THE MINAMATA CONVENTION ON MERCURY IN SLOVENIA: AN EVALUATION OF POLICY IMPLEMENTATION AND EFFECTIVENESS IN RELATION TO THE PHASE-OUT OF DENTAL AMALGAM

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Doctoral Dissertation

MINAMATSKA KONVENCIJA O ŽIVEM SREBRU V SLOVENIJI: VREDNOTENJE IZVAJANJA IN UČINKOVITOSTI POLITIK V POVEZAVI Z OPUSTITVIJO UPORABE ZOBNEGA AMALGAMA

Doktorska disertacija

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To You, who believed in me, then and now, beyond the stars …
Tebi, ki si verjel vame, takrat in zdaj, onkraj zvezd …

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Abstract

The present dissertation evaluates the effectiveness of the Minamata Convention implementation in Slovenia with a specific focus on regulatory measures related to dental amalgam phase-out, by drawing on administrative and environmental metrics. It first examines policy implementation in the dental sector, particularly the phase-out of dental amalgam, and then evaluates actual mercury exposure patterns through human biomonitoring in children. Consistent with Article 22 of the Minamata Convention, these two components were used to determine how regulatory measures translate into measurable outcomes.

The administrative component of the dissertation investigates the responses of 171 dentists to a comprehensive questionnaire to understand current practice regarding the use and phase-out of dental amalgam. It assesses compliance with EU Regulation 2017/852, its 2024 amendment (Regulation (EU) 2024/1849), and the Minamata Convention. Conducted as a cross-sectional study, the research collected information on amalgam use, alternative restorative materials, legislation, and separator practices, while also identifying challenges and support needs for transitioning to mercury-free dentistry. The results revealed regional and sector specific variations in amalgam use, emphasizing the role of education, financial incentives, and safety standards on professional practices and the environmental impact. Amalgam use varied the most in adult clinics, influenced by clinical needs, patient preferences, and systemic barriers related to the reimbursement of costs for alternative materials that were not covered by health insurance until recently. Paediatric clinics demonstrated higher compliance with phase-out guidelines, highlighting the effectiveness of targeted training and policy interventions. These findings provide valuable insights for policymakers and other stakeholders to enhance and improve the planning and implementation of measures (primarily regulative) and support mechanisms to mitigate health risks associated with the use of mercury, and encourage transition to safer dental practices. Since the level of compliance with regulatory requirements varies across regions, targeted measures, particularly in adult clinics, were suggested to improve the transition process. Targeted educational programs and financial incentives are crucial for successful gradual phase-out of dental amalgam.

The environmental component of the dissertation analysed urinary mercury (U-Hg) concentrations in 1.412 Slovenian children across four human biomonitoring campaigns conducted between 2007 and 2024. Median U-Hg levels declined from 0.76 ng mL^{-1} in the 2007 PHIME cohort to 0.22 ng mL^{-1} in the 2018–2024 SLO-HBM-II cohort, paralleling reductions in the prevalence of amalgam fillings (from 65% to 3%) and the average number of fillings per child. Multilevel mixed-effects models showed a consistent temporal decline in U-Hg after controlling for demographic and environmental covariates, whereas including amalgam number substantially attenuated the time trend, suggesting that reduced amalgam use contributed to the overall decrease. As amalgam prevalence declined, other sources of exposure, such as fish consumption, became relatively more influential predictors of U-Hg, while children living in historically Hg-contaminated areas exhibited persistently higher levels. Although Slovenia phased down dental amalgam use in children before

ratifying the Minamata Convention, these long-term biomonitoring data illustrate how shifts in exposure sources are reflected in internal mercury levels and demonstrate the value of repeated national HBM programmes for tracing exposure pathways, monitoring their evolution, and providing evidence relevant to effectiveness-evaluation frameworks under Article 22 of the Minamata Convention.

Povzetek

Pričujoče delo ocenjuje učinkovitost izvajanja Minamatske konvencije v Sloveniji, s poudarkom na regulativnih ukrepih, povezanih s postopnim opuščanjem zobnega amalgama, ob upoštevanju administrativnih in okoljskih kazalnikov. V prvem delu obravnava izvajanje politik v zobozdravstvenem sektorju, zlasti postopno opuščanje uporabe zobnega amalgama, v drugem delu pa analizira dejanske vzorce izpostavljenosti živemu srebru na podlagi podatkov humanega biomonitoringa pri otrocih. V skladu z 22. členom Minamatske konvencije ta dva sklopa omogočata presojo, v kolikšni meri se regulativni ukrepi odražajo v merljivih učinkih.

Administrativni del naloge temelji na analizi odgovorov 171 zobozdravnikov, zbranih z obsežnim vprašalnikom, namenjenim razumevanju trenutnih praks glede uporabe in postopnega opuščanja zobnega amalgama. Ocenjena je skladnost zobozdravstvene prakse z Uredbo (EU) 2017/852, njeno spremembo iz leta 2024 (Uredba (EU) 2024/1849) ter Minamatsko konvencijo. Raziskava je bila izvedena kot presečna študija, pri kateri so bili z vprašalnikom zbrani podatki o uporabi amalgama, alternativnih materialih, poznavanju zakonodaje in praksah glede uporabe amalgamskih separatorjev, hkrati pa so opredeljeni ključni izzivi in potrebe po podpornih mehanizmih za prehod v zobozdravstvo brez uporabe živega srebra. Študija je pokazala regionalne in sektorske razlike pri uporabi amalgama ter poudarila ključno vlogo izobraževanja, finančnih spodbud, pomen ohranjanja varnostnih standardov za zobozdravstvene strokovnjake in varovanje okolja. Uporaba amalgama je bila najbolj variabilna v ambulantah za odrasle, kjer so nanjo vplivale klinične potrebe, preference pacientov in sistemske ovire, povezane s povračilom stroškov za alternativne materiale, ki jih obvezno zdravstveno zavarovanje do nedavnega ni priznalo. Pediatrične ambulante so pokazale višjo skladnost s smernicami za postopno opuščanje amalgama, kar poudarja učinkovitost ciljnega izobraževanja in političnih ukrepov. Rezultati študije nudijo dragocen vpogled v problemska področja, omogočajo podlago za snovalce politik in odločevalce ter druge, ki si prizadevajo za izboljšanje načrtovanja in izvajanje ukrepov (predvsem predpisov) in podpornih mehanizmov za zmanjšanje zdravstvenih tveganj, povezanih z uporabo živega srebra. Spodbujajo bolj učinkovit prehod na varnejšo zobozdravstveno varstvo. Ker se stopnja skladnosti s predpisanimi zahtevami med regijami razlikuje, so bili za izboljšanje procesa prehoda predlagani ciljno usmerjeni ukrepi, zlasti v ambulantah za odrasle. Ciljno usmerjeni izobraževalni programi in finančne spodbude so ključnega pomena za uspešno postopno popolno opuščanje zobnega amalgama.

Okoljski del doktorske naloge obravnava koncentracije živega srebra v urinu (U-Hg) pri 1.412 slovenskih otrocih, vključenih v štiri kampanje humanega biomonitoringa, izvedene med letoma 2007 in 2024. Mediana koncentracij U-Hg se je v tem obdobju znižala z 0,76 ng mL^{-1} v študijski populaciji PHIME leta 2007 na 0,22 ng mL^{-1} v študijski populaciji SLO-HBM-II v obdobju 2018–2024, kar sovpada z izrazitim zmanjšanjem razširjenosti amalgamskih zalivk (s 65 % na 3 %) in znižanjem povprečnega števila zalivk na otroka. Večnivojski mešani modeli z naključnimi učinki so pokazali dosleden časovni upad koncentracij U-Hg tudi po upoštevanju demografskih in okoljskih spremenljivk. Vključitev števila amalgamskih zalivk v modele je bistveno oslabila časovni trend, kar kaže, da je

zmanjšana uporaba amalgama pomembno prispevala k splošnemu zmanjšanju izpostavljenosti živemu srebru. Z upadanjem razširjenosti amalgama so drugi viri izpostavljenosti, zlasti uživanje rib, postali relativno pomembnejši napovedniki koncentracij U-Hg, medtem ko so otroci, ki živijo na območjih z zgodovinsko onesnaženostjo z živim srebrom, še naprej izkazovali višje ravni. Čeprav je Slovenija postopno opuščanje uporabe zobnega amalgama pri otrocih uvedla že pred ratifikacijo Minamatske konvencije, dolgoročni podatki humanega biomonitoringa ponazarjajo, kako se spremembe virov izpostavljenosti odražajo v notranjih ravneh živega srebra, ter potrjujejo pomen ponavljajočih se nacionalnih programov humanega biomonitoringa za sledenje potem izpostavljenosti, spremljanja njihovega razvoja in zagotavljanja podatkov, pomembnih za ocenjevanje učinkovitosti ukrepov v okviru 22. člena Minamatske konvencije.

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Abbreviations

ACGIH	... American Conference of Governmental Industrial Hygienists
AMAP	... Arctic Monitoring and Assessment Programme
ARIS	... Slovenian Research and Innovation Agency
ARSO	... Slovenian Environment Agency
B-Hg	... blood mercury
BMI	... body mass index
CHMS	... Canadian Health Measures Survey
COPHES	... Consortium to Perform Human Biomonitoring on a European Scale
CROME	... Cross-Mediterranean Environment and Health Network
CVAAS	... cold vapor atomic absorption spectrometry
DEMOCOPHES	... Demonstration of a Study to Coordinate and Perform Human Biomonitoring on a European Scale
EMEP	... European Monitoring and Evaluation Programme
ESBIO	... Expert Team to Support Biomonitoring in Europe
EU	... European Union
G-EQUAS	... German External Quality Assessment Scheme
GMR	... geometric mean ratio
HBM	... human biomonitoring
HBM4EU	... European Human Biomonitoring Initiative
HCWH	... Health Care Without Harm
Hg	... mercury
Hg^0	... elemental mercury
Hg^{+1} / Hg^{+2}	... inorganic mercury
ICP-MS	... inductively coupled plasma mass spectrometry
JSI	... Jožef Stefan Institute
LMMs	... linear mixed-effects models
LODs	... limits of detection
Me_2Hg	... methylmercury
MeHg	... dimethylmercury
MOPE	... Ministry of Environment, Climate and Energy
MVZI	... Ministry of Higher Education, Science and Innovation
MZ	... Ministry of Health
NIJZ	... National Institute of Public Health
NRC	... U.S. National Research Council
PARC	... European Partnership for the Assessment of Risks from Chemicals
PHIME	... Public Health Impact of Long-Term, Low-Level Mixed Element Exposure
QA	... Quality Assurance
QQQ-ICP-MS	... triple quadrupole inductively coupled plasma mass spectrometry
ReV	... reference values
SLO-HBM-II	... Second National Human Biomonitoring Program Study Population

TKI Hrastnik	. . . Chemical Industry Hrastnik
U-Hg	. . . urinary mercury
U-THg	. . . urinary total mercury
UNEP	. . . United Nations Environment Programme
URSK	. . . Chemical Office of the Republic of Slovenia
USEPA	. . . U.S. Environmental Protection Agency
WHA	. . . World Health Assembly
WHO	. . . World Health Organization
ZEOS	. . . Waste Electrical and Electronic Equipment Management Organization
ZZZS	. . . Health Insurance Institute of Slovenia

Chapter 1

Introduction

Mercury (Hg) has been known for a very long time as a toxic element that can cause serious harm to both the environment and human health. Its adverse effects have been documented for decades, particularly its impact on the nervous system and its tendency to persist and accumulate in natural ecosystems (UNEP/WHO, 2008; UNEP, 2019; AMAP/UNEP, 2013; Pacyna, 2020). Although these risks were recognized early by the scientific community, it took many years before this knowledge was translated into a coordinated international response. This long process eventually led to the adoption of the Minamata Convention on Mercury, which established a global framework for reducing Hg use, emissions, and releases (Science for Environment Policy, 2017; Toda et al., 2020; Basu et al., 2023). In this context, the Minamata Convention distinguishes between "emissions", referring to Hg releases to the atmosphere (air), and "releases", referring to discharges to land and water (UNEP, 2024).

The Convention addresses Hg from several different perspectives, ranging from environmental protection and public health to the regulation of Hg-containing products (Selin et al., 2018; UNEP, 2024; Basu et al., 2023). One of these perspectives concerns the Hg use in dentistry, specifically in dental amalgam. While amalgam has been widely used for more than a century because of its durability and affordability, it also represents a continuous source of Hg exposure for patients, dental professionals, and the environment (Tibau & Grube, 2019; Environmental Medicine, 2022; Tuček et al., 2020; HCWH Europe, 2017; European Commission, 2020). For this reason, dental amalgam has become an important focus of international and European Hg policies and is the central topic of this work.

This thesis is organized to reflect these considerations. The first part outlines the regulatory framework on Hg at the global, European Union, and national (Slovenian) levels, with particular attention to measures related to dental amalgam. The following subchapters address Hg exposure pathways, associated health effects, and the role of human biomonitoring in evaluating policy effectiveness, in line with the objectives of the Minamata Convention. The core of the thesis combines two complementary components, an administrative and policy-oriented assessment based on a nationwide survey of dental professionals, and an environmental and health-oriented assessment based on long-term human biomonitoring data collected in four cohorts of Slovenian children. Together, they enable evaluation of both the implementation of regulatory measures and their effects on internal Hg exposure trends. An integral part of the thesis is formed by the appendices. Appendices A and B contain the questionnaire for dental practitioners in English and in the original Slovene version, designed to collect data on current practices, regulatory awareness, and challenges related to the phase-down of dental amalgam and the use of amalgam separators. Appendix C provides access to the complete anonymized survey

dataset, and Appendix D presents the evidence package supporting the human biomonitoring analyses included in this work.

1.1 Regulatory Framework on Mercury

1.1.1 Global Level: The Minamata Convention on Mercury

The Minamata Convention is a multilateral environmental agreement, a global, legally binding treaty, which aims to protect human health and the environment from anthropogenic emissions and releases of Hg and its compounds. It was named after the city of Minamata in Japan where the release of MeHg in industrial wastewater from a chemical factory caused Hg poisoning and severe neurological damage to a local population. The Convention entered into force on 16 August 2017, and as of March 2026, it comprises 153 Parties (152 countries and the European Union). It has an important role in the broader agenda of management, environmental protection and sustainable development related to hazardous substances and chemicals (UNEP 2021; UNEP 2019; Shrama et al. 2019; Platjouw at al. 2018).

The Convention (UNEP, 2013; UNEP, 2024) covers all aspects of the Hg life cycle, controlling and reducing Hg use and supply across a range of products, processes and industries. This includes the control regarding:

- Hg supply sources and trade (Article 3);
- Hg use in products (Article 4);
- manufacturing processes that use Hg (Article 5);
- Hg use in artisanal and small-scale gold mining (ASGM; Article 7);
- air Hg emissions from coal-fired power facilities and other sectors (Article 8);
- releases of Hg to land and water (Article 9);
- interim storage of commodity Hg (Article 10);
- management of Hg-containing wastes (Article 11) and
- management of contaminated sites with Hg (Article 12).

Countries that have ratified the Convention are legally bound by international law to implement these controls and ensure the sound management of chemicals and hazardous waste. The Minamata Convention builds upon the Basel, Rotterdam, and Stockholm Conventions by establishing similar substantive obligations, while also mobilizing awareness-raising, technical assistance and financial resources for implementation, particularly in developing countries (UNEP, 2021; UNEP, 2024; Sharma et al., 2019). This integrated approach supports the science–policy interface and facilitates effective national-level implementation. Nonetheless, its success ultimately depends on national-level implementation and enforcement. Since 2021, parties must submit national reports every four years describing implementation measures, their effectiveness, and related challenges (UNEP, 2019; Platjouw et al., 2018).

In dentistry, the Convention calls for a phase-down of amalgam use, especially in children under 15 years, pregnant women, and nursing mothers, while promoting Hg-free alternatives and environmentally sound waste management (UNEP, 2013; UNEP, 2019; Varkey et al., 2014; Deloitte INERIS, 2020; UNEP, 2024). This commitment is further embedded in Article 4, which regulates Hg-added products, including dental amalgam. Annex A, Part II (UNEP, 2024) specifies that Parties must implement at least two of nine

measures, selected according to national conditions and international recommendations, to support the phase-down of dental amalgam use:

1. Setting national objectives aiming at dental caries prevention and health promotion, thereby minimizing the need for dental restoration;
2. Setting national objectives aiming at minimizing its use;
3. Promoting the use of cost-effective and clinically effective Hg-free alternatives for dental restoration;
4. Promoting research and development of quality Hg -free materials for dental restoration;
5. Encouraging representative professional organizations and dental schools to educate and train dental professionals and students on the use of Hg-free dental restoration alternatives and on promoting best management practices;
6. Discouraging insurance policies and programmes that favour dental amalgam use over Hg-free dental restoration;
7. Encouraging insurance policies and programmes that favour the use of quality alternatives to dental amalgam for dental restoration;
8. Restricting the use of dental amalgam to its encapsulated form; and
9. Promoting the use of best environmental practices in dental facilities to reduce releases of Hg and Hg compounds to water and land.

In addition, Parties that have not yet fully phased out the use of dental amalgam are required to submit a national action plan or a progress report to the secretariat every four years, as part of their regular national reporting, outlining the measures taken and progress achieved toward the phase-down or phase-out of dental amalgam (UNEP, 2024).

The Minamata Convention guidance on phase-down of use of dental amalgam provides a transitional period for countries to strengthen oral disease prevention and oral health promotion, reshape curricula of dental schools, adapt national health insurance schemes, and improve Hg waste management practices while effective and affordable Hg-free alternatives become increasingly available (Evers et al., 2016; HCWH Europe, 2017). Building on these gradual efforts, amendments to Annex A were adopted at the sixth meeting of the governing body of the Minamata Convention - Conference of the Parties (COP-6), establishing a global phase-out of dental amalgam by 2034. This decision was broadly acknowledged as a major milestone due to its science-based, time-bound commitment to eliminating Hg use in dentistry and protecting public health (UN Environment Programme, 2025).

Public health considerations are addressed most directly through Article 16 (Health Aspects), which encourages Parties to identify populations at risk of Hg exposure and to implement science-based measures aimed at reducing health impacts. These include preventive strategies, public information and education, and the strengthening of health-care services capable of addressing Hg related risks. The scientific basis for exposure assessment is provided by Article 19 (Research, Development and Monitoring), which calls for research and monitoring activities to assess Hg levels and their impacts on both human health and the environment. The article emphasizes the need for geographically representative monitoring and for the development of harmonized approaches to data collection and assessment. Within this framework, HBM represents a practical means of tracking population-level exposure and identifying temporal and spatial trends, even

though it is not explicitly mandated or methodologically standardized under the Convention (UNEP, 2024).

These health and monitoring elements are complemented by Articles 17 (Information exchange) and 18 (Public information, awareness and education), promoting the dissemination of scientific and epidemiological information on Hg risks, and strengthen education, training and public awareness related to the Hg exposure. Together, these provisions support the translation of monitoring data into risk communication and policy-relevant knowledge and are operationalized through Articles 20 (Implementation Plans) and 21 (Reporting). These two articles require Parties to integrate monitoring and assessment activities into domestic implementation frameworks and to report regularly on measures taken and their effectiveness. The reporting obligations provide the basis for comparing national progress and identifying remaining challenges (UNEP, 2024).

The evaluation of overall progress is formalized in Article 22 (Effectiveness Evaluation), which mandates periodic assessments of the Convention's effectiveness based on comparable monitoring data from environmental media and also biotic media and human populations (UNEP, 2024). The first effectiveness evaluation, initiated in 2023, marked an important step in assessing whether global efforts to Hg control are translating into measurable reductions in emissions, releases, and human exposure. At the same time, variability in exposure pathways, environmental responses, and health outcomes continues to introduce uncertainty into such assessments, highlighting the need for robust and transparent monitoring frameworks. Taken together, these provisions establish a governance structure in which HBM serves as a key, cross-cutting tool for evaluating the health relevance of Hg policies. However, despite its recognized importance, no universally agreed methodology, standardized framework, or harmonized time scale for human biomonitoring currently exists under the Minamata Convention. This lack of harmonization limits data comparability across countries and over time and remains a critical challenge for assessing global progress in reducing Hg-related health risks (Selin et al., 2018; Basu et al., 2018; Kocman et al., 2018; Evers et al., 2016).

1.1.2 EU Level: EU Mercury Regulation (EU Regulation 2017/852; Amending EU Regulation 2024/1849)

The European Union became a party to the Minamata Convention on Mercury in 2013, and aligned its Hg legislation with Convention's objectives through Regulation (EU) 2017/852, adopted in May 2017. This EU Regulation is binding in its entirety and directly applicable in all Member States. The regulation identifies dental amalgam as the Union's largest Hg use and a significant source of environmental contamination. Accordingly, it establishes a phased reduction of Hg use, with a particular focus on dental amalgam. In line with the strategic interventions outlined in Annex A, Part II of the Minamata Convention, the regulation addresses waste management, health system strengthening, and knowledge management, all of which are essential for reducing Hg exposure (European Parliament & Council, 2017).

The regulation (European Parliament & Council, 2017) places the use of dental amalgam within a structured phase-down approach. Article 10 sets out the parameters for the use of dental amalgam. It stipulates that from 1 January 2019, amalgam may only be used in pre-dosed encapsulated form, while the use of bulk Hg in dentistry is prohibited. Preventive health protection for vulnerable groups is prioritized. Since 1 July 2018, dental amalgam may not be used for dental treatment of deciduous teeth, children under 15, or pregnant and breastfeeding women unless strictly justified by a dental practitioner on

medical grounds. By 1 July 2019, each Member State was required to submit and publish a national plan outlining the measures it intends to implement to phase down the use of dental amalgam, in line with the Convention's recommendations.

Environmental protection measures have also been institutionalized. Article 10 obliges all dental facilities that use or remove amalgam to install amalgam separators from 1 January 2019. Separators introduced after 2018 must achieve a minimum retention capacity of 95% of amalgam particles, and all separators in use must meet this standard by 1 January 2021. These devices must be maintained according to manufacturer instructions to ensure optimal level of retention. Article 10 further mandates that amalgam waste, including amalgam residues, particles and fillings, and teeth, or parts thereof, contaminated by dental amalgam, is handled and collected by authorized waste management operators. Under no circumstances may such waste be discharged into the environment (European Parliament & Council, 2017).

The EU approach extends beyond product and process regulation by emphasizing professional training and systemic capacity-building. Its preamble underscores the importance of educating dental practitioners and dentistry students about Hg-free alternatives, particularly in the treatment of vulnerable populations. As well as the carrying out of oral health research and innovation in order to improve knowledge of existing materials, restoration techniques, and development of new materials (European Parliament & Council, 2017). This provision aligns closely with the Minamata Convention's broader objectives of knowledge development and health system strengthening.

Regulation (EU) 2017/852 also obliges Member States to establish effective enforcement mechanisms. Article 16 requires national legislation to provide penalties that are effective, proportionate, and dissuasive (European Parliament & Council, 2017). By August 2021, fifteen Member States had notified the European Commission of penalty structures addressing non-compliance, including breaches related to improper amalgam waste disposal or violations of restrictions applicable to vulnerable groups. In Sweden, Finland and Denmark dentist risk a fine or an imprisonment for up to two years. In Germany and Bulgaria, the fines are up to 50.000 €, in Austria up to 40.000 € (in case of repetition) in the Czech Republic up to 7.800 €, Slovakia up to 3.319 €, Romania up to 1.600 €, Latvia up to 1.400 € and Lithuania up to 600 € (Environment Medicine, 2021).

In 2024, the Union strengthened its regulatory approach through Regulation (EU) 2024/1849, which amends Regulation (EU) 2017/852 (European Parliament & Council, 2024). This amendment establishes a full phase-out of dental amalgam, prohibiting its use in the EU from 1 January 2025, except where a dental practitioner determines that amalgam is strictly necessary to address a specific medical need. A transitional derogation until 30 June 2026 applies to Member States in which dental amalgam is the only reimbursed restoration material and reimbursed at a rate of at least 90%, namely the Czech Republic and Slovenia. The amendment also prohibits the export of dental amalgam from 1 January 2025, and bans its manufacturing and import from 1 July 2026, with exemptions limited to medically justified uses. Furthermore, Annex II is expanded to prohibit six additional Hg-added products, demonstrating the EU's continued leadership in reducing Hg exposure.

The EU Regulation also imposes ethical obligations for dentists. To meet the legal and ethical obligations dental practitioners must repair or remove existing amalgam fillings only if they are deteriorating. There is no requirement to replace functioning amalgam fillings. The use of dental amalgam is allowed only when deemed strictly necessary, based on the individual needs of the patient, and in accordance with the Dental Council's Code of Practice on Professional Behavior and Ethical Conduct. Before using dental amalgam, dentists must ensure that explicit and informed consent has been obtained from the patient. This consent must be recorded in the patient's file and updated as necessary. The records

should clearly indicate that the decision to proceed with amalgam was made with the patient's or parent's full understanding and consent (Dental Council, 2025). The use of dental amalgam varies significantly among EU member states, influenced by professional, socio-economic, and environmental factors. Several countries have implemented stricter measures beyond the Minamata Convention. Norway and Sweden introduced national bans on dental amalgam in 2008 and 2009, while other EU countries, including France, Germany, Finland, and Austria have restricted its use in sensitive groups such as pregnant women, children, and patients with kidney disease (HCWH Europe, 2017; UNEP, 2016). Consequently, some Member States have begun transitioning to alternative restorative materials in public dental services or at least provide Hg-free options under the same reimbursement conditions as amalgam. When effective and aesthetically acceptable materials are reimbursed, demand for standard insured services may increase, leading to fewer private out-of-pocket payments for dental care. This shift affects both health insurance providers and dentists. Importantly, alternative filling materials are more tooth- and environmentally friendly, clinically effective, and no longer associated with elevated material costs, making the transition to Hg-free dentistry increasingly inevitable. These policies illustrate a broader trend toward reducing and ultimately eliminating Hg exposure from dental sources (HCWH Europe, 2017; HCWH Europe, 2018; UNEP, 2016). However, obstacles such as unequal levels of environmental awareness among dentists and varying skills in Hg-free techniques remain. Some Member States could therefore benefit from the experiences of Nordic countries, where Hg-free fillings have been in use for a longer period (Praktikertjänst AB, 2019).

1.1.3 Slovenia: National Implementation and Stakeholders

Slovenia is also among the countries that signed the Minamata Convention, and aligned its Hg legislation with the EU legal framework. In practice, implementation is ensured through a suite of EU regulations and directives, complemented by national acts, decrees and rules that cover all key stages of the Hg life cycle (Kocman et al., 2018; Chemicals Office of the Republic of Slovenia, 2021):

– For **Hg-added products and chemicals**, Slovenia relies on Regulation (EU) 2017/852 on Hg, which was subsequently amended by Regulation (EU) 2024/1849, introducing a reinforced phase-out of dental amalgam in the EU. These provisions operate alongside broader horizontal legislation, including Regulation (EU) No 649/2012 concerning the export and import of hazardous chemicals, Regulation (EC) No 1907/2006 (REACH)—in particular Annex XVII on restrictions—Directive 2011/65/EU on the restriction of hazardous substances in electrical and electronic equipment (RoHS), Regulation (EC) No 1223/2009 on cosmetic products, Regulation (EU) No 528/2012 on biocidal products, Regulation (EC) No 1107/2009 on plant protection products, and Directive 2006/66/EC on batteries and accumulators. At the national level, these instruments are complemented by the Pravilnik o vsebnosti nevarnih snovi v materialih in sestavnih delih motornih vozil (Rules on the content of dangerous substances in the materials and components of motor vehicles), as well as dedicated amalgam-related measures such as the Uredba o ravnanju z amalgamskimi odpadki, ki nastanejo pri opravljanju zdravstvene dejavnosti in z njo povezanih raziskavah (Decree on the management of amalgam waste generated by health services and related research activities) and the Nacionalni načrt o ukrepih za opustitev uporabe

amalgama v zobozdravstvu (National plan concerning the measures to implement the phase-out of the use of dental amalgam).

- **Control of industrial air emissions** from coal-fired power plants, industrial boilers, cement clinker production and waste incineration, is grounded in Directive 2010/75/EU on industrial emissions and the associated best available techniques (BAT) conclusions (Commission Implementing Decision 2013/163/EU for cement, lime and magnesium oxide), with implementation through national legislation. Key Slovenian instruments include the Zakon o varstvu okolja (Environmental Protection Act), the Uredba o vrsti dejavnosti in naprav, ki povzročajo industrijske emisije (Decree on the types of activities and installations that cause industrial emissions), the Uredba o mejnih vrednostih emisije snovi v zrak iz velikih kurilnih naprav (Decree on limit values for emissions from large combustion plants into the atmosphere), the Pravilnik o prvih meritvah in obratovalnem monitoringu emisije snovi v zrak iz nepremičnih virov onesnaževanja ter o pogojih za njegovo izvajanje (Rules on initial measurements and operational monitoring of the emission of substances into the atmosphere from stationary pollution sources and on the conditions for their implementation), and the Uredba o sežigalnicah odpadkov in napravah za sosežig odpadkov, together with its amending decree (Uredba o spremembi in dopolnitvi Uredbe o sežigalnicah odpadkov in napravah za sosežig odpadkov) (Decree on waste incineration and co-incineration plants).
- **Releases to water** are regulated primarily through the Uredba o emisiji snovi in toplote pri odvajanju odpadnih voda v vode in javno kanalizacijo (Decree on the emission of substances and heat when discharging waste water into waters and the public sewage system) and the Pravilnik o prvih meritvah in obratovalnem monitoringu odpadnih voda (Rules on initial measurements and operational monitoring of wastewater), which define emission limit values, monitoring regimes and reporting obligations for both municipal and industrial wastewater discharges. Waste management and landfilling of Hg-containing wastes are governed by the Uredba o odpadkih (Decree on waste), the Uredba o predelavi nenevarnih odpadkov v trdno gorivo in njegovi uporabi (Decree on the recycling of non-hazardous waste into solid fuel and on its use), and, for final disposal, the Uredba o odlagališčih odpadkov (Decree on waste landfill), which establishes detailed provisions on operational monitoring of meteorological parameters, landfill gas, leachate, surface and groundwater quality, and annual reporting.
- **Management of contaminated sites**, particularly those related to the historic Idrija Hg mine and its downstream basin, is framed by mining-specific legislation including the Zakon o rudarstvu (Mining Act), the Zakon o preprečevanju posledic rudarjenja v rudniku živega srebra Idrija (Prevention of Effects of Mining in the Idrija Mercury Mine Act), the Odločba Ministrstva za infrastrukturo o prenehanju rudarskih pravic RŽS Idrija ter prenosu vzdrževanja nezalitega dela jame in monitoringa vplivnega območja rudnika na CUDHg Idrija (Decision of the Ministry of Infrastructure on termination of mining rights of the Idrija Hg Mine and transfer of maintenance and monitoring to the Idrija Hg Heritage Management Centre), and the "Rudarski projekt - Opazovanje (monitoring) vplivnega območja Rudnika živega srebra Idrija po končanih delih«, authorised by the Ministry of Economic Development and Technology ("Mining project - Monitoring of the impact area of the Idrija Hg Mine after closure").

Taken collectively, this coordinated EU–national framework enables the practical implementation of Slovenia's commitments under the Minamata Convention, encompassing product regulation, industrial processes, emission and release controls, waste management, and the remediation of contaminated sites.

Within Slovenia's Hg regulatory framework, the EU Mercury Regulation (EU) 2017/852, directly binding across all Member States, serves as the key instrument governing the use of dental amalgam. Slovenia has implemented this regulation by prohibiting bulk amalgam and permitting only pre-dosed encapsulated formulations. In addition, dental practices are required to install and maintain amalgam separators with a minimum retention capacity of 95%, ensuring the capture of particles containing Hg during clinical procedures and preventing Hg-contaminated waste from entering wastewater systems. In 2021, the Slovenian Ministry of Health introduced a National Plan on Measures for the Gradual Phase-Out of Dental Amalgam Use by 2030, subsequently revised in 2024 following the adoption of amending Regulation (EU) 2024/1849 (Slovenian Ministry of Health, 2021, 2024a, 2024b). Although the amendment establishes an EU-wide ban on the use of dental amalgam from 1 January 2025, Slovenia formally invoked the derogation clause due to socioeconomic considerations surrounding access to care, allowing the continued use of amalgam until 30 June 2026. This exemption reflects the structure of the national public healthcare system, in which amalgam remains the only restorative material fully reimbursed, resulting in its continued use in more than 30% of dental restorations (Perharič, 2014). From 1 July 2026 onwards, newly placed composite fillings will be covered under compulsory health insurance, whereas elective replacement of intact amalgam restorations will remain self-paid unless clinically justified (Zavod za zdravstveno zavarovanje Slovenije, 2024).

Another challenging issue factor is the lack of comprehensive quantitative data on amalgam consumption, waste generation, and disposal pathways (Deloitte INERIS, 2020), which limits the capacity to accurately assess environmental releases and human exposure. In alignment with Article 19 of the Minamata Convention, Slovenia therefore aims to strengthen inventory methodologies, expand representative monitoring of Hg levels in vulnerable population groups and natural environments, and improve assessments of Hg-related risks to human health and ecosystems.

In Slovenia, various institutions and stakeholders play a key role in implementing legislation and the Minamata Convention, as well as addressing related educational, health and environmental issues, as presented in Figure 1. Together they form an interconnected and coordinated framework to address Hg pollution, from legislation to monitoring and education to ensure effective outcomes. The Ministry of Environment, Climate and Energy (Ministrstvo za okolje, podnebje in energijo, MOPE) is responsible for implementing environmental policies, developing strategies to reduce Hg emissions and ensuring compliance with EU and global regulations, including the Minamata Convention. At the same time, the Ministry of Health (Ministrstvo za zdravje, MZ) works closely with MOPE on policies to limit Hg use, raise awareness of its negative health effects and address the public health impacts of Hg exposure. The Ministry of Higher Education, Science and Innovation (Ministrstvo za visoko šolstvo, znanost in inovacije, MVZI), together with universities and research institutions such as the Jožef Stefan Institute (JSI), integrates Hg-related educational issues into their programs, raising awareness about Hg pollution and its environmental and health risks. This collaborative effort is crucial for ensuring that both the general public and the oral health professionals are informed and prepared for transition to safer, Hg-free alternatives. Evidence-based reviews also encourage insurance companies to support policies that favor the use of safe, Hg-free materials, such as composites (Kocman et al., 2018; Usenik et al., 2025).

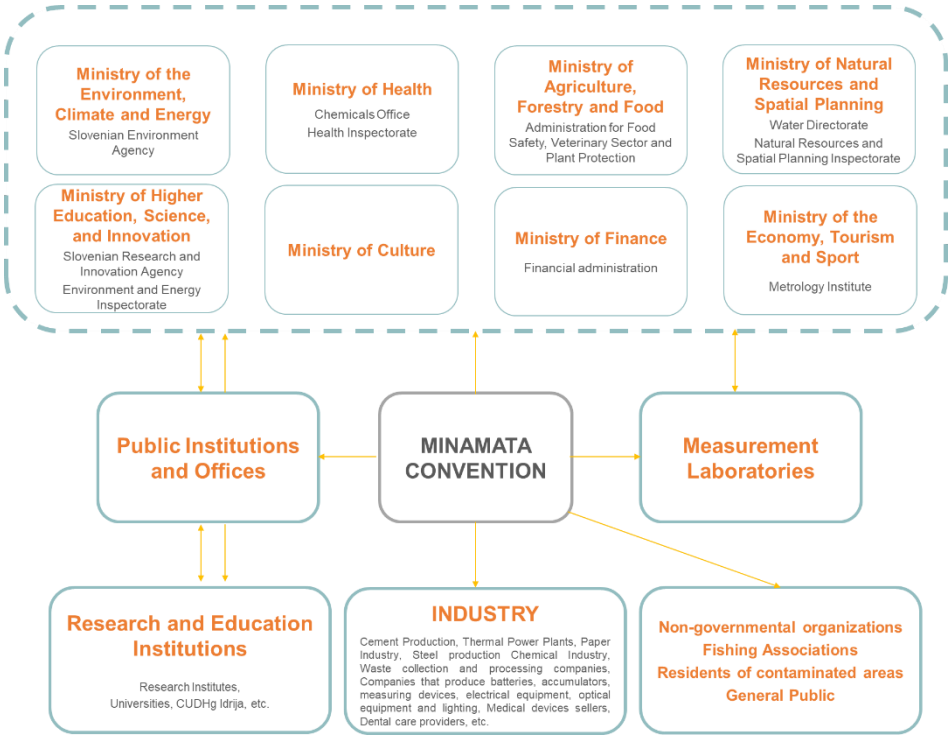


Figure 1: The interconnections among political institutions and stakeholders addressing educational, health, and environmental issues are crucial for the implementation of legislation and the Minamata Convention in Slovenia (Usenik et al., 2025).

Efficient waste management is essential to ensure the safe handling, disposal, and recycling of Hg-containing materials, particularly dental amalgam. Slovenia has already established robust waste management systems that monitor and control Hg emissions from various sectors, including dental practices. The Slovenian Environment Agency (Agencija Republike Slovenije za okolje, ARSO) plays a key role by monitoring Hg content in air, water, and soil, as well as providing data in accordance with international standards to support policy making. This ensures that Hg is managed safely throughout its lifecycle, contributing to both environmental protection and public health. Industries like Alpacem Anhovo and Chemical Industry Hrastnik (TKI Hrastnik) and Waste Electrical and Electronic Equipment Management Organization (ZEOS) take care about implementing the measures to prevent the release of Hg into the environment due to their industrial processes. Furthermore, local governments implement national policies at the local level to ensure the safe disposal of Hg-containing products (Kocman et al., 2018; Usenik et al., 2025).

Although the country has an established and functioning waste management system, challenges remain in the final disposal of hazardous waste, which is currently exported abroad, exposing gaps in infrastructure due to the lack of a dedicated disposal facility (Chemicals Office of the Republic of Slovenia, 2021). Additionally, cremation of individuals with amalgam fillings remains an insufficiently regulated source of Hg emissions. Although crematoria contribute less to overall Hg emissions compared to major sectors like energy production and waste incineration, their proximity to residential areas and lower emission release points suggest that the risks of local exposure may be underestimated. This

highlights a clear gap in current regulatory and monitoring frameworks and underscores the need for more targeted policy measures (Štamfelj et al., 2025).

Slovenia's health system is already aligned with the National Plan for the gradual phase-out of dental amalgam, with steps taken to ensure that the oral health workforce is adequately trained and equipped to handle new materials. The National Institute of Public Health (Nacionalni inštitut za javno zdravje, NIJZ) plays an important role in developing health guidelines and recommendations on Hg exposure, conducting research, and actively communicating with the public about the health risks posed by Hg. Following health guidelines and recommendations regarding Hg exposure, as well as legislative requirements and commitments under the Minamata Convention, the Medical Chamber and dentists strive to minimize health risks associated with exposure to amalgam fillings (Kocman et al., 2018; Usenik et al., 2025). In line with these commitments and the Minamata Convention, Slovenia has also implemented a national HBM programme within the framework of the Chemicals Act, aimed at tracking environmental exposure trends and evaluating the effectiveness of health and environmental policies (Snoj Tratnik et al., 2019a; NIJZ, 2023).

A collaborative approach among political institutions and stakeholders ensures reaching their common goal of reducing Hg exposure, protecting public health and preserving the environment. However, effective implementation of the Convention will depend on a clear allocation of responsibilities across institutions and sectors. Establishing an intersectoral committee could help coordinate cooperation, planning, and the implementation of Convention-related activities (Kocman et al., 2018; Fisher et al., 2018; Usenik et al., 2025).

1.2 Hg Sources and Environmental Fate

Hg is a naturally occurring environmental pollutant that is toxic to humans and wildlife (Driscoll et al., 2013; Basu et al., 2018). Because of its persistence in the environment, its ability to bioaccumulate, and its wide range of adverse health effects, the WHO has identified Hg as one of the ten chemicals of greatest public health concern (UNEP, 2021). Once introduced in the environment from variety of natural and anthropogenic sources, Hg cycles between atmosphere, terrestrial and aquatic systems. This global cycling enables Hg to spread far from its original source, resulting in widespread environmental contamination and long-term ecological and human health impacts, causing severe damage to the environment and humanity as a whole (UNEP, 2021; EEA, 2018; AMAP/UNEP, 2013; AMAP/UN Environment, 2019; Evers et al., 2016).

In the environment it exists in three main chemical forms: elemental mercury (Hg^0), inorganic mercury (Hg^{+1} and Hg^{+2}), and organic Hg species such as methylmercury (MeHg) and dimethylmercury (Me_2Hg). These forms differ substantially in their environmental behavior, bioavailability, and toxicokinetic properties (Driscoll et al., 2013; Basu et al., 2018; Jirau-Colón et. al, 2019; Esteban-López et al., 2022).

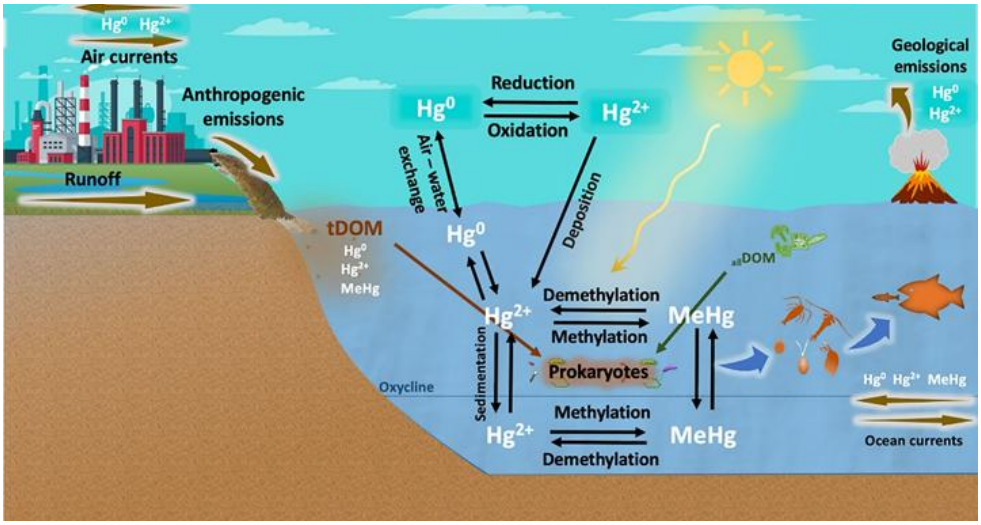


Figure 2: Geobiochemical Hg Cycle (Reproduced from Rodríguez, 2023).

Natural processes such as volcanic eruptions, soil erosion, wetlands, and oceanic emissions contribute to the atmospheric Hg levels, but human activities remain the dominant driver of global pollution. The combustion of fossil fuels, industrial activities, and the use of Hg containing products represent the main anthropogenic sources. Hg released from these sources is predominantly emitted as elemental mercury (Hg^0), which can be transported over long distances by atmospheric currents (UNEP, 2021; EEA, 2018; AMAP/UNEP, 2013; AMAP/UN Environment, 2019; Evers et al., 2016). Hg^0 can be oxidized by halogen compounds, nitrate radicals, or ozone, forming divalent Hg^{2+}, which is then deposited into terrestrial and aquatic environments (Ariya and Peterson, 2005; AMAP/UNEP, 2013). While part of the deposited Hg^{2+} can be reduced back to Hg^0 and subsequently emitted to the atmosphere, the majority of Hg^{2+} binds to stable molecules in surface waters and sediments, where it can persist for long periods (Krabbenhoft and Sunderland, 2013). In aquatic ecosystems, microbial methylation transforms inorganic Hg to MeHg. This transformation enhances its bioavailability and facilitates its uptake by biota, with subsequent bioaccumulation and biomagnification across food webs (Ullrich et al., 2001; AMAP/UNEP, 2013; Rodríguez, 2023) (Figure 2).

In the process of industrialization, human activities have contributed to a multiple-fold increase in Hg levels across various environmental compartments, ultimately leading to widespread human exposure to Hg around the world. Industrial processes such as metal smelting and processing, Hg-added manufacturing processes and waste disposal, fossil fuel combustion, are anthropogenic actions that raise Hg levels locally, regionally and globally (UNEP, 2021; EEA, 2018: UNEP, 2019; Science for Environment Policy, 2017; AMAP/UNEP, 2013; AMAP & UN Environment; 2019). Economic and population growth, increased consumption and industrial production are expected to have significant effects on global, regional and local Hg cycles, with unexpected feedback and nonlinear impacts on exposure (Pacyna et al., 2008; Sundseth et al. 2013).

Asia currently represents the largest contributor to global Hg emissions, while Europe's share is limited to about 4.5% (AMAP/UN Environment, 2019; Driscoll et al., 2013). Despite the transboundary Hg nature, only the EU and a few other countries (e.g., Norway, Switzerland, the USA, Canada and Japan) have implemented measures to reduce or phase out Hg use, while several Asian countries have seen increasing Hg pollution driven by industrialization (Deloitte INERIS, 2020). Consequently, it has been recognized by the scientific community that international commitment is needed to face the Hg problem on

a global scale, and the world community took decisive action by agreeing on the Minamata Convention on Mercury, the most recent global agreement on environment and health, adopted in 2013 and entered into force in 2017, addressing the entire Hg lifecycle, with the primary objective of establishing control measures to limit global Hg supply in order to protect human health and the environment (UNEP, 2021; EEA, 2018: UNEP, 2019).

1.3 Human Health Implications

Global exposure to Hg varies geographically and demographically. The general population is most frequently exposed to MeHg through the consumption of fish and seafood, while Hg^0 exposure originates from consumer products (e.g., some skin-lightening cosmetics, broken thermometers or fluorescent bulbs) and dental amalgam (see Figure 3) (Driscoll et al., 2013; Basu et al., 2018; Jirau-Colón et al., 2019; Varkey et al., 2014; Boerleider et al., 2017; Goodrich et al., 2016; European Human Biomonitoring Initiative, 2022). Occupational exposure to elemental and inorganic Hg is found in settings such as chlor-alkali plants, Hg mining, artisanal gold and silver extraction, metal refineries, thermometers and Hg-based chemical manufacturing, and dental clinics with inadequate handling. Once emitted, the atmospheric Hg is deposited in aquatic ecosystems. There, microorganisms convert it into MeHg, which accumulates and biomagnifies through aquatic food chains (Driscoll et al., 2013). Monitoring of seafood has consistently shown elevated Hg levels in predatory fish such as tuna, swordfish, shark, and pike, making the consumption of contaminated fish, shellfish, and marine mammals a major exposure pathway worldwide (Esteban-López et al., 2022; European Food Safety Authority, 2012; European Human Biomonitoring Initiative, 2022). In certain contaminated regions, rice cultivated on Hg-polluted soils can also represent a meaningful dietary source of exposure (Rothenberg et al., 2014).

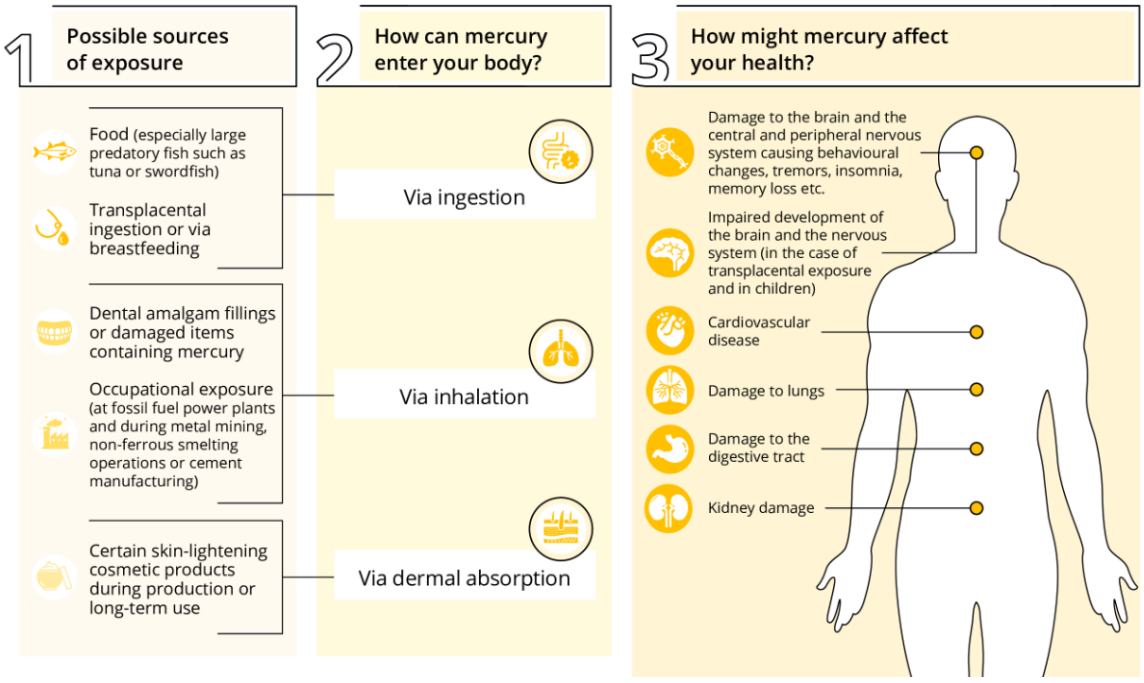


Figure 3: Overview of Hg exposure sources, pathways and health effects (Reproduced from European Human Biomonitoring Initiative, 2022).

Evidence from HBM studies demonstrates that, despite regulatory progress, legacy Hg contamination remains a persistent source of internal human exposure, especially in regions with a long history of industrial Hg use or mining. Past activities continue to pollute soils and aquatic bodies, especially in regions with a long history of industrial Hg use or mining (Basu et al., 2018; UNEP/WHO, 2008). In Slovenia, elevated Hg levels in soil, particularly in the town of Idrija, are a result of over 500 years of mining and smelting activities, as well as the natural geological Hg presence. These high soil Hg concentrations have led to increased Hg levels in local food products (Kocman et al., 2011; Miklavčič et al., 2013), which poses a potential route for inorganic Hg exposure among the town residents. Moreover, certain areas in Idrija still experience high Hg vapor concentrations in the air, especially during the summer when higher temperatures occur. Previous research in Idrija has shown that residents, including children, have higher urinary and blood Hg concentrations than those in uncontaminated areas (Kobal et al., 2017; Snoj Tratnik, 2019a). This reflects the long-standing contamination of multiple environmental compartments (air, soil, water) in Idrija, resulting from centuries of mining and smelting. For children, inhalation of Hg from ambient air is likely the predominant exposure pathway, as ingestion of locally sourced foods such as seasonal vegetables and fish from the Idrijca river or local markets probably represents only a minor contribution (Kobal et al., 2017). This pattern is consistent with international evidence showing that children living in historically polluted regions across Europe also exhibit elevated U-Hg levels (Astolfi et al., 2020), and parallels observations from artisanal gold mining areas in Asia and Africa, where legacy contamination increased Hg biomarkers in children even without major dietary or dental sources (Ha et al., 2017; Bose-O'Reilly et al., 2010). Together, these findings demonstrate that although the relative contribution of environmental Hg exposure has declined over time, legacy pollution continues to measurably increase body burden. This underscores the need for targeted surveillance and remediation strategies, in line with recommendations from European HBM coordination initiatives to systematically integrate legacy contamination sites into national monitoring frameworks (Den Hond et al., 2015; Schindler et al., 2014).

Among different Hg species, MeHg is considered particularly hazardous for human health implications because microbial methylation converts inorganic Hg into a more bioavailable form that is readily absorbed by organisms, bioaccumulates over time, and biomagnifies through aquatic food webs (UNEP, 2021; EEA, 2018; AMAP/UNEP, 2013; AMAP & UN Environment, 2019; Evers et al., 2016). Elemental Hg^0 vapor also poses substantial risks, as it easily crosses the blood–brain and placental barriers and can affect the central nervous system (Homme et al., 2014; Varkey et al., 2014). Early-life exposure is especially dangerous, fetuses and young children being highly vulnerable to irreversible neurodevelopmental impairments (AMAP/UNEP, 2013; EEA, 2018; Evers et al., 2016; Boerleider et al., 2017; Esteban-López et al., 2022). A wide variety of symptoms has been reported, and these symptoms are generally comparable regardless of the specific Hg compound to which one is exposed. Notable neurological manifestations include tremors, emotional lability, insomnia, memory loss, neuromuscular changes, headaches, polyneuropathy, and performance deficits in tests of cognitive and motor function. While many neurological issues tend to improve upon removal of persons from the source of exposure, some changes may be irreversible (WHO, 2003).

1.4 Dental Amalgam as an Exposure Source

Amalgam has been in clinical use for more than 150 years, largely due to its durability and low cost. Despite its utility, dental amalgam is now the largest intentional use of Hg in the European Union (EU) and a significant contributor to global Hg pollution, particularly after the phase-out of Hg in the chlor-alkali industry in 2017, with estimates suggesting that more than 1.000 tonnes of Hg are present in the mouths of EU residents (European Environment Agency, 2019; HCWH Europe, 2017).

Composed primarily of 50% Hg, along with silver (35%), and small amounts of tin, copper, and zinc, its composition has raised longstanding concerns about human exposure to Hg vapor released during the placement, use, and removal of amalgam fillings, affecting not only patients but also dental workers who may experience occupational exposures during these procedures (Kall et al., 2016; Picard et al., 2025).

The extent of exposure depends on the number and surface area of restorations, individual oral habits, the body's ability to excrete Hg, the age and quality of the amalgams, as well as the frequency of consuming hot food and drinks (Brownawell et al., 2005; Perharič, 2014; Varkey et al., 2014; Environmental Medicine, 2022). Hg vapor is continuously released from amalgam fillings, particularly during chewing and tooth brushing, and may accumulate in various organs, especially the kidneys and brain (Mutter et al., 2004; Astolfi et al., 2020). For most individuals, daily Hg exposure from amalgam is estimated to be below 5 µg, although reported intakes vary between 1 and 27 µg per day (WHO, 2003; Kall et al., 2016). Amalgam fillings release Hg into the oral cavity as inhalable vapor, as dissolved ionic Hg after oxidation, or as amalgam particles suspended in saliva. Corrosion, mechanical stress, and removal of amalgam restorations by drilling can markedly enhance Hg vapor release, thereby substantially increasing individual exposure. Over time, chewing, brushing teeth, consuming hot beverages, and teeth corrosion can deteriorate the fillings, contributing to Hg in human waste waters (excrets and feces) (Homme et al., 2014; Kall et al, 2016; Picard et al., 2025).

Dental personnel are among the largest occupational groups exposed to elemental Hg^0, primarily through Hg vapor released during amalgam preparation and tooth restoration (Manyani et al., 2021; Bjørklund et al., 2019). Measurements in clinical settings indicate relevant concentrations. Personal air sampling in dental workplaces detected average total Hg levels of approximately 2.2 µg m^{-3} for dentists and 3.0 µg m^{-3} for dental nurses, underscoring the persistence of occupational exposure (Tuček et al., 2020). In addition, the introduction of high-speed dental drills has increased Hg exposure. Compared to slower rotary systems, they create much finer particles and generate more heat during amalgam removal, which leads to higher Hg vapor release. Cooling with water helps lower the temperature, but it also results in a greater amount of Hg entering the wastewater (Praktikertjänst AB, 2019). Goodrich et al. (2016) reported that, despite the ongoing occupational exposure, urinary Hg levels among dental professionals in US have declined over the past several decades due to the implementation of improved safety measures and changes in workplace practices.

Expert panels from Europe, the United States, Canada, and Australia have found no conclusive evidence linking dental amalgam to adverse health effects in the general population, apart from rare cases of hypersensitivity (Brownawell et al., 2005; Driscoll et al., 2013). Nevertheless, precautionary measures are recommended, particularly for sensitive groups such as pregnant or breastfeeding women, children, and individuals with pre-existing neurological or renal conditions (Basu et al., 2023; Geier & Geier, 2024). Infants and young children constitute a highly vulnerable subgroup due to higher relative

exposure to environmental contaminants, greater gastrointestinal absorption, and immature hepatic and renal detoxification pathways (Grandjean & Landrigan, 2006).

Countries are at markedly different stages in adopting the dental amalgam phase-down. While several high-income countries discontinued its use more than 15 years ago, many low- and middle-income countries still report high usage, constrained by funding limitations, weak policy support, and insufficient awareness or dental training in alternatives (Kisumbi et al., 2025). Cost concerns persist across all income levels and disproportionately affect underprivileged populations, despite growing consumer awareness of environmental and indirect health impacts and the aesthetic advantages of Hg-free restorative materials, which have become key drivers of reduced amalgam use (European Commission, 2020). According to Minamata Convention Full National Reports 2021 and Minamata Initial Assessments the global transition toward Hg-free dentistry is advancing, with 43 countries banning amalgam by law, 10 withdrawing it from public programs or prohibiting import and manufacture, 13 reporting it is no longer used, and 12 restricting its use in children under 15, pregnant, and breastfeeding women (Figure 4) (EnvMed Network, 2025). Nevertheless, substantial regional variation in amalgam use necessitates reinforced preventive measures and systematic biomonitoring for professionals exposed to it (Kall et al., 2016; Picard et al., 2025; Manyani et al., 2021). Although Hg-free alternatives are widely available and clinically suitable for most indications, adoption remains limited due to higher treatment costs, insufficient professional training, perceived lower durability, and reluctance to change established practices or invest in equipment (Praktikertjänst AB, 2019). WHO emphasizes that strong multisectoral collaboration mechanism between ministries of health and environment, supported by time-bound national roadmaps with clearly defined stakeholder roles, is essential to accelerate amalgam phase-down (UNEP, 2023). Moreover, targeted education, improved awareness of clinical benefits, and financial incentives such as reimbursement schemes are needed to enable equitable access and foster a sustainable transition to Hg-free restorative dentistry (UNEP, 2023; European Commission, 2016).

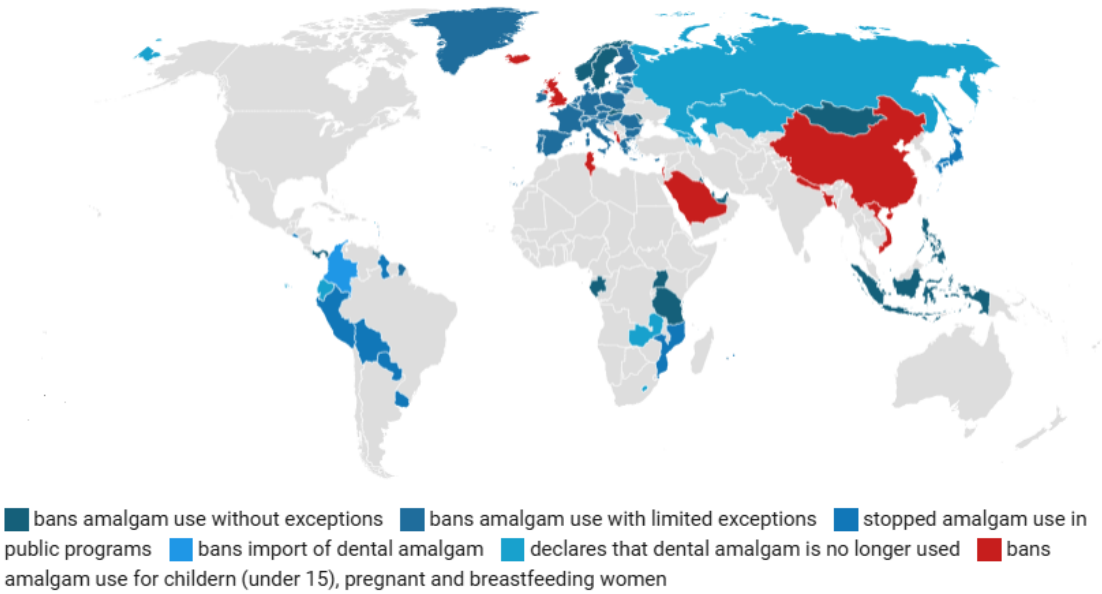


Figure 4: Global overview of countries phasing out dental amalgam (Reproduced from EnvMed Network, 2025).

Aside from individual exposure, dental amalgam represents a significant contributor to environmental Hg pollution, with Hg being released through wastewater, human waste, cremation, burial of deceased with amalgam fillings, and Hg vapor emissions, all of which contaminate air, soil, and water (Fisher et al., 2018; Tibau & Grube, 2019; Floyd et al. 2002; HCWH Europe, 2018) (see Figures 5 and 6).

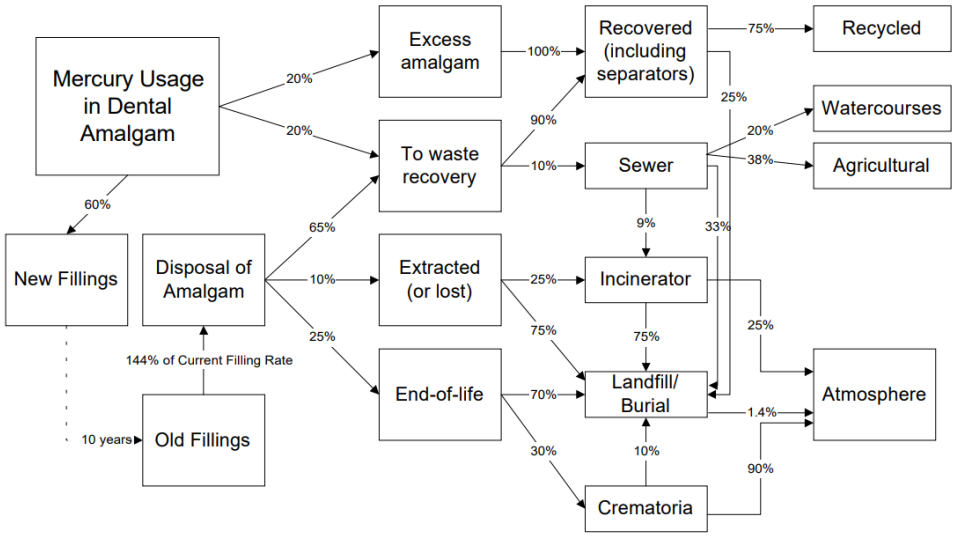


Figure 5: Dental Amalgam Hg Lifecycle & Emissions (Reproduced from Floyd et al. 2002).

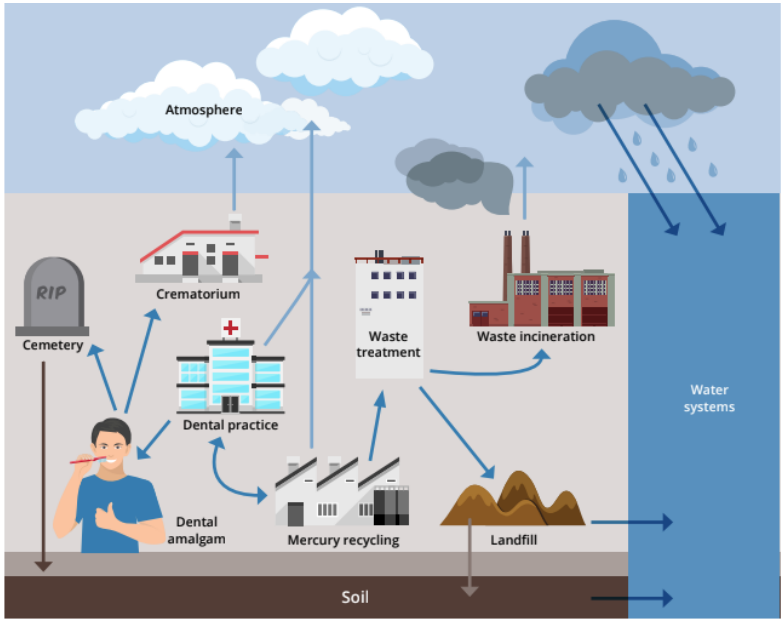


Figure 6: Dental Hg pathways to the environment (Reproduced from HCWH Europe, 2018).

A study by Stone et al. (2003) detected MeHg in wastewater from dental units in the USA, with particularly high concentrations found in holding tanks of larger clinics. This suggests that methylation process occurs within these tanks, likely due to sulfate-reducing bacteria present in the human oral cavity. In contrast, MeHg levels in chair-side wastewater were much lower. This highlights the ongoing environmental challenges posed by dental amalgam waste and its contribution to the contamination of air, soil, and water. Current Hg decontamination methods for dental clinic wastewater primarily rely on amalgam separators, which capture and remove large fragments and particles of dental amalgam by sedimentation, filtration, or centrifugation (Roth et al., 2025). While effective amalgam separator technology exists and is recommended as best practice, it has not been universally operated (Praktikertjänst AB, 2019).

Globally, the dental sector consumes 270–340 tonnes of Hg annually, of which 70–100 tonnes (20–30%) are realized into the environment via fertilizers, landfills, or air through disposal, incineration, and wastewater discharges (Fisher et al., 2018; Tibau & Grube, 2019). Although approximately 75% of EU dental facilities are equipped with these separators, it is estimated that 45 tonnes of Hg per year still enter clinic effluents, partly due to technical inefficiencies and poor maintenance, particularly in older dental units (Deloitte INERIS, 2020; Praktikertjänst AB, 2019).

Only 69% of amalgam waste is managed as hazardous waste, underscoring the need for improved waste management practices (HCWH Europe, 2017). In addition to emissions originating from dental practices, Hg is also released into the environment through the cremation of human remains containing amalgam fillings. Global Hg emissions from cremation were estimated at 3.6 (0.9-11.9) tonnes in 2010 (AMAP/UNEP, 2013). Unlike dental amalgam use and wastewater management, emissions from crematoria remain largely unregulated at the EU level and are not explicitly addressed under the Minamata Convention (Mari & Domingo, 2010; UNEP, 2024). This highlights the dual challenge of amalgam use: potential health effects from direct exposure to Hg vapor and its broader environmental footprint. Understanding the global environmental impact and health risks associated with the use of dental amalgam is crucial for establishing coordinated efforts across different sectors to reduce its use.

1.5 Human Biomonitoring as Evidence for Policy Evaluation

HBM is a fundamental instrument for generating evidence on exposure to environmental chemicals, providing direct measurement of internal exposure by analyzing substances or their metabolites in body fluids and tissues from various sources and pathways (Schlinder et al., 2014; WHO, 2023). HBM allows the characterization of exposure across different spatial patterns and temporal trends, enabling the identification and monitoring of the general population, particularly those in higher-risk groups. By quantifying contaminants in biological tissues and fluids such as blood, urine, and hair, HBM integrates exposure from all relevant pathways, linking biomonitoring outcomes with environmental and health data. This approach is crucial for evaluating the effectiveness of environmental policy interventions and improving public health strategies. Therefore, HBM provides a scientifically grounded basis for identifying exposure trends, assessing regulatory measures' effectiveness, and detecting gaps in population protection, making it of great importance for both scientists and policymakers (Angerer et al., 2007; Haines & Murray, 2012; WHO, 2015; WHO, 2023).

Historically, HBM has been recognized as an essential tool for evaluating environmental exposures, especially in the context of occupational health. Initially used in occupational

medicine since the early 1930s to assess exposure in workers, HBM's scope expanded in the late 1980s to include the measurement of metal exposure, particularly in populations exposed to environmental sources, such as industrial pollution and agricultural chemicals. Over time, HBM has transitioned from being a tool used primarily in industrial settings to a global initiative for assessing exposure to environmental contaminants, with a particular focus on toxic metals like Hg (Angerer et al., 2007; Černá et al., 2012; Schlinder et al., 2014; WHO, 2015; Kolossa-Gehring, 2012).

The demand for comparable HBM data across study populations and national borders has steadily increased over the years. This growing need has been accompanied by the development of numerous national, regional, and global HBM programs. At the global level, two major international agreements, the Stockholm Convention on Persistent Organic Pollutants and the Minamata Convention on Mercury, have played a pivotal role in the advancement of HBM. These conventions emphasize the importance of regular monitoring of Hg exposure, particularly for vulnerable populations, and encourage countries to establish HBM programs to assess Hg levels and evaluate the effectiveness of exposure reduction policies (Basu et al., 2018; Kolossa-Gehring, 2012).

The HBM typically involves measuring total Hg or its species in biological matrices such as urine, blood, cord blood, maternal milk, or hair, providing reliable indicators of cumulative exposure, with the relative contribution of different exposure routes depending on the matrix analyzed (Den Hond et al., 2015; Ruggieri et al., 2017; Boerleider et al., 2017; Horvat et al., 2011). The comparability of HBM results and the capacity building of qualified laboratories can only be achieved through the harmonization and standardization of both the pre-analytical (sampling, storage, etc.) and analytical phases. Limited presence of long-term HBM programs in many countries over the world hampers the regular incorporation of such data into regulations. Many countries and geographic regions lack sufficient data, therefore improved methodologies, including better standardization and integration of HBM data into policy-making processes, is crucial to strengthen the connection between HBM studies and policy decisions (Basu et al., 2018; Schlinder et al., 2014; Joas et al., 2012).

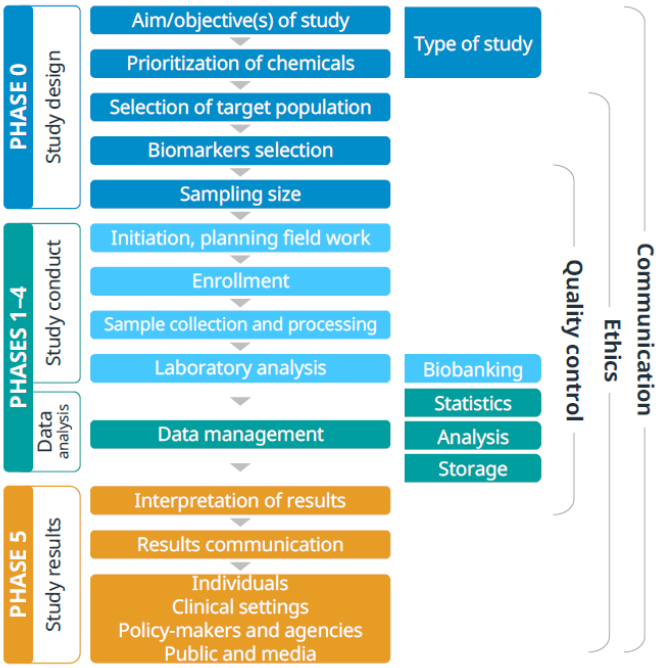


Figure 7: HBM Study (Reproduced from WHO, 2023).

As presented in Figure 7, the HBM is a multi-stage process requiring multidisciplinary expertise. It starts with planning and design, followed by fieldwork, analysis, and result communication. Ethics, communication, and quality control must be integrated at all stages. Furthermore, due to methodological limitations, HBM cannot address all exposure-related questions. Interpretation and communication of HBM results are challenging, as they involve addressing the complexities of the data while ensuring that the findings are accurately conveyed to stakeholders (Zare et al. 2021; Basu et al., 2018; Schlinder et al., 2014; WHO, 2023).

On the EU level, several international initiatives have been established to strengthen the role of HBM in policy development and public health, following the "European Environment and Health Action Plan". Projects such as ESBIO, COPHES, DEMOCOPHES, and HBM4EU have harmonized methodologies, ensuring data comparability across regions. The PARC Partnership under Horizon Europe, along with WHO efforts (i.e., WHO Chemicals Road Map), enhances HBM and supports chemical risk assessment, providing critical baseline data on Hg and other chemicals to inform policy development and protect vulnerable populations. National programs like NHANES (U.S.), CHMS (Canada), and Germany's Human Biomonitoring Program have also played a key role in establishing baseline data, further supporting policy-making and risk assessment. In Europe, HBM was reaffirmed as a priority in the 2023 Budapest Declaration and the establishment of the EHP Partnership on Human Biomonitoring, in line with the World Health Assembly's Resolution 76.17 on chemicals, waste, and pollution (Kolossa-Gehring, 2012; Schlinder et al., 2014; WHO, 2023; Den Hond et al, 2015). Many countries already possess foundational infrastructure through occupational, nutritional, or public health surveillance, as well as fragmented academic or regional studies. To further strengthen these efforts, policy-makers can promote the establishment of national HBM programmes, prepare legal frameworks enabling the use of HBM for exposure and risk assessment, ensure stable financial, technical, and human resources, and secure regular programme implementation to monitor temporal exposure trends, evaluate the effectiveness of risk-reduction measures, and protect population health over time (WHO, 2015; Joas et al., 2012).

Through its participatory approach, HBM not only generates scientific evidence but also engages citizens, raising awareness of exposure sources and empowering them to take informed actions, ultimately strengthening both policy impact and public health outcomes (Reynders et al., 2017; Den Broeder et al., 2018). Findings from cross-country qualitative research indicate that citizens clearly understand pathways of exposure, expect transparent decision-making from stakeholders, and value sensitive and trustworthy communication of scientific results, which can foster engagement, rebuild trust in a context of widespread misinformation, and encourage citizens to exert pressure on policymakers to act in alignment with societal needs (Uhl et al., 2021).

1.5.1 HBM for Dental Amalgam and Hg Biomarkers

HBM is a crucial tool for assessing Hg exposure, including exposure from dental amalgams, through blood, urine, and hair, each of which serves as a biomarker for different forms and timeframes of exposure. Collecting multiple biomarkers from individuals allows for a comprehensive exposure assessment to understand both acute and chronic Hg exposures, particularly from dental amalgams and seafood consumption. This combination of HBM data contributes to policy decisions that aim to reduce Hg exposure and mitigate health risks (Basu et al., 2018; Evers et al., 2016).

Beyond the biological meaning of the sampled matrix, several additional factors are important when setting up a HBM program, including simplicity and costs, the degree of invasiveness and the suspected exposure source (Figure 8) (Esteban-López et al., 2022 Basu et al., 2018; Evers et al., 2016; Zare et al., 2021; Boerleider et al., 2017; Horvat et al., 2011). Hair and urine are widely used in HBM because they allow low-cost, non-invasive assessment of exposure to major Hg forms, are simple to sample with basic training, and benefit from established quality assurance and reference materials that support comparability of results (Evers et al., 2016; Basu et al., 2018). These matrices are suitable for large populations and particularly advantageous when monitoring children. In comparison, blood sampling is invasive, requires medically trained staff, involves biosafety considerations, and is therefore more expensive and complex to implement at scale (Den Hond et al., 2015; Esteban & Castaño, 2009). Given the logistical demands and high costs of HBM fieldwork, sampling strategies should be designed around the research objectives, considering whether invasive blood collection can be avoided without compromising essential information, or if non-invasive biomarkers can sufficiently capture exposure patterns (Esteban-López et al., 2022).

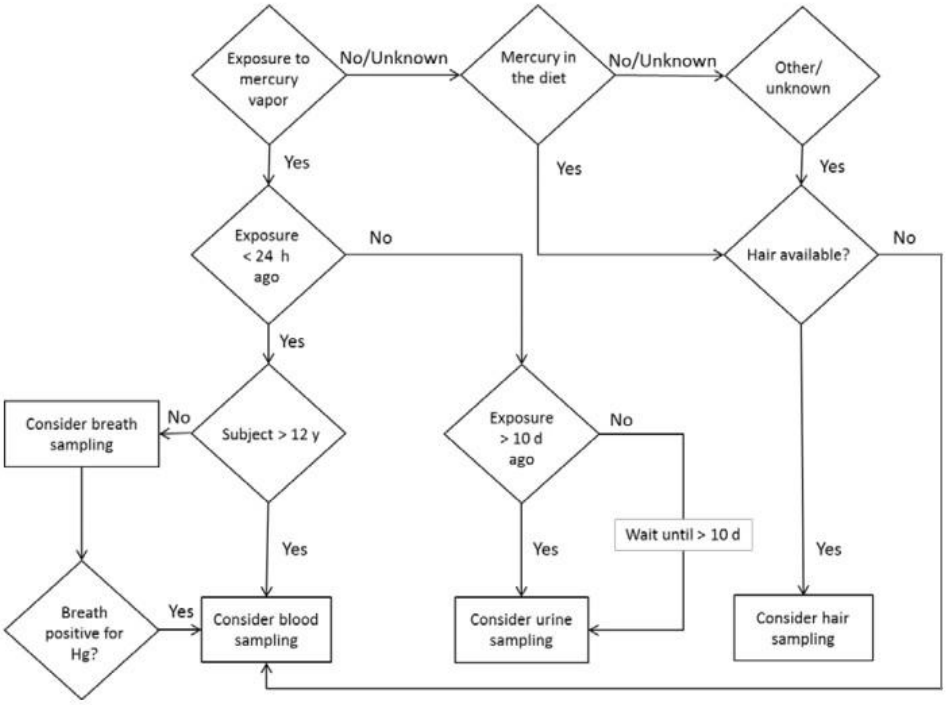


Figure 8: Tentative selection of the most appropriate biological medium for HBM of THg (Reproduced from Boerleider et al., 2017).

1.5.1.1 Urinary Hg: A Reliable Measure of Inorganic and Elemental Hg Exposure

Urine is a key matrix for monitoring inorganic and elemental Hg exposure from dental amalgams. It reflects recent exposure, as Hg^0 vapor is absorbed through inhalation and efficiently excreted via kidneys and urine. Upon inhalation, Hg^0 vapor is transported and metabolized into inorganic mercury (Hg^{2+}), which accumulates in the kidneys, leading to its excretion in urine. This inhalation of Hg^0 vapor is a key route of occupational exposure,

particularly in dental workers handling dental amalgam materials, as well as in patients exposed to Hg^0 vapor during dental procedures involving amalgam fillings. In addition, inorganic Hg^{2+} exposure can also result from the corrosion and dissolution of dental amalgam fillings, being also reflected in urinary Hg levels (Basu et al., 2018; Schulz et al., 2011; Boerleider et al., 2017).

To account for urine dilution and enable meaningful comparison across individuals Hg concentrations are typically adjusted to creatinine levels or normalized to specific gravity (Basu et al., 2018). The German Human Biomonitoring Commission sets reference values (ReV) for populations without amalgam fillings at 1 µg/L for adults and 0.4 µg/L for children. For individuals with amalgam fillings, the HBM-I guidance level is 7 µg/L (or 5 µg/g creatinine), and HBM II 25 µg/L or (20 µg/g creatinine). These thresholds serve as decision-making tools that guide clinical recommendations and regulatory interventions, while requiring periodic revision to account for changing environmental conditions and exposure trend (Basu et al., 2018; Schulz et al., 2011; WHO, 2015; Boerleider et al., 2017).

Urinary Hg (U-Hg) is also influenced by dietary MeHg intake, since a fraction of ingested MeHg from fish and seafood undergoes demethylation to inorganic Hg^{2+}, which is subsequently excreted in urine (Nicolae et al., 2013; Astolfi et al., 2020; Sherman et al., 2013). Consequently, U-Hg reflects not only inorganic and elemental Hg exposure (e.g., from dental amalgam), but also, to a lesser extent dietary MeHg exposure. This dual origin is particularly relevant in the interpretation of biomonitoring data and is one of the reasons why fish consumption is included as a covariate in statistical models (Usenik et al., 2026).

1.5.1.2 Hair Hg: Tracking MeHg Exposure Over Time

Hair is widely recognized as a reliable biomarker for evaluating long-term exposure to MeHg, predominantly originating from the consumption of contaminated seafood. During hair formation, MeHg becomes incorporated into the keratin matrix and remains permanently trapped, providing a history of MeHg exposure. Hair grows at an average rate of about 1 cm per month, therefore segmental analysis allows time-resolved tracking of exposure and provides an integrated estimate over extended periods (Manyani et al., 2021; Basu et al., 2018; Sherman et al. 2015). Hair Hg levels are therefore particularly informative for evaluating dietary MeHg intake, as they reflect cumulative exposure rather than short-term fluctuations that are typically captured in blood or urine. In individuals with low seafood consumption, hair Hg concentrations are commonly around 1–2 µg/g, whereas levels may exceed 10 µg/g in frequent consumers of marine products (Manyani et al., 2021; Basu et al., 2018). For populations with low seafood intake, the United States Environmental Protection Agency (USEPA) has established a reference level of 1 µg/g of Hg in hair, below which the risk of adverse health effects is considered minimal. Those who do not consume fish typically exhibit hair Hg concentrations below 0.5 µg/g, and blood Hg levels are approximately 250-fold lower than corresponding hair concentrations. Within hair, most Hg is present in its organic form, with MeHg accounting for roughly 80–90% of total Hg, and exposure patterns tend to be higher in mothers than in children, reflecting dietary differences (Basu et al., 2018; WHO, 2015). Hair is generally not a reliable biomarker for exposure to elemental Hg^0 vapor, and its use can lead to misleading conclusions, particularly at the individual level (Boerleider et al., 2017).

Although hair samples are easy to collect and transport, cultural resistance may arise in some communities. Moreover, in highly contaminated settings, external Hg deposition can complicate interpretation (Sherman et al., 2015). Therefore, caution is required when

interpreting total hair Hg levels in such environments. In these cases, measuring MeHg rather than total Hg provides a more accurate indicator of dietary exposure, particularly when supported by well-designed survey instruments (Sherman et al., 2015; Basu et al., 2018).

1.5.1.3 Blood Hg: A Biomarker of Recent Hg Exposure

Blood is a widely used biomarker for assessing recent exposure to both MeHg and inorganic Hg^0. Blood concentrations are typically lower than in hair but provide a useful measure of short-term Hg exposure. As Hg is measured in whole blood, blood Hg (B-Hg) typically reflects exposure over the preceding 1–2 months, making it suitable for detecting recent intake of contaminated fish, dental amalgam exposure, or inhalation of elemental Hg^0 vapor (Basu et al., 2018; Boerleider et al., 2017). MeHg is mainly acquired through ingestion, efficiently absorbed in the gastrointestinal tract, and widely distributed throughout the body, particularly in populations with high fish consumption (Boerleider et al., 2017). When speciated, blood measurements can also distinguish Hg sources, but this requires advanced laboratory instrumentation and rigorous sample preparation (Basu et al., 2018).

Compared with hair, B-Hg is a dynamic marker that fluctuates in response to recent intake, limiting its ability to reflect long-term exposure or total body burden. This short-term sensitivity, however, is advantageous in occupational contexts (e.g., dental practice, Hg-based industries), where exposed workers consistently show higher B-Hg levels than controls (Basu et al., 2018; Boerleider et al., 2017).

In terms of risk thresholds, the U.S. National Research Council (NRC) and the U.S. Environmental Protection Agency (USEPA) consider B-Hg concentrations above 5 µg/L as indicative of potential health concern. For occupational settings, the American Conference of Governmental Industrial Hygienists (ACGIH) established a Biological Exposure Index (BEI) of 15 µg/L, reflecting levels associated with short-term, higher exposures to metallic Hg (Boerleider et al., 2017). Across European biomonitoring surveys, geometric mean B-Hg values are typically at or below ~1 µg/L, but certain subgroups, particularly with high fish consumption or occupational exposure, exceed the HBM-I threshold of 5 µg/L (WHO, 2015). Blood collection, storage, and transport are more complex and costly than urine or hair sampling, which may introduce logistical limitations in large-scale biomonitoring applications (Basu et al., 2018).

Chapter 2

Aims and Hypothesis

In line with Article 22 of the Minamata Convention, the overarching aim of this research is to evaluate the effectiveness of the Convention's implementation in Slovenia, with particular emphasis on Hg exposure linked to the use and phase-out of dental amalgam. Accordingly, the specific aims of the doctoral dissertation were to:

- integrate administrative/policy metrics and environmental/health metrics, and assess their capacity to evaluate effectiveness of Hg exposure reduction;
- assess the impact of regulatory measures within the dental sector, including the phase-out of dental amalgam, the introduction of Hg-free alternatives, and the implementation of amalgam separators;
- monitor Hg exposure among children using HBM data, with emphasis on trends in U-Hg concentrations before and after policy interventions;
- investigate the relationship between administrative actions and exposure outcomes, determining whether policy adoption and compliance are reflected in measurable reductions in children's Hg burden.

To address these aims, the thesis is guided by the following hypotheses:

1. The phase-out of dental amalgam, combined with the introduction of Hg-free alternatives, results in a measurable decrease in Hg exposure among children, reflected in declining U-Hg levels.
2. Dental amalgam restorations contribute to increased U-Hg levels in children.
3. The implementation of dental amalgam phase-down measures is reflected in reduced amalgam use, which is in turn associated with lower U-Hg concentrations in children.
4. Despite regulatory prohibition of amalgam in vulnerable populations, barriers such as reimbursement policies and costs of Hg-free alternatives limit full compliance, affecting the pace of exposure reduction.

Chapter 3

Materials and Methods

3.1 Assessment Framework

The study seeks to determine whether existing regulatory measures and their practical application within the dental sector are capable of reducing Hg emissions and mitigating exposure among vulnerable groups. To address this objective, the assessment framework combines administrative/policy metrics, which reflect institutional and professional compliance with regulatory mandates, and environmental/health metrics, which provide empirical evidence of changes in internal Hg burden over time.

Administrative metrics evaluate how national policies related to the use of dental amalgam are translated into practice, including the progressive phase-out of amalgam and its restrictions for children, pregnant women and breastfeeding women, the adoption and availability of Hg-free restorative materials, and the mandatory use of amalgam separators alongside appropriate waste-management procedures. In this study, these aspects were investigated through a structured questionnaire administered to Slovenian dentists in public and private practices. The study captured their awareness of regulatory requirements, current approaches to amalgam use and alternatives, adherence to separator-related waste protocols, perceived challenges during the transition to safer materials, and views on the effectiveness of national measures and the support required for successful implementation. These indicators reveal compliance patterns, professional attitudes, structural obstacles and socioeconomic factors influencing the adoption of Hg-free technologies.

Environmental and health indicators rely primarily on HBM as a direct measure of population-level exposure. Children represent the key target group due to their heightened Hg susceptibility and their central role in the Convention's phase-out provisions. National HBM programmes, established under the Act of Chemicals, provide spatial and temporal datasets on chemicals present in the population, including Hg in blood, hair and urine (Snoj Tratnik et al., 2019a). Urinary total mercury (U-THg) serves as the core biomarker of dental-related Hg exposure. Therefore, longitudinal HBM data collected between 2007 and 2024 were analyzed to assess temporal exposure trends, compare children with and without dental amalgam fillings, examine geographical variability across urban, rural and historically contaminated regions, and evaluate the relative contribution of amalgam, environmental emissions and dietary factors such as fish consumption. These metrics demonstrate how regulatory measures translate into real-world reductions in internal dose, providing a direct indicator of policy impact.

As illustrated in Figure 9, the combined metrics enable a clear assessment of how policy measures translate into real-world outcomes, forming the basis for recommendations that support continued monitoring and alignment with the Minamata Convention's objectives.

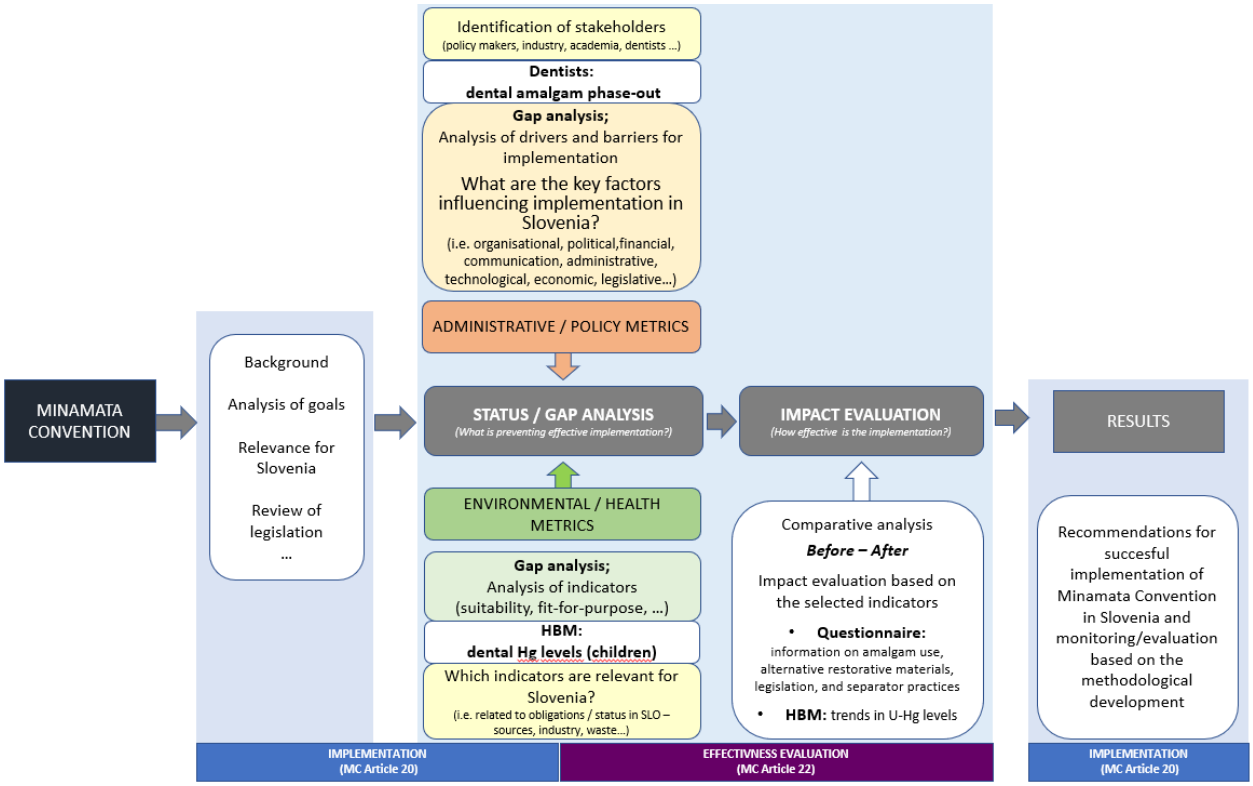


Figure 9: The scheme of the proposed Minamata Convention effectiveness evaluation in Slovenia.

3.2 Administrative/Policy Metrics: Dental Professionals Study

The text related to Section 3.2 is based on our published article Usenik et al., 2025.

To evaluate the progress in phase-out of dental amalgam in Slovenia, a comprehensive study was conducted among dental professionals. The study was carefully designed to collect detailed insights while ensuring anonymity to encourage open and honest participation, without collecting personal health data. All data gathered through this research is treated as strictly confidential and is securely protected in compliance with the Personal Data Protection Act (Official Gazette of the Republic of Slovenia, No. 67/07) and the General Data Protection Regulation (EU 2016/679). Respondents were informed about the study's purpose, voluntary nature, and the anonymity of their responses, with implied consent through participation. Data were securely stored and analysed in aggregate form to maintain confidentiality.

The research was conducted as a cross-sectional study distributed to general dentists and dental specialists across Slovenia. The target population included dental professionals working in public and private sectors to capture a wide range of practices and experiences. Participation was voluntary, while anonymity was emphasized to reduce response bias. A comprehensive questionnaire was developed based on a review of relevant literature and regulatory frameworks, including Regulation (EU) 2017/852 and the Minamata Convention. It was prepared in the Slovenian language. The questionnaire included closed-

ended and open-ended questions, covering demographic data, frequency of amalgam use, awareness related to regulatory frameworks, preparedness for the phase-out and perceived barriers or incentives in adopting alternative materials and the use of amalgam separators. The questionnaire was delivered in the Slovenian language (available in Appendix B), while the translation to English is provided in the Appendix A. Based on an official statement from the National Medical Ethics Committee of the Republic of Slovenia, no ethical approval was required for this anonymous questionnaire-based study.

The questionnaire was distributed electronically through professional networks, dental associations and targeted email lists to ensure broad geographic coverage and accessibility. Distribution channels included direct emails to dental offices with publicly available contact information, the eZobozdravnik portal, secretariats and contact forms of general hospitals, as well as the Medical Chamber of Slovenia (MCS), the Health Insurance Institute of Slovenia (Zavod za zdravstveno zavarovanje Slovenije, ZZZS) and other relevant organizations. Despite these efforts, we faced challenges in reaching individual dentists, as most dental offices do not have officially published email addresses, or they provide only a general office email used by multiple dentists. Therefore, we cannot precisely determine how many dentists received the questionnaire or what proportion of them completed it. However, based on the MCS data (Chamber of Slovenian Dentists, 2022) as of August 2022 there are nearly 1.700 active dentists in Slovenia. From this group, we received 171 completed surveys, representing approximately 10% of all active dentists. Possible reasons for the low response rate could include limited access to direct contact information for individual dentists, the high volume of general emails received by dental offices, a lack of time or interest among dentists to complete the questionnaire, or insufficient promotion of the survey. As no technical issues were reported by participants, these are not considered a contributing factor to the response rate.

Data were analyzed using a combination of descriptive and comparative statistics in Microsoft Excel. Percentages were calculated based on the total number of responses, with 100% representing all responses to this question. Descriptive statistics summarized demographic data, amalgam usage patterns, and regulatory awareness, while comparative analyses were conducted to identify patterns across different sectors and regions. Open-ended responses were analyzed thematically to extract qualitative insights into barriers, incentives and professional attitudes. Thematic analysis was performed through manual review and categorization of responses. The raw survey data are provided via a link included in the Appendix C of this doctoral thesis.

3.3 Environmental/Health Metrics: HBM in Children Cohorts

The text related to Section 3.2 is based on our published article Usenik et al., 2026.

The target population consisted of school-aged children (6–11 years) living in Slovenia. Participants were recruited through four different cross-sectional biomonitoring studies conducted between 2007 and 2024: PHIME (2007), DEMOCOPHES (2011–2012), CROME (2016), and SLO-HBM-II (2018–2024).

The pooled dataset comprised 1412 children; 1388 had valid U-Hg measurements and 1386 had valid creatinine-adjusted values. All sampling campaigns were designed and conducted by the same research group at the Department of Environmental Sciences, Jožef Stefan Institute, and all urinary Hg analyses were performed in the same laboratory.

Children were recruited through primary schools in predefined urban, rural, and historically Hg-contaminated towns, using structured convenience sampling with

approximately balanced sex distributions and at least three years of residence in the area. This non-probability design was intended to capture key exposure settings rather than to obtain a nationally representative sample. Most towns were sampled only once (within a single study period), whereas the capital city of Ljubljana (urban) and the town of Idrija (former Hg mining area), were included in multiple campaigns. Initial contact was established with school headmasters, followed by informational meetings with parents, and ultimately, children. Written informed consent was obtained from a parent or guardian for each participant, and oral consent was obtained from each child prior to sampling.

Parents completed detailed questionnaires covering dietary habits, dental health, socioeconomic background, residential conditions, and basic medical history. For the present work, the following variables were extracted: child's age, sex, height, weight, residence area type, presence and number of dental amalgam fillings, and fish consumption habits.

The HBM data used in this dissertation were obtained from multiple nationwide research studies conducted over different periods, each employing standardized methods for Hg measurement in biological samples, particularly U-Hg. Despite minor differences in study designs and cohort-specific factors, the data were harmonized and analysed using multilevel mixed-effects models. These models accounted for variations in sample sizes, missing data, and geographical context, ensuring comparability across studies. By utilizing comparable analytical techniques, limits of detection (LOD), and reference materials, the approach facilitated a robust analysis of temporal trends and exposure patterns. This methodology enabled a meaningful evaluation of the effectiveness of Hg-related policies, ensuring the datasets were harmonised and suitable for assessing the impact of regulatory measures.

Having established the methodