Training should also cover the recognition of clinical signs requiring referral to oral health care professionals, protocols for communication about shared patients and clarity on scope of practice.

5.3 Waste management of dental products (dental amalgam and mercury-free alternatives) used in oral health care facilities

5.3.1 Reducing the environmental impact of waste from dental amalgam and mercury-free dental products

The environmental impact of dental products can be addressed across the entire supply chain—from resource extraction to clinical use and end-of-life disposal. Each stage contributes to waste, including resource extraction, synthesis of constituents, product manufacturing, packaging and clinical use (*92*). Stakeholders and regulators may need to share responsibility for waste generation and implement mitigation strategies to reduce it sustainably, starting at the point of creation.

Significant reductions could be achieved by minimizing packaging, redesigning it for recyclability and improving recovery systems. Dental materials such as dental amalgam, resin-based composites and glass ionomer cements are often packaged in single-use plastic containers, which are difficult to recycle and are typically discarded with residual material. These are further wrapped in secondary and tertiary packaging, adding to the waste burden. The containers and packaging are composed of heteropolymers assembled as complex compound structures, making them difficult to recycle. Residual unused material may also remain in the containers and is likewise disposed of in the waste streams.

Sustainability in oral health care must be addressed as a supply chain challenge, requiring collaboration among manufacturers, distributors and clinical users. Mitigating strategies can target key waste-generation stages in the supply chain, namely:

- manufacturing (including extraction of natural resources, synthesis or refinement of constituents, and product creation);
- packaging (types and quantities); and

- clinical use (optimized for predictability and durability) (*131*).

Efforts should focus on reducing packaging and increasing recycling in both clinical and preclinical settings. In addition, collaboration in research and development between dental manufacturers and plastic suppliers could lead to recyclable, safe and durable materials. Downstream, partnerships with recyclers might help to develop technologies for efficient material recovery (*131*). It should be noted, however, that recycling itself has an environmental impact.

5.3.2 Sound management of dental amalgam waste

Adequate dental amalgam waste management in oral health care services involves installing chairside traps and, where feasible and appropriate, certified dental amalgam separators, in accordance with national regulations, with regular inspection and cleaning (*132*). Non-contact amalgam waste (materials that have not been in contact with a patient's mouth) and contact amalgam waste should be stored in sealed plastic containers clearly labelled 'amalgam waste (hazardous)'. These containers must then be collected and transported to a designated hazardous waste disposal facility.

Health facilities should maintain accurate records of waste transfer notes for audit purposes. Regular training for health personnel on proper waste segregation, handling, storage, and emergency spill protocols is crucial for maintaining compliance and minimizing risks.

Functional dental amalgam restorations should not be removed from any patient, including pregnant women and children, unless restoration replacement is necessary. If removal is required, a safe protocol should be followed to minimize mercury exposure through inhalation, ingestion or mucosal absorption. One recognized protocol is the Safe Mercury Amalgam Removal Technique (SMART), developed by the International Academy of Oral Medicine and Toxicology, which outlines detailed safety measures and equipment for safe removal (*133, 134*). In settings where such protocols cannot be implemented, oral health care professionals may consider the repair of the restoration with resin-based composites (*135, 136*).

Oral health care professionals, together with other health professionals, should encourage the use of mercury-free restorative materials for caries management in order to reduce reliance on dental amalgam.

5.3.3 Adapting waste management systems

Health care systems could adopt green purchasing policies by prioritizing biodegradable items, BPA-free plastics and paper in place of plastic, for both clinical and administrative use. Integrating sustainability criteria into supplier contracts could encourage environmentally friendly manufacturing and reduce hazardous and non-recyclable waste, on the understanding that the best waste is no waste.

Strategic planning and budgeting could support the development of comprehensive waste management systems. Once resources are secured, a safe and comprehensive waste management system can be established. This should include the proper segregation of recyclables, non-hazardous non-recyclable waste, infectious waste, sharps (such as needles), chemical waste (such as mercury waste, expired or unused resin-based composites or radiography solutions), and pharmaceutical waste (such as anaesthetics or medications). This process should also ensure that all waste is treated and disposed of by licensed companies.

To reduce chemical waste, health facilities could also switch to light-emitting diode (LED) lighting and adopt digital radiography. Recycling programmes for paper, plastic and glass, together with safe reuse of sterilizable instruments, could further reduce non-hazardous waste.

5.3.4 Improving health care waste management systems

Improving waste management systems in health care facilities can be integrated into broader infection prevention and control (IPC) and water, sanitation and hygiene (WASH) strategies. Such integration not only helps to prevent infections but also contributes to climate resilience and public health by minimizing environmental hazards. Alternatively, waste management can be pursued as a standalone strategy. Regardless of the approach, all waste types should be addressed, with clear procedures and monitoring in place. Where separate strategies are developed, they must be aligned and streamlined to ensure coherence and maximize effectiveness.

A waste management strategy must be developed within the cultural and socioeconomic context of the region where it will be implemented *(131)*. The suitability, effectiveness and impact of recommendations and solutions will differ greatly depending on the country and its capacity for change. Conducting a local assessment is therefore essential to determine what is feasible and what will have the greatest impact *(137)*.

A robust health care waste management strategy – whether as an independent plan or as a component of broader strategies – must establish clear procedures for every stage of waste handling, including segregation, collection, internal transport, storage, treatment and final disposal. All categories of waste, ranging from general non-hazardous to infectious, sharps and chemicals should be comprehensively addressed. Equally important are provisions for training staff in these procedures, defining responsibilities, maintaining documentation and implementing regular monitoring.

In oral health care settings, strategies could include proper disposal of mercury waste (as described in the previous section), expired or unused resin-based composites, curing light components (including LED chips, disposable sleeves, filters and batteries) and packaging. Quality control processes could further support effective implementation.

Ministries of Health and Environment are encouraged to monitor the status of their waste management practices and policies. The WHO/UNICEF Joint Monitoring Programme provides an international framework for tracking national policies on safe waste management, including waste segregation and treatment, as part of Sustainable Development Goal 6 (clean water and sanitation). This tracker also supports reporting in line with the 2023 United Nations General Assembly resolution on sustainable, safe and universal water, sanitation, hygiene, waste and electricity services in health care facilities.

5.4 Preservation of ecosystems and sustainable development

5.4.1 Adopting sustainable practices

Emphasizing health promotion and preventive care improves patient oral health outcomes and reduces the overall demand for dental treatments and associated resources, thereby supporting environmental sustainability. Transitioning to products with less environmental impact, such as mercury-free dental materials, and minimizing the use of hazardous chemicals further contribute to safer, more sustainable practices. In addition, careful prescribing practices – such as avoiding the over-prescription of antibiotics or anaesthetics – can help to reduce pharmaceutical waste and limit the environmental impact of unused medicines.

By adopting sustainable practices, oral health care facilities can enhance the quality and safety of care while sustaining and expanding access to services. Reducing operational costs through environmental initiatives can also make care more affordable.

These efforts support the broader goal of achieving universal coverage for oral health care (*138, 139*). To successfully implement these changes, oral health care facilities should be supported with appropriate programmes that facilitate the adoption of new, sustainable practices (*140*).

Oral health care facilities can reduce reliance on single-use products by autoclaving and sterilizing dental instruments rather than relying on disposable options. They can also reduce the use of products packaged in single-use plastics or with excessive packaging. When reduction is not feasible, facilities should opt for products with less environmentally impactful packaging alternatives.

Strategic communication can help health care systems, together with both public and private providers, to promote a shared vision of human and planetary health. Framing oral health care within the context of the nine planetary boundaries may encourage more sustainable practices (*128*).

5.4.2 Strengthening the robustness and resilience of oral health care facilities to environmental hazards

Collective measures to promote oral health and prevent oral diseases should be supported in conjunction with the eco-design of care and the right-care approach. The provision of mercury-free oral health care is a fundamental component of environmentally sustainable practice. Oral health and the implementation of the Minamata Convention on Mercury can be integrated into national health policy and strategies to preserve biodiversity and reduce environmental pollution, designating the national oral health unit as one focal point within the Ministry of Health.

Complementary measures should be integrated and developed, including:

- controlling energy consumption through the elimination of energy waste;
- adopting infrastructure policies that promote less energy-intensive cooling and heating systems that do not rely on ozone-depleting substances or carbon-intensive gases;
- increasing the use of LED lighting, natural ventilation and passive heating and cooling solutions; and
- supporting the development of renewable energy sources.

Measures should also address the use of chemicals in oral health care and treatment, as well as in maintenance and disinfection procedures. Materials should be selected that do not present risks to aquatic organisms or human health, including carcinogenic, mutagenic and reprotoxic substances, nanomaterials and mercury-free dental products without controversial compounds. Measures may also include replacing chemical radiological developers with digital radiology, while reducing the environmental impact of digital activities. Procurement policies can promote the use of low-carbon and environmentally sustainable products within oral health care facilities. Engaging suppliers can help reduce carbon emissions across the supply chain while promoting transparency and accountability. This can be supported by reducing energy consumption, encouraging local production and fostering innovation. Ordering products in large batches and sourcing from nearby providers can further minimize the environmental impact associated with the distribution of mercury-free dental products, provided this is balanced against product shelf-life and utilization rates. In addition, providing oral health care in the nearest clinical facility and minimizing the number of dental appointments can reduce the environmental impact, particularly that associated with patient travel.

Health care systems and private providers could:

- undertake assessments to evaluate how pollution of natural environments, biodiversity loss and climate change currently affect, and may continue to impact, oral health programmes, with particular attention to the availability of essential dental medicines and the resilience of their supply chains; and
- design and implement oral health programmes and operations that incorporate findings from these assessments, ensuring that both current and projected effects of global environmental changes (such as climate change, biodiversity loss and pollution) – especially in low-resource settings – are addressed to maintain continuity and quality of care.

Health systems and private providers could adopt sustainability reporting on climate resilience and environmental sustainability for oral health care delivery. This should include integrated quality, safety and environmental measures, as well as the procurement, use, disposal and waste management of mercury-free dental products. Health systems can measure, document and report on these activities, advancing oral health metrics to enhance the usability of information within the context of the Sustainable Development Goals (SDGs) and other key global health agendas.

To strengthen governance, essential dental medicines for oral disease prevention and control can be integrated into health security, pandemic and emergency preparedness, and humanitarian response frameworks. This will help to build resilient oral health systems capable of effective emergency response. Adopting a whole-of-government and whole-of-society approach through the “Health in All Policies” framework is key for health security and emergency preparedness.

5.4.3 Ensuring a reliable, affordable, and sustainable supply of mercury-free dental products

Transitioning away from mercury-based dental amalgam is a critical step towards more environmentally sustainable oral health care. To ensure this transition is equitable, effective, and scalable – particularly in low-resource settings– countries must adopt a comprehensive approach that includes strengthening the robustness and resilience of supply chains for dual-use mercury-free dental products. These include essential dental materials and techniques that can be applied with hand instruments when traditional restorative treatments are impractical or suboptimal, and can also be used in conventional restorative procedures with modern dental equipment.

Promoting local production of mercury-free restorative materials can significantly reduce emissions, enhance affordability and improve supply chain security, particularly in low-resource settings. Active engagement with suppliers is also essential to drive innovation in sustainable product design and packaging, reduce carbon footprints and promote transparency and accountability across the supply chain.

6. Guideline relevant research needs and limitations

6.1 Important evidence gaps remain on the clinical effectiveness and cost-effectiveness of mercury-free dental products

The long-term clinical performance of most mercury-free dental products remains uncertain, compounded by the rapid pace of product development. Findings from earlier clinical trials may no longer be relevant, as the products evaluated have since been improved. Key gaps in knowledge include identifying which interventions are most effective for caries prevention and the nonrestorative management of carious lesions, as well as establishing optimal delivery protocols, such as application frequency and concentration. For silver diamine fluoride in particular, modifications to reduce tooth discoloration or improve stability should be evaluated for clinical effectiveness. In addition, for the restorative management of dental caries, long-term evaluations (more than 10 years) are needed, especially to assess the clinical performance of mercury-free dental products that have remained on the market.

Pragmatic clinical trials in primary care settings are ideal for evaluating the longevity of different mercury-free dental products. These can be complemented by observational studies that follow cohorts of patients receiving various dental treatments. Together, these primary studies provide valuable information on clinical effectiveness for specific clinical situations (such as load-bearing teeth and multi-surface restorations) and population subgroups (including older adults and children).

Comprehensive, real-world economic evaluations that are realistic and free from conflicts of interest, integrating clinical outcomes and environmental costs, are needed to identify truly cost-effective interventions for preventing and managing dental caries. Achieving this will likely require a mix of methodologies, including both within-trial evaluations and modelling studies, to ensure results are as generalizable as possible. Such evaluations should fully incorporate potential health risks and the environmental impact associated with mercury-free dental products. Long-term economic evaluations should be conducted in diverse populations and health care systems, particularly in low- and middle-income countries where cost and access to oral health care are critical factors.

6.2 Continued monitoring of occupational exposure to mercury-free dental products

Continued monitoring of occupational exposure to mercury-free dental products in public and private oral health care facilities is recommended, as their components continue to evolve in tandem with regulatory factors and clinician and patient demands. With increasing interest in endocrine-disrupting chemicals and microplastics found in everyday products, ongoing monitoring is essential to evaluate the long-term safety of both existing and future mercury-free dental products, particularly resin-based composites. The potential toxicity of dental adhesives with resin-based composites also warrants thorough evaluation.

Sodium fluoride was recently proposed to the European Chemicals Agency (ECHA) for classification as an endocrine-disrupting chemical. At the time of guideline development, the scientific evaluation process to determine the classification was still underway. Given sodium fluoride's well-established role in preventing dental caries, this assessment warrants close attention. The findings from this evaluation will be reviewed and incorporated into future updates of the guideline.

Regular reassessments should be conducted as new evidence emerges, ensuring that these alternatives do not introduce additional risks to human health. The potential toxicological risks associated with mercury-free dental products should be monitored on an ongoing basis. Post-marketing surveillance can be carried out through adverse event monitoring, whereby health professionals, patients and manufacturers report any suspected side effects or unexpected reactions. These reports are collected in national and international databases and analysed for patterns that might indicate new risks. Manufacturers may also be required to submit periodic safety update reports to regulatory agencies, communicating findings to health care providers and patients. However, the limitations of post-marketing surveillance must be recognized, particularly in relation to measuring risks associated with exposure to endocrine disruptors (such as non-linear dose–response relationships or delayed effects).

Pharmacokinetic studies can also play a role in monitoring the safety of mercury-free dental products. They can measure the levels of specific components, such as bisphenol A (BPA), in biological fluids (for example, urine) before (baseline level) and after dental procedures in the absence of other sources of BPA. Longer evaluations (more than 1 week) are needed to confirm whether effects are transient. By modelling these concentrations and their progression over time, researchers can assess the extent of systemic exposure and compare it with established safety thresholds. This approach can help determine whether the release of components from mercury-free dental products poses any adverse health effects in the short or long term. Future research studies should find appropriate methods for evaluating combined effects and transgenerational risks.

6.3 Further research and continued monitoring on environmental risks and sustainability

The environmental impact of mercury-free dental products is not well known. This lack of information does not mean that there is no effect; rather, it suggests that sufficient evidence is not yet available and that ongoing monitoring and surveillance are essential. Evaluation of best practices for caries prevention and management should be balanced with a thorough assessment of their environmental impact. This includes consideration of substance and plastic release, resource depletion and waste management challenges. Integrating both clinical effectiveness and sustainability into decision-making will help ensure that oral health care delivers optimal patient outcomes while minimizing negative effects on the environment.

Mercury-free dental products continue to evolve, with improved formulations and new products regularly entering the market. To meet the growing demand for a wider range of mercury-free options that offer enhanced tooth-colour matching, reduced costs and greater durability, manufacturers are increasingly incorporating nanoscale particles and fillers, often without comprehensive prior risk assessment. Nanoscale particles and fillers associated with mercury-free dental products can pass through dental chair and dental amalgam separator filters, ultimately entering the dental wastewater system. This is particularly relevant in the context of emerging contaminants such as microplastics, nanoparticulate waste and small particles in the environment (*98*). With the widespread adoption of mercury-free dental products, further research is needed to investigate methods for improving the capture and management of micro- and nanoparticulate waste. There is also a need to assess the sustainability of mercury-free dental products by evaluating whether current and emerging disposal methods affect water, air and soil quality.

Increased monitoring and further research are also needed on the environmental impact of mercury-free dental products across their full life cycle, from production to disposal (the cradle-to-grave journey of these materials). Comprehensive life cycle assessments (LCAs) could help to determine which mercury-free dental products, waste management strategies and types of dental waste (such as empty composite capsules and associated packaging) have the most favourable environmental impact (*141*).

Dissemination, monitoring and updating

The guideline is available online, including all evidence reviewed by the Guideline Development Group (GDG), both within the main text and web annexes. A series of brief technical notes on the different mercury-free dental products included in the guideline web annex – namely fluoride varnish, silver diamine fluoride, fissure sealants, glass ionomer cements and resin-based composites – have been developed to complement the recommendations and serve as supporting material, not as standalone sources of guidance. The guideline will be translated into the United Nations official languages and disseminated via the WHO website, including the WHO guideline library, the WHO oral health page, the WHO initiative page on oral health care and the environment and the UNEP Global Mercury Partnership project knowledge hub.

The guideline will be presented to the 158th Executive Board and the Seventy-ninth World Health Assembly as part of the consolidated report on noncommunicable diseases (NCDs), in alignment with the mandate outlined in the resolution on oral health (WHA74.5). The dissemination strategy will include a series of webinars across all WHO regions and a targeted social media campaign. The launch will be promoted through WHO regional and country offices, global and regional websites, UNEP and other relevant United Nations agencies and partners.

The implementation of this guideline can be monitored at country level. Globally, implementation will be monitored as part of the WHO Global Oral Health Action Plan 2023–2030, with a focus on global target 1.2 for environmentally sound oral health care. Implementation and monitoring will be supported through a coordinated effort between Member States, international partners, civil society organizations, the private sector and WHO.

The guideline recommendations will remain in effect for five years. During this period, the Steering Committee will review emerging scientific evidence and user feedback to determine whether updates are necessary, following the formal procedure described in the WHO Handbook for Guideline Development. The Committee will also monitor research developments in dental caries prevention and management, as well as in the sustainability of oral health care. Particular attention will be given to areas where systematic reviews identified evidence gaps, low-certainty findings or evolving formulations of mercury-free dental products, as new substances are introduced. These insights will guide decisions on whether new or revised recommendations are required.

Glossary

Caries arrest: Stage at which dental caries (tooth decay) stop progressing and become inactive; the lesion has halted and is no longer causing further damage to the tooth structure.

Caries reversal: Process of halting and potentially reversing the early stages of tooth decay through remineralization of the tooth enamel, when the balance between demineralization and remineralization shifts in favour of remineralization, allowing the tooth to repair itself without invasive dental procedures.

Class I restoration: Restoration of cavities in pits and fissures on the occlusal surfaces of molars and premolars, the buccal or lingual pits of molars, and the lingual surfaces of maxillary incisors.

Class II restoration: Restoration of cavities on the proximal surfaces (mesial or distal) of premolars and molars.

Class III restoration: Restoration of cavities on the proximal surfaces of anterior teeth (incisors and canines) that do not involve the incisal edge.

Class IV restoration: Restoration of cavities on the proximal surfaces of anterior teeth that involve the incisal edge.

Class V restoration: Restoration of cavities on the cervical third of the facial or lingual surfaces of any tooth.

Health workers: The term used to refer to all types of health professionals, including oral health professionals and other health professionals.

Life cycle assessment (LCA): Systematic method for evaluating the environmental impact of a chemical product, process or service across its entire life cycle, from raw material extraction, manufacturing and use to disposal or recycling.

- Cradle-to-grave LCA: includes all life-cycle stages, from raw material extraction to disposal or recycling.
- Cradle-to-gate LCA: evaluates impact from raw material extraction through manufacturing, up to the point where the product leaves the factory gate; excludes use phase and end-of-life processes.

Mercury-free dental products: All professionally applied products used for preventing and managing dental caries; broader than "mercury-free dental materials", which are most often associated only with direct restorations (fillings).

Non-invasive intervention in oral health care: Methods and treatments that prevent or arrest dental caries without drilling or removal of healthy tooth structure. This aligns with WHO's broader goals of integrating oral health into universal health coverage, phasing out the use of dental amalgam and reducing reliance on complex, costly, and invasive dental procedures.

Minimal intervention restoration/minimally invasive intervention in oral health care: Methods and treatments that restore tooth structure, oral health function and aesthetics without extensive drilling, or removal of healthy tooth structure. The intervention aims to preserve as much of the natural tooth as possible, avoiding actions that result in unnecessary pain, infection and permanent damage to teeth, while preventing and treating dental caries. This aligns with WHO's broader goals of integrating oral health into universal health coverage, phasing out the use of dental amalgam, and reducing reliance on complex, costly, and invasive dental procedures.

Oral health professionals: Group of health workers whose skills align with oral health occupations, including dentists, dental therapists, dental hygienists and dental assistants.

Vulnerable populations: Groups at increased risk of adverse health outcomes, examples include children and adolescents, pregnant and breastfeeding women, older adults and individuals with atopic conditions.

Annex 1. Members of the WHO–UNEP Steering Committee

MEMBERS OF THE WHO–UNEP STEERING COMMITTEE	
Benoit Varenne	Oral Health Programme | Department of Noncommunicable Diseases, Rehabilitation and Disability (NCD Department) | WHO Headquarters, Switzerland
Nicole Rendell	Oral Health Programme | NCD Department | WHO Headquarters, Switzerland
Yuriko Harada	Oral Health Programme | NCD Department | WHO headquarters, Switzerland
Eduardo Bernabé	Oral Health Programme | NCD Department | WHO headquarters, Switzerland
Gabriela Sardon Panta	Oral Health Programme | NCD Department | WHO headquarters, Switzerland
Lesley Onyon	Chemical Safety and Health Unit Department of Environment, Climate Change and Health (ECH Department) | WHO headquarters, Switzerland
Richard Brown	Chemical Safety and Health Unit Department of Environment, Climate Change and Health (ECH Department) | WHO headquarters, Switzerland
Margaret Montgomery	Water Sanitation and Hygiene | ECH Department | WHO headquarters, Switzerland
Megha Rathi	Safeguards, Climate Change and Health | ECH Department | WHO headquarters, Switzerland
Christine Nkerifac	Environmental Health Promotion/Chemicals | WHO Regional Office for Africa, Republic of the Congo
Yuka Makino	Technical officer for oral health | WHO Regional Office for Africa, Republic of the Congo
Samar Elkefy	Focal point for oral health | WHO Regional Office for the Eastern Mediterranean, Egypt
Elena Tsoy	Focal point for oral health | WHO Regional Office for Europe, Denmark
Irina Zastenskaya	Focal point for Chemical Safety - Living and Working Environments Programme | WHO Regional Office for Europe, Germany
Carolina Hommes	Focal point for oral health | WHO Regional Office for the Americas, the United States of America
Nalika Gunawardena	Focal point for oral health | WHO Regional Office for South-East Asia, India
Sangeeta Singh	Focal point for oral health | WHO Regional Office for the Western Pacific, The Philippines
Mady Ba	Focal point for GEF7 Phasing Down Dental Amalgam project | WHO Senegal, Senegal
Sushera Bunluesin	Focal point for GEF7 Phasing Down Dental Amalgam project | WHO Thailand, Thailand
Eisaku Toda	Minamata Convention on Mercury Secretariat | UNEP Headquarters, Switzerland
Grace Halla	GEF Chemicals and Waste Unit | Chemicals and Health Branch | UNEP Headquarters, Austria
Imelda Dossou Etui	Global Mercury Partnership | Chemicals and Health Branch | UNEP Headquarters, Switzerland
Kenneth Davis	Global Mercury Partnership | Chemicals and Health Branch | UNEP Headquarters, Switzerland

Annex 2. Members of the Guideline Development Group and their special advisers

MEMBERS OF THE GUIDELINE DEVELOPMENT GROUP	
Alice Baras	Ecoresponsabilité Promotion Santé (ECOPS), France | Areas of expertise: planetary and territorial health promotion, oral health, environmental medicine
Carlos Alberto Feldens	Universidade Federal do Rio Grande do Sul, Brazil | Areas of expertise: dental caries prevention, public health, oral health
Edward Lo	University of Hong Kong, China, Hong Kong Special Administrative Region | Areas of expertise: epidemiology of oral diseases, prevention and treatment of dental decay (clinical trials); oral health care services, human resources, and utilization of services
Ellen Bruzell	Nordic Institute of Dental Materials, Norway | Areas of expertise: mercury-free materials, phototoxicity and chemical toxicity to cells and microorganisms, food chemical risk assessment
Florian Schulze	European Network for Environmental Medicine, Germany | Areas of expertise: eliminating the use of dental amalgam, chemicals policy, sustainability
Homa Kashani	University of Social Welfare and Rehabilitation Sciences, the Islamic Republic of Iran | Areas of expertise: biostatistics, environmental statistics, epidemiology, public health, chemical risk assessment
Richard Niederman	New York University, WHO Collaborating Centre, the United States of America | Area of expertise: dental materials, clinical effectiveness, public health, oral health
Rico Euripidou	Groundwork, South Africa | Area of expertise: chemicals policy, climate change and public health, environmental epidemiology
Ritu Duggal	All India Institute of Medical Sciences, WHO Collaborating Centre, India | Area of expertise: dental materials, public health, oral health promotion and disease prevention
Waranun Buajeeb	Mahidol University, WHO Collaborating Centre, Thailand | Area of expertise: dental materials, public health, oral health promotion and disease prevention

SPECIAL ADVISERS TO THE GUIDELINE DEVELOPMENT GROUP	
Adriana Otheguy	Ministerio de Salud Pública, Uruguay
Aristomenis Syngelakis	Ministry of Health, Greece
Fauziah Binti Ahmad	Ministry of Health, Malaysia
Noormi Othman	Ministry of Health, Malaysia
Mane Codou Badiane	Ministère de la Santé, Senegal
Rami Ahmad Assad	Ministry of Public Health, Qatar

Note: Noormi Othman contributed to this report during the initial phase of the process until her retirement, before the systematic review team concluded the research. Fauziah Binti Ahmad subsequently joined the GDG to continue the inputs.

Annex 3. Members of the External Review Group

MEMBERS OF THE EXTERNAL REVIEW GROUP	
Ali Kazemian	Iranian Association of Community Oral Health | Mashhad University of Medical Sciences, the Islamic Republic of Iran
Janet Clarkson	Cochrane Oral Health Group | University of Manchester, the United Kingdom
Tanya Walsh	Cochrane Oral Health Group | University of Manchester, the United Kingdom
Murray Thomson	University of Otago, New Zealand
Nigel Pitts	King's College London, the United Kingdom
Nilantha Ratnayake	National Institute of Oral Health, Sri Lanka
Roberto Ruggiero Braga	Universidade de São Paulo, Brazil
Satoshi Imazato	International Association for Dental, Oral and Craniofacial Research (IADR) | University of Osaka, Graduate School of Dentistry, Japan
Sudeshni Naidoo	University of the Western Cape | WHO Collaborating Centre, South Africa

Annex 4. Summary and management of confidentiality of undertaking and declarations of interests

To ensure a robust and inclusive development process, several expert groups were established.

GDG

Composed of 10 international, independent experts serving in their personal capacities, the GDG provided technical input on the recommendations based on the best available scientific evidence. They also supported the drafting of various sections of the technical guidance. All members of the Guideline Development Group (GDG) completed the Confidentiality of Undertaking (CoU) and Declaration of Interest (DoI) forms. Following an internal review, three members declared interests, however, these were assessed as minimal due to the interest ceasing prior to their involvement in the guideline development or were deemed not to constitute a conflict of interest.

Additionally, five Chief Dental Officers (national oral health leads) at the Ministry of Health level from different WHO regions participated as special advisers to the group. Their role was to provide contextual insights from country-level experiences to help ensure the recommendations are practical and implementable across diverse settings. Special advisers were not members of the GDG and did not participate in the formulation or decision-making process regarding the recommendations. All special advisers also completed CoU and DoI forms. No interests were declared.

Expert Contributions

Three experts were invited to contribute to the "implementation considerations" section of the guideline. Their role was to reflect on the recommendations and provide complementary perspectives and practical insights that may not have been fully captured through the systematic reviews but were relevant to the scope and application of the guideline. All three experts completed the CoU and DoI forms. Following an internal review, one expert declared interests, however, these were classified as minimal, as they had ceased prior to the expert's involvement in the guideline.

ERG

Composed of nine experts, this group was tasked with reviewing the advanced draft of the guideline. Their role was to ensure clarity, completeness, scientific accuracy and practical relevance. They provided critical feedback to refine the final version and enhance its usability for a global audience. All nine external reviewers completed CoU and DoI forms. Following an internal review, two experts declared interests; however, these were assessed as minimal due to their limited relevance to the scope of the guideline or because they had ceased prior to involvement.

Annex 5. Key questions in PICO format

A series of five systematic reviews provided the evidence base to inform the content of this technical guidance.

Systematic review 1: clinical effectiveness and cost-effectiveness of mercury-free dental materials used for caries prevention and control

Prospero registration: https://www.crd.york.ac.uk/PROSPERO/view/CRD42024569615

PICO question: What is the clinical effectiveness (longevity and annual failure rate, or equivalent outcome measure) and cost-effectiveness of mercury-free dental materials used for caries prevention and control?

Population
Patients receiving a dental preventive or restorative treatment approach

Intervention(s) or exposure(s)
Dental prevention or treatment using mercury-free dental materials (composite/adhesive resin, compomer, glass ionomer cement, resin-modified glass ionomer cement, tricalcium silicate, topical fluoride, amorphous calcium phosphate, dental sealant, amorphous calcium phosphate, monomer, methacrylate, indirect restoration)

Comparator(s) or control(s)
Control without intervention (prevention). Comparison with different dental materials (restorative treatment).

Main outcomes
Clinical outcomes
- Prevention: occurrence of new carious lesions, prevalence of caries
- Restorative treatment: failure rate (FDI/USPHS criteria), secondary lesions, marginal integrity, fractures, loss of retention and restoration quality

Economic outcomes
- Cost-effectiveness
- Cost per application/restoration

Additional outcomes
Secondary outcomes
1. Time until restoration failure or re-treatment
2. Discomfort during restorative treatment or within 24 hours after treatment
3. Patient's/carer's perceptions of the restorative treatment
4. Factors influencing the clinical effectiveness of the restorative treatment: type of tooth, affected tooth surface(s), preoperative radiograph, caries lesion depth, extent of carious tissue removal, isolation technique, type of adhesive and restorative material

Systematic review 2: cytotoxicity and biocompatibility of mercury-free dental materials or their chemical compounds

Prospero registration: https://www.crd.york.ac.uk/PROSPERO/view/CRD42024571363

PICO question: What is the cytotoxicity and biocompatibility of mercury-free dental materials or their chemical compounds?

Population
Human cells, animals, human subjects exposed to resin-based dental materials, glass ionomer based materials and their singular components.

Intervention(s) or exposure(s)
Exposure to resin-based dental caries restorative and preventive materials and their singular components.

Comparator(s) or control(s)
Human cells, animals, human subjects exposed to controls materials and placebo.

Main outcomes
Cytotoxicity and biocompatibility of mercury-free dental materials used for caries prevention and

control such as change in viability of treated cells, apoptosis rates, inflammatory responses, tissue integration, adverse events, allergic reactions, tissue toxicity, mucosa toxicity, genotoxicity and skin toxicity.

Additional outcomes
Additional outcomes to be measured and assessed include the release of inflammatory cytokines and chemokines, oxidative stress markers, and changes in gene expression related to cytotoxic and immune responses. Evaluation of cell morphology and ultrastructural changes using microscopy techniques, the potential for genotoxic effects, such as DNA damage and mutagenesis.

Systematic review 3: release of substances from mercury-free dental materials into the oral environment

Prospero registration: https://www.crd.york.ac.uk/PROSPERO/view/CRD42024571374

PICO question: To what extent are substances released from mercury-free dental materials into the oral environment?

Population
Patients of any age undergoing routine dental restorative or preventive procedures
For *in vitro* or pre-clinical research, any type of procedure simulating in *vivo* practice

Intervention(s) or exposure(s)
Measurement of monomer or other substance levels in body fluids after dental procedures *in vivo* or in artificial liquids *in vitro*

Comparator(s) or control(s)
Patients without any dental treatments or no comparison

Main outcomes
Monomers, nanoparticles or by-products release from mercury-free dental materials

Additional outcomes
Not applicable

Systematic review 4: health effects of mercury-free dental materials on patients and dental health personnel

Prospero registration: https://www.crd.york.ac.uk/PROSPERO/view/CRD42024571590

PICO question: What are the health effects of mercury-free dental materials on patients and health personnel?

Population
Inclusion criteria
- Patients of any age or gender who are following a professional protocol for caries prevention using mercury-free dental materials
- Patients with long-term or from recent dental restorations for treatment of caries with mercury-free dental materials
- Dental professionals, including dentists, dental assistants, dental nurses and dental hygienists (without any limitation of age, gender, experience or seniority) who use mercury-free dental materials daily

Exclusion criteria
Patients who have dental materials outside of the context of preventive and restorative dentistry

Intervention(s) or exposure(s)
- Professional protocols for dental caries prevention with mercury-free dental materials
- Treatment of dental caries with mercury-free dental materials

Comparator(s) or control(s)
Absence of dental caries prevention or absence of dental caries treatment or treatment of caries with amalgam

Main outcomes
Health effects on any organ or system or physical or psychosocial function

Additional outcomes
Not applicable

Systematic review 5: environmental effects associated with the manufacturing, distribution, clinical care use and waste management of mercury-free dental materials

Prospero registration: https://www.crd.york.ac.uk/PROSPERO/view/CRD42024571615

PICO question: What are the environmental effects (e.g. on water, air, land and wildlife) associated with the manufacturing, distribution, clinical care use and waste management of mercury-free dental materials?

Population
The review will include studies examining environmental systems, including ecosystems, wildlife, and human populations affected by the lifecycle of mercury-free dental materials. Inclusion criteria are studies that assess the environmental impacts related to manufacturing, distribution, clinical use, and waste management of these materials. Exclusion criteria are studies focused solely on the clinical efficacy or health outcomes of the materials without addressing environmental effects.

Intervention(s) or exposure(s)
The interventions/exposures to be reviewed encompass all stages of the lifecycle of mercury-free dental materials. This includes the environmental impacts arising from the manufacturing processes, the logistics of distribution, the clinical use in dental practices, and the subsequent waste management practices, including disposal and recycling.
The review will focus on identifying pollutants, emissions, resource use, and ecological disturbances associated with each of these stages to assess their comprehensive environmental footprint.

Comparator(s) or control(s)
The comparators/control for this review will include the environmental impacts associated with the lifecycle of mercury-containing dental materials, as well as other non-mercury dental materials, if applicable. Additionally, baseline environmental conditions with no exposure to dental materials will serve as a control to evaluate the relative impact. This comparison will help to contextualize the environmental footprint of mercury-free dental materials against traditional and other alternative materials.

Main outcomes
The primary outcomes of the review are the quantified environmental impacts associated with the lifecycle of mercury-free dental materials. These include changes in:

- water quality (e.g., contamination levels of specific pollutants);
- air quality (e.g., emission levels of greenhouse gases and other pollutants); soil quality (e.g., presence of contaminants and land degradation); and
- wildlife health (e.g., biodiversity loss and toxicity effects).

These outcomes will be measured using various environmental assessment tools and indicators, such as pollutant concentration levels, emission inventories, and ecological health indices.

Additional outcomes
The secondary outcomes of the review will include:

1. Resource consumption: quantification of energy and water usage during the manufacturing, distribution, clinical use, and waste management of mercury-free dental materials
2. Carbon footprint: measurement of greenhouse gas emissions associated with the entire lifecycle of mercury-free dental materials
3. Waste generation: assessment of the volume and type of waste produced at each stage of the lifecycle, including potential recyclability
4. Ecotoxicity: evaluation of the toxic effects of mercury-free dental materials on aquatic and terrestrial organisms
5. Human health indirect effects: investigation of any indirect effects on human health resulting from environmental contamination linked to mercury-free dental materials

References

1. GBD 2021 Oral Disorders Collaborators. Trends in the global, regional, and national burden of oral conditions from 1990 to 2021: a systematic analysis for the Global Burden of Disease Study 2021. Lancet 2025, 405, 897-910 (https://doi.org/10.1016/s0140-6736(24)02811-3).
2. Global strategy and action plan on oral health 2023–2030. Geneva: World Health Organization; 2024 (https://iris.who.int/handle/10665/376623).
3. WHO handbook for guideline development, 2nd ed. Geneva: World Health Organization; 2014 (https://iris.who.int/handle/10665/145714).
4. Prevention and treatment of dental caries with mercury-free products and minimal intervention: WHO oral health briefing note series. Geneva: World Health Organization; 2022 (https://iris.who.int/handle/10665/352480).
5. Jevdjevic M, Listl S. Global, Regional, and Country-Level Economic Impacts of Oral Conditions in 2019. J Dent Res 2025, 104, 17-21 (https://doi.org/10.1177/00220345241281698).
6. The 10 chemicals of major public health concerns [website]. Geneva: World Heatlh Organization; 2020 (https://www.who.int/news-room/photo-story/detail/10-chemicals-of-public-health-concern, accessed 28 January 2026).
7. Mercury [website]. Geneva: United Nations Environment Programme; 2024 (https://www.unep.org/topics/chemicals-and-pollution-action/chemicals-management/pollution-and-health/heavy-metals-1, accessed 28 January 2026).
8. Kang B, Wang J, Guo S, Yang L. Mercury-induced toxicity: mechanisms, molecular pathways, and gene regulation. Sci Total Environ 2024, 943, 173577 (https://doi.org/10.1016/j.scitotenv.2024.173577).
9. Health Effects of Exposures to Mercury [website]. Washington DC: United States Environmental Protection Agency; 2024 (https://www.epa.gov/mercury/health-effects-exposures-mercury, accessed 28 January 2026).
10. Bastiansz A, Ewald J, Rodríguez Saldaña V, Santa-Rios A, Basu N. A systematic review of mercury exposures from skin-lightening products. Environ Health Perspect 2022, 130, 116002 (https://doi.org/10.1289/ehp10808).
11. Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR). The safety of dental amalgam and alternative dental restoration materials for patients and users. Luxemburg: European Commission; 2015 (https://data.europa.eu/doi/10.2772/42641).
12. Khangura SD, Seal K, Esfandiari S, Quiñonez C, Mierzwinski-Urban M, Mulla SM et al. Composite resin versus amalgam for dental restorations: a health technology assessment. Ottawa (ON): Canadian Agency for Drugs and Technologies in Health; 2018.
13. Tibau AV, Grube BD. Mercury contamination from dental amalgam. J Health Pollut 2019, 9, 190612 (https://doi.org/10.5696/2156-9614-9.22.190612).
14. Minamata Convention on Mercury (Text and Annexes) [website]. United Nations Environment Programme (https://minamataconvention.org/en/documents/minamata-convention-mercury-text-and-annexes, accessed 28 January 2026).
15. Bangkok declaration - No health without oral health. Geneva: World Health Organization; 2025 (https://www.who.int/publications/m/item/bangkok-declaration---no-health-without-oral-health).
16. Future use of materials for dental restoration. Geneva: World Health Organization; 2010 (https://iris.who.int/handle/10665/202500).
17. WHO model list of essential medicines – 22nd list, 2021. Geneva: World Health Organization; 2021 (WHO/MHP/HPS/EML/2021.02; https://iris.who.int/handle/10665/345533).
18. WHO model list of essential medicines – 23rd List, 2023. Geneva: World Health Organization; 2023 (WHO/MHP/HPS/EML/2023.02; https://iris.who.int/handle/10665/376570).
19. Follow-up to the political declaration of the third high-level meeting of the General Assembly on the prevention and control of noncommunicable diseases: Prevention and management of noncommunicable diseases, promotion of mental health and well-being, and treatment and care of mental health conditions: report by the Director-General (EB154/7). Geneva: World Health Organization, 154th Session of the Executive Board, Provisional Agenda Item 7; 2024 (https://apps.who.int/gb/ebwha/pdf_files/EB154/B154_7-en.pdf, accessed 28 January 2026).
20. WHO handbook for the development of normative products. Geneva: World Health Organization; 2025.
21. Kérourédan O, Salerno C, Washio A, Ribeiro A, Doméjean S, Ardan R et al. Clinical-effectiveness and cost-effectiveness of mercury-free dental materials used for caries prevention and control: a systematic review. J Evid Based Dent Pract 2026, (submitted).
22. Jedlinski M, Corridore D, Mocquot C, Ardan R, Porporatti A, Sardon Panta G et al. Cytotoxicity and biocompatibility of mercury-free dental materials: a systematic review. Dent Mater 2026, (submitted).
23. Dantagnan CA, Tran TT, Ardan R, Mazur M, Banerjee A, Deliga Schroder AG et al. Substances release from mercury-free dental materials: a systematic review. J Biomed Mater Res Part B 2026, (submitted).
24. Jedeon K, Mutale D, Campus G, Ardan R, Porporatti A, Sardon Panta G et al. Health effects of mercury-free dental materials on patients and health personnel: a systematic review. Community Dent Oral Epidemiol 2026, (submitted).
25. Mazur M, Porporatti A, Walendzik B, Ardan R, Ottolenghi L, Sardon Panta G et al. The environmental impact of mercury-free dental materials used for caries treatment: a systematic review. Ecotoxicol Environ Saf 2026, (submitted).
26. Schünemann H, Brożek J, Guyatt G, Oxman A. GRADE Handbook - Handbook for grading the quality of evidence and the strength of recommendations using the GRADE approach. The GRADE Working Group, 2013.
27. Rehfuess EA, Stratil JM, Scheel IB, Portela A, Norris SL, Baltussen R. The WHO-INTEGRATE evidence to decision framework version 1.0: integrating WHO norms and values and a complexity perspective. BMJ Glob Health 2019, 4, e000844 (https://doi.org/10.1136/bmjgh-2018-000844).
28. Guyatt GH, Alonso-Coello P, Schünemann HJ, Djulbegovic B, Nothacker M, Lange S et al. Guideline panels should seldom make good practice statements: guidance from the GRADE Working Group. J Clin Epidemiol 2016, 80, 3-7 (https://doi.org/10.1016/j.jclinepi.2016.07.006).
29. Marinho VC, Worthington HV, Walsh T, Clarkson JE. Fluoride varnishes for preventing dental caries in children and adolescents. Cochrane Database Syst Rev 2013, 2013, Cd002279 (https://doi.org/10.1002/14651858.CD002279.pub2).
30. Zhang J, Sardana D, Li KY, Leung KCM, Lo ECM. Topical fluoride to prevent root caries: systematic review with network meta-analysis. J Dent Res 2020, 99, 506-513 (https://doi.org/10.1177/0022034520906384).
31. Manchanda S, Sardana D, Liu P, Lee GHM, Li KY, Lo ECM et al. Topical fluoride to prevent early childhood caries: systematic review with network meta-analysis. J Dent 2022, 116, 103885 (https://doi.org/10.1016/j.jdent.2021.103885).
32. Worthington HV, Lewis SR, Glenny A-M, Huang SS, Innes NPT, O'Malley L et al. Topical silver diamine fluoride (SDF) for preventing and managing dental caries in children and adults. Cochrane Database Syst Rev 2024, 11, Cd012718 (https://doi.org/10.1002/14651858.CD012718.pub2).
33. Kashbour W, Gupta P, Worthington HV, Boyers D. Pit and fissure sealants versus fluoride varnishes for preventing dental decay in the permanent teeth of children and adolescents. Cochrane Database Syst Rev 2020, 11, Cd003067 (https://doi.org/10.1002/14651858.CD003067.pub5).
34. Li F, Jiang P, Yu F, Li C, Wu S, Zou J et al. Comparison between fissure sealant and fluoride varnish on caries prevention for first permanent molars: a systematic review and meta-analysis. Sci Rep 2020, 10, 2578 (https://doi.org/10.1038/s41598-020-59564-5).
35. Leite KLF, Rodrigues GF, Chevitarese AB, Magno MB, Marañón-Vásquez GA, Pintor AVB et al. Are pit and fissure sealants effective in preventing and arresting occlusal caries in primary

and permanent teeth? An overview of systematic reviews. J Evid Based Dent Pract 2024, 24, 102010 (https://doi.org/10.1016/j.jebdp.2024.102010).

36. Nguyen TM, Tonmukayakul U, Le LK, Calache H, Mihalopoulos C. Economic evaluations of preventive interventions for dental caries and periodontitis: a systematic review. Appl Health Econ Health Policy 2023, 21, 53-70 (https://doi.org/10.1007/s40258-022-00758-5).

37. Davidson T, Blomma C, Bågesund M, Krevers B, Vall M, Wärnberg Gerdin E et al. Cost-effectiveness of caries preventive interventions - a systematic review. Acta Odontol Scand 2021, 79, 309-320 (https://doi.org/10.1080/00016357.2020.1862293).

38. Dhyppolito IM, Nadanovsky P, Cruz LR, de Oliveira BH, Dos Santos APP. Economic evaluation of fluoride varnish application in preschoolers: a systematic review. Int J Paediatr Dent 2023, 33, 431-449 (https://doi.org/10.1111/ipd.13049).

39. Milgrom P, Taves DM, Kim AS, Watson GE, Horst JA. Pharmacokinetics of fluoride in toddlers after application of 5% sodium fluoride dental varnish. Pediatrics 2014, 134, e870-874 (https://doi.org/10.1542/peds.2013-3501).

40. Twetman S, Stecksén-Blicks C. Urinary fluoride excretion after a single application of fluoride varnish in preschool children. Oral Health Prev Dent 2018, 16, 351-354 (https://doi.org/10.3290/j.ohpd.a40959).

41. Mascarenhas AK. Is fluoride varnish safe?: Validating the safety of fluoride varnish. J Am Dent Assoc 2021, 152, 364-368 (https://doi.org/10.1016/j.adaj.2021.01.013).

42. Weber B, Karels S, Neeley A. Colophony in dentistry: routes of exposure and reported reactions. Dermatitis 2025, 36, 452-455 (https://doi.org/10.1089/derm.2024.0356).

43. Wong MC, Zhang R, Luo BW, Glenny A-M, Worthington HV, Lo EC. Topical fluoride as a cause of dental fluorosis in children. Cochrane Database Syst Rev 2024, 6, Cd007693 (https://doi.org/10.1002/14651858.CD007693.pub3).

44. Lyne A, Ashley P, Johnstone M, Duane B. The environmental impact of community caries prevention - part 1: fluoride varnish application. Br Dent J 2022, 233, 287-294 (https://doi.org/10.1038/s41415-022-4901-7).

45. Elleray E, Lyne A, Duane B. Sustainability of different fluoride delivery methods. Dental Update 2025, 50, 707-709.

46. Morgan-Trimmer S, Chadwick BL, Hutchings S, Scoble C, Lisles C, Drew CJ et al. The acceptability of fluoride varnish and fissure sealant treatments in children aged 6-9 delivered in a school setting. Community Dent Health 2019, 36, 33-38 (https://doi.org/10.1922/CDH_4263Morgan-Trimmer06).

47. Seifo N, Cassie H, Radford JR, Innes NPT. Silver diamine fluoride for managing carious lesions: an umbrella review. BMC Oral Health 2019, 19, 145 (https://doi.org/10.1186/s12903-019-0830-5).

48. Lim SP, Zainal Aalam N, Chik Z, Musa S. The pharmacokinetics of 38% silver diamine fluoride in healthy children with dental caries: a quasi-experimental study. Eur Arch Paediatr Dent 2023, 24, 737-749 (https://doi.org/10.1007/s40368-023-00837-8).

49. Raghuthaman S, Bansal K, Quadri JA, Mathur VP, Tewari N, Morankar R. Salivary and urinary assessment of fluoride and silver ion concentrations after silver diamine fluoride application in children: a prospective cohort study. Eur Arch Paediatr Dent 2024, 25, 409-415 (https://doi.org/10.1007/s40368-024-00897-4).

50. Lin YS, Rothen ML, Milgrom P. Pharmacokinetics of 38% topical silver diamine fluoride in healthy adult volunteers. J Am Dent Assoc 2019, 150, 186-192 (https://doi.org/10.1016/j.adaj.2018.10.018).

51. Ruff RR, Whittemore R, Grochecki M, Bateson J, Barry Godin TJ. Silver diamine fluoride and oral health-related quality of life: a review and network meta-analysis. PLoS ONE [Electronic Resource] 2022, 17, e0261627 (https://doi.org/10.1371/journal.pone.0261627).

52. Haiat A, Ngo HC, Samaranayake LP, Fakhruddin KS. The effect of the combined use of silver diamine fluoride and potassium iodide in disrupting the plaque biofilm microbiome and alleviating tooth discoloration: a systematic review. PLoS One 2021, 16, e0252734 (https://doi.org/10.1371/journal.pone.0252734).

53. Magno MB, Silva LPD, Ferreira DM, Barja-Fidalgo F, Fonseca-Gonçalves A. Aesthetic perception, acceptability and satisfaction in the treatment of caries lesions with silver diamine fluoride: a scoping review. Int J Paediatr Dent 2019, 29, 257-266 (https://doi.org/10.1111/ipd.12465).

54. A Ahovuo-Saloranta A, Forss H, Walsh T, Nordblad A, Mäkelä M, Worthington HV. Pit and fissure sealants for preventing dental decay in permanent teeth. Cochrane Database of Systematic Reviews 2017, 7, CD001830 (https://doi.org/10.1002/14651858.CD001830.pub5).

55. Ramamurthy P, Rath A, Sidhu P, Fernandes B, Nettem S, Fee PA et al. Sealants for preventing dental caries in primary teeth. Cochrane Database of Systematic Reviews 2022, 2, CD012981 (https://doi.org/10.1002/14651858.CD012981.pub2).

56. Lam PPY, Sardana D, Ekambaram M, Lee GHM, Yiu CKY. Effectiveness of pit and fissure sealants for preventing and arresting occlusal caries in primary molars: a systematic review and meta-analysis. J Evid Based Dent Pract. 2020, 20, 101404 (https://doi.org/10.1016/j.jebdp.2020.101404).

57. Lam PPY, Lo ECM, Yiu CKY. Effectiveness of glass-ionomer sealant versus fluoride varnish application to prevent occlusal caries among preschool children over 18–24 months - a randomised controlled trial. J Dent 2024, 150, 105356 (https://doi.org/10.1016/j.jdent.2024.105356).

58. Morgan AG, Madahar AK, Deery C. Acceptability of fissure sealants from the child's perspective. Br Dent J 2014, 217, E2 (https://doi.org/10.1038/sj.bdj.2014.553).

59. Zhang B, Zhao M, Duan S, Tian J, Lei L, Huang R. An economic evaluation of pit and fissure sealants and fluoride varnishes in preventing dental caries: a systematic review. J Clin Pediatr Dent 2023, 47, 4-11 (https://doi.org/10.22514/jocpd.2023.048).

60. Akinlotan M, Chen B, Fontanilla TM, Chen A, Fan VY. Economic evaluation of dental sealants: a systematic literature review. Community Dent Oral Epidemiol 2018, 46, 38-46 (https://doi.org/10.1111/cdoe.12326).

61. Urquhart O, Tampi MP, Pilcher L, Slayton RL, Araujo MWB, Fontana M et al. Nonrestorative treatments for caries: systematic review and network meta-analysis. J Dent Res 2019, 98, 14-26 (https://doi.org/10.1177/0022034518800014).

62. Johhnson B, Serban N, Griffin PM, Tomar SL. Projecting the economic impact of silver diamine fluoride on caries treatment expenditures and outcomes in young U.S. children. J Public Health Dent 2019, 79, 215-221 (https://doi.org/10.1111/jphd.12312).

63. Nguyen TM, Tonmukayakul U, Hall M, Calache H. Cost-effectiveness analysis of silver diamine fluoride to divert dental general anaesthesia compared to standard care. Aust Dent J 2022, 67, 352-361 (https://doi.org/10.1111/adj.12936).

64. Schwendicke F, Göstemeyer G. Cost-effectiveness of root caries preventive treatments. J Dent 2017, 56, 58-64 (https://doi.org/10.1016/j.jdent.2016.10.016).

65. Yeung SST, Argáez C. Silver diamine fluoride for the prevention and arresting of dental caries or hypersensitivity: a review of clinical effectiveness, cost-effectiveness and guidelines. Ottawa (ON): Canadian Agency for Drugs and Technologies in Health; 2017.

66. Tan SHX, Wang Y, Lai CWM, Gao X, Wee H L, Lai BWP et al. Cost-effectiveness of silver diamine fluoride depends on caries activity: a decision analytic model. Caries Res 2025, 59, 1-10 (https://doi.org/10.1159/000544001).

67. Seifo N, Robertson M, MacLean J, Blain K, Grosse S, Milne R et al. The use of silver diamine fluoride (SDF) in dental practice. Br Dent J 2020, 228, 75-81 (https://doi.org/10.1038/s41415-020-1203-9).

68. Slayton RL, Urquhart O, Araujo MWB, Fontana M, Guzmán-Armstrong S, Nascimento MM et al. Evidence-based clinical practice guideline on nonrestorative treatments for carious lesions: A report from the American Dental Association. J Am Dent Assoc 2018, 149, 837-849 e819 (https://doi.org/10.1016/j.adaj.2018.07.002).

69. Heintze SD, Rousson V, Hickel R. Clinical effectiveness of direct anterior restorations--a meta-analysis. Dent Mater 2015, 31, 481-495 (https://doi.org/10.1016/j.dental.2015.01.015).

70. Heintze SD, Loguercio AD, Hanzen TA, Reis A, Rousson V. Clinical efficacy of resin-based direct posterior restorations and glass-ionomer restorations - an updated meta-analysis of clinical outcome parameters. Dent Mater 2022, 38, e109-e135 (https://doi.org/10.1016/j.dental.2021.10.018).

71. Veloso SRM, Lemos CAA, de Moraes SLD, do Egito Vasconcelos BC, Pellizzer EP, de Melo Monteiro GQ. Clinical performance of bulk-fill and conventional resin composite restorations in posterior teeth: a systematic review and meta-analysis. Clin Oral Investig 2019, 23, 221-233 (https://doi.org/10.1007/s00784-018-2429-7).

72. Pilcher L, Pahlke S, Urquhart O, O'Brien KK, Dhar V, Fontana M et al. Direct materials for restoring caries lesions: systematic review and meta-analysis - a report of the American Dental Association Council

on Scientific Affairs. J Am Dent Assoc 2023, 154, e1-e98 (https://doi.org/10.1016/j.adaj.2022.09.012).

73. Schwendicke F, Göstemeyer G, Stolpe M, Krois J. Amalgam alternatives: cost-effectiveness and value of information analysis. J Dent Res 2018, 97, 1317-1323 (https://doi.org/10.1177/0022034518782671).

74. da Costa JB, Frazier K, Duong ML, Khajotia S, Kumar P, Urquhart O et al. Defective restoration repair or replacement: an American Dental Association Clinical Evaluators Panel survey. J Am Dent Assoc 2021, 152, 329-330.e2 (https://doi.org/10.1016/j.adaj.2021.01.011).

75. Kanzow P, Wiegand A, Schwendicke F. Cost-effectiveness of repairing versus replacing composite or amalgam restorations. J Dent 2016, 54, 41-47 (https://doi.org/10.1016/j.jdent.2016.08.008).

76. Dorri M, Martinez-Zapata MJ, Walsh T, Marinho VCC, Sheiham (deceased) A, Zaror C. Atraumatic restorative treatment versus conventional restorative treatment for managing dental caries. Cochrane Database Syst Rev 2017, 12, CD008072 (https://doi.org/10.1002/14651858.CD008072.pub2).

77. Brenes-Alvarado A, Cury JA. Fluoride release from glass ionomer cement and resin-modified glass ionomer cement materials under conditions mimicking the caries process. Oper Dent 2021, 46, 457-466 (https://doi.org/10.2341/19-296-l).

78. Bapat RA, Parolia A, Chaubal T, Dharamadhikari S, Abdulla AM, Sakkir N et al. Recent update on potential cytotoxicity, biocompatibility and preventive measures of biomaterials used in dentistry. Biomater Sci 2021, 9, 3244-3283 (https://doi.org/10.1039/d1bm00233c).

79. Samuelsen JT, Dahl JE. Biological aspects of modern dental composites. Biomater Investig Dent 2023, 10, 2223223 (https://doi.org/10.1080/26415275.2023.2223223).

80. Member State Committee support document for identification of 4,4′-sulphonyldiphenol as a substance of very high concern. Helsinki: European Chemicals Agency; 2022.

81. Paula AB, Toste D, Marinho A, Amaro I, Marto C-M, Coelho A. Once resin composites and dental sealants release bisphenol-A, how might this affect our clinical management? —a systematic review. Int J Environ Res Public Health 2019, 16, 1627 (https://doi.org/10.3390/ijerph16091627).

82. Löfroth M, Ghasemimehr M, Falk A, Vult von Steyern P. Bisphenol A in dental materials - existence, leakage and biological effects. Heliyon 2019, 5, e01711 (https://doi.org/10.1016/j.heliyon.2019.e01711).

83. Marzouk T, Sathyanarayana S, Kim AS, Seminario AL, McKinney CM. A systematic review of exposure to bisphenol A from dental treatment. JDR Clin Trans Res 2019, 4, 106-115 (https://doi.org/10.1177/2380084418816079).

84. Tichy A, Srolerova T, Schwendicke F. Release of bisphenol A from dental materials: risks and future perspectives. J Dent Res 2025, 104, 1051-1060 (https://doi.org/10.1177/00220345251337728).

85. De Nys S, Duca RC, Vervliet P, Covaci A, Boonen I, Elskens M et al. Bisphenol A release from short-term degraded resin-based dental materials. J Dent 2022, 116, 103894 (https://doi.org/10.1016/j.jdent.2021.103894).

86. Lisiecka MZ. Allergic reactions in dental practice: classification of medicines, mechanisms of action, and clinical manifestations. Clin Rev Allergy Immunol 2025, 68, 17 (https://doi.org/10.1007/s12016-025-09032-7).

87. Paqué PN, Özcan M. A Review on biocompatibility of dental restorative and reconstruction materials. Curr Oral Health Rep 2024, 11, 68-77 (https://doi.org/10.1007/s40496-023-00358-9).

88. Chartres N, Cooper CB, Bland G, Pelch KE, Gandhi SA, BakenRa A et al. Effects of microplastic exposure on human digestive, reproductive, and respiratory health: a rapid systematic review. Environ Sci Technol 2024, 58, 22843-22864 (https://doi.org/10.1021/acs.est.3c09524).

89. Wang J, Xie LG, Wu XF, Zhao ZG, Lu Y, Sun HM. Impact of micro-nano plastics in daily life on human health: toxicological evaluation from the perspective of normal tissue cells and organoids. Toxicol Res (Camb) 2024, 13, tfae205 (https://doi.org/10.1093/toxres/tfae205).

90. Schmalz G, Widbiller M. Biocompatibility of amalgam vs composite - a review. Oral Health Prev Dent 2022, 20, 149-156 (https://doi.org/10.3290/j.ohpd.b2831749).

91. Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR). Final opinion on the guidance on the determination of potential health effects of nanomaterials used in medical devices. Luxemburg: European Commission; 2015 (https://data.europa.eu/doi/10.2772/41391).

92. Smith L, Ali M, Agrissais M, Mulligan S, Koh L, Martin N et al. A comparative life cycle assessment of dental restorative materials. Dent Mater 2023, 39, 13-24 (https://doi.org/10.1016/j.dental.2022.11.007).

93. Carbon modelling within dentistry: towards a sustainable future. London: Public Health England; 2018.

94. Mulligan S, Hatton PV, Martin N. Resin-based composite materials: elution and pollution. Br Dent J 2022, 232, 644-652 (https://doi.org/10.1038/s41415-022-4241-7).

95. Iliadi A, Koletsi D, Eliades T, Eliades G. Particulate production and composite dust during routine dental procedures. A Systematic Review with Meta-Analyses. Materials (Basel) 2020, 13, 2513 (https://doi.org/10.3390/ma13112513).

96. Mulligan S, Kakonyi G, Moharamzadeh K, Thornton SF, Martin N. The environmental impact of dental amalgam and resin-based composite materials. Brit Dent J 2018, 224, 542-548 (https://doi.org/10.1038/sj.bdj.2018.229).

97. Majstorović M, Babić Brčić S, Malev O, Par M, Živković I, Marciuš M et al. Environmental implications of dental restorative materials on the zebrafish Danio rerio: Are dental chair drainage systems an emerging environmental threat? Environ Toxicol Pharmacol 2024, 110, 104499 (https://doi.org/10.1016/j.etap.2024.104499).

98. Harding M, Sullivan T, Binner H, Kamali N, Hayes M. Assessment of the environmental and health impacts arising from mercury-free dental restorative materials. Wexford: Environmental Protection Agency; 2022.

99. Schmalz G, Schwendicke F, Hickel R, Platt JA. Alternative direct restorative materials for dental amalgam: a concise review based on an FDI policy statement. Int Dent J 2024, 74, 661-668 (https://doi.org/10.1016/j.identj.2023.11.004).

100. Santos M, Zare E, McDermott P, Santos Junior GC. Multifactorial contributors to the longevity of dental restorations: an integrated review of related factors. Dent J (Basel) 2024, 12 (https://doi.org/10.3390/dj12090291).

101. Suzuki M, Jordan RE. Glass ionomer-composite sandwich technique. J Am Dent Assoc 1990, 120, 55-57 (https://doi.org/10.14219/jada.archive.1990.0001).

102. Croll TP, Cavanaugh RR, Pedley RD. Posterior resin-based composite restorations: a second opinion. J Esthet Restor Dent 2002, 14, 303-312 (https://doi.org/10.1111/j.1708-8240.2002.tb00526.x).

103. Croll TP. The “sandwich” technique. J Esthet Restor Dent 2004, 16, 210-212 (https://doi.org/10.1111/j.1708-8240.2004.tb00037.x).

104. Panetta A, Lopes P, Novaes TF, Rio R, Fernandes GVO, Mello-Moura ACV et al. Evaluating glass ionomer cement longevity in the primary and permanent teeth—an umbrella review. J Funct Biomater 2024, 15, 48 (https://doi.org/10.3390/jfb15020048).

105. Raggio DP, Tedesco TK, Calvo AF, Braga MM. Do glass ionomer cements prevent caries lesions in margins of restorations in primary teeth?: A systematic review and meta-analysis. J Am Dent Assoc 2016, 147, 177-185 (https://doi.org/https://dx.doi.org/10.1016/j.adaj.2015.09.016).

106. Ge KX, Quock R, Chu CH, Yu OY. The preventive effect of glass ionomer restorations on new caries formation: A systematic review and meta-analysis. J Dent 2022, 125, 104272 (https://doi.org/10.1016/j.jdent.2022.104272).

107. Zulkifli S, Rahman AA, Kadir S, Nor NSM. Bisphenol A and its effects on the systemic organs of children. Eur J Pediatr 2021, 180, 3111-3127 (https://doi.org/10.1007/s00431-021-04085-0).

108. Mundstock Dias GR, Freitas Ferreira AC, Miranda-Alves L, Graceli JB, Pires de Carvalho D. Endocrine disruptors chemicals: impacts of bisphenol A, tributyltin and lead on thyroid function. Mol Cell Endocrinol 2025, 599, 112467 (https://doi.org/10.1016/j.mce.2025.112467).

109. Geens T, Aerts D, Berthot C, Bourguignon J-P, Goeyens L, Lecomte P et al. A review of dietary and non-dietary exposure to bisphenol-A. Food Chem Toxicol 2012, 50, 3725-3740 (https://doi.org/10.1016/j.fct.2012.07.059).

110. Ramírez V, Merkel S, Tietz T, Rivas A. Risk assessment of food contact materials. EFSA j 2023, 21, e211015 (https://doi.org/10.2903/j.efsa.2023.e211015).

111. Covaci A, Den Hond E, Geens T, Govarts E, Koppen G, Frederiksen H et al. Urinary BPA measurements in children and mothers from six European member states: overall results and determinants of exposure. Environ Res 2015, 141, 77-85 (https://doi.org/10.1016/j.envres.2014.08.008).

112. Govarts E, Gilles L, Rodriguez Martin L, Santonen T, Apel P, Alvito P et al. Harmonized human biomonitoring in European children, teenagers and adults: EU-wide exposure data of 11 chemical substance groups from the HBM4EU Aligned Studies (2014-2021). Int J Hyg Environ Health 2023, 249, 114119 (https://doi.org/10.1016/j.ijheh.2023.114119).

113. Kahn LG, Philippat C, Nakayama SF, Slama R, Trasande L. Endocrine-disrupting chemicals: implications for human health. Lancet Diabetes Endocrinol 2020, 8, 703-718 (https://doi.org/10.1016/s2213-8587(20)30129-7).

114. Choi J, Rotter S, Ritz V, Schöne K, Stöger R, Kortenkamp A. Thresholds of adversity for endocrine disrupting substances: a conceptual case study. Arch Toxicol 2024, 98, 2019-2045 (https://doi.org/10.1007/s00204-024-03748-9).

115. Demeneix B, Vandenberg LN, Ivell R, Zoeller RT. Thresholds and endocrine disruptors: an endocrine society policy perspective. J Endocr Soc 2020, 4, bvaa085 (https://doi.org/10.1210/jendso/bvaa085).

116. Brescia S. Thresholds of adversity and their applicability to endocrine disrupting chemicals. Crit Rev Toxicol 2020, 50, 213-218 (https://doi.org/10.1080/10408444.2020.1740973).

117. van den Beld AW, Kaufman J-M, Zillikens MC, Lamberts SWJ, Egan JM, van der Lely AJ et al. The physiology of endocrine systems with ageing. Lancet Diabetes Endocrinol 2018, 6, 647-658 (https://doi.org/10.1016/s2213-8587(18)30026-3).

118. Dantagnan C-A, Babajko S, Nassif A, Houari S, Jedeon K, François P et al. Analysis of resin-based dental materials' composition depending on their clinical applications. Polymers (Basel) 2024, 16, 1022 (https://doi.org/10.3390/polym16081022).

119. Vom Saal FS, Antoniou M, Belcher SM, Bergman A, Bhandari RK, Birnbaum LS et al. The conflict between regulatory agencies over the 20,000-fold lowering of the Tolerable Daily Intake (TDI) for bisphenol A (BPA) by the European Food Safety Authority (EFSA). Environ Health Perspect 2024, 132, 45001 (https://doi.org/10.1289/ehp13812).

120. EFSA Panel on Food Contact Materials, Enzymes and Processing Aids (CEP); Lambré C, Barat Baviera JM, Bolognesi C, Chesson A, Cocconcelli PS et al. Re-evaluation of the risks to public health related to the presence of bisphenol A (BPA) in foodstuffs. EFSA J 2023, 21, e06857 (https://doi.org/10.2903/j.efsa.2023.6857).

121. Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR). Opinion on the safety of the use of bisphenol A in medical devices. Luxemburg: European Commission; 2015 (https://data.europa.eu/doi/10.2772/75546).

122. Prueitt RL, Goodman JE. Evidence evaluated by European Food Safety Authority does not support lowering the temporary tolerable daily intake for bisphenol A. Toxicol Sci 2024, 198, 185-190 (https://doi.org/10.1093/toxsci/kfad136).

123. Report on divergent views between EFSA and EMA on EFSA's updated bisphenol A assessment. European Food Safety Authority/European Medicines Agency; 2023.

124. Fletcher R, Harrison W, Crighton A. Dental material allergies and oral soft tissue reactions. Br Dent J 2022, 232, 620-625 (https://doi.org/10.1038/s41415-022-4195-9).

125. Ahsan A, Ashley M. Hypersensitivity to dental composites and resin-bonding agents. Dent Update 2016, 43, 836-838, 841-832 (https://doi.org/10.12968/denu.2016.43.9.836).

126. Schmalz G, Hickel R, van Landuyt KL, Reichl FX. Scientific update on nanoparticles in dentistry. Int Dent J 2018, 68, 299-305 (https://doi.org/10.1111/idj.12394).

127. Colombo S, Beretta M, Ferrazzano GF, Paglia L. Dental sealants part 4: bisphenol A: what dentists should know. Eur J Paediatr Dent 2018, 19, 333-334 (https://doi.org/10.23804/ejpd.2018.19.04.15).

128. Richardson K, Steffen W, Lucht W, Bendtsen J, Cornell SE, Donges JF et al. Earth beyond six of nine planetary boundaries. Sci Adv 2023, 9, eadh2458 (https://doi.org/10.1126/sciadv.adh2458).

129. Integrating the social determinants of health into health workforce education and training. Geneva: World Health Organization; 2023 (https://iris.who.int/handle/10665/373710).

130. Global competency and outcomes framework for the essential public health functions. Geneva: World Health Organization; 2024 (https://iris.who.int/handle/10665/376577).

131. Martin N, Mulligan S, Shellard IJ, Hatton PV, editors. Consensus on environmentally sustainable oral healthcare: a joint stakeholder statement. York (UK): White Rose University Press; 2022 (https://doi.org/10.22599/OralHealth).

132. Amalgam (Part 1): Safe Management of Waste and Mercury: Adopted by the FDI General Assembly: 27-29 September 2021, Sydney, Australia. Int Dent J 2022, 72, 10-11 (https://doi.org/10.1016/j.identj.2021.11.008).

133. Colson DG. A safe protocol for amalgam removal. J Environ Public Health 2012, 2012, 517391 (https://doi.org/10.1155/2012/517391).

134. The Safe Mercury Amalgam Removal Technique (SMART). Florida (USA): International Academy of Oral Medicine and Toxicology; 2019.

135. Opdam NJ, Bronkhorst EM, Loomans BA, Huysmans MC. Longevity of repaired restorations: a practice based study. J Dent 2012, 40, 829-835 (https://doi.org/10.1016/j.jdent.2012.06.007).

136. Hopkins CE, Restrepo-Kennedy N, Elgreatly A, Comnick C, Vargas M, Teixeira EC et al. Fracture resistance of defective amalgam restorations repaired with a resin-based composite material. J Am Dent Assoc 2023, 154, 141-150 (https://doi.org/10.1016/j.adaj.2022.10.012).

137. Martin N, Hunter A, Constantine Z, Mulligan S. The environmental consequences of oral healthcare provision by the dental team. J Dent 2024, 142, 104842 (https://doi.org/10.1016/j.jdent.2024.104842).

138. WHO guidance for climate-resilient and environmentally sustainable health care facilities. Geneva: World Health Organization; 2020 (https://iris.who.int/handle/10665/335909).

139. Operational framework for building climate resilient and low carbon health systems. Geneva: World Health Organization; 2023 (https://iris.who.int/handle/10665/373837).

140. Baras A. Acting for planetary health by integrating an eco-responsible approach in practices : a French experiment in dental practice. International Health Trends and Perspectives 2022, 2, 27-47 (https://doi.org/10.32920/ihtp.v2i3.1713).

141. Martin N, Smith L, Mulligan S. Sustainable oral healthcare and the environment: mitigation strategies. Dental Update 2021, 48, 524-531 (https://doi.org/10.12968/denu.2021.48.7.524).

World Health Organization
Department of Noncommunicable Diseases and Mental Health
20 Avenue Appia
1211 Geneva 27 Switzerland
www.who.int
https://www.who.int/health-topics/oral-health

9789240116955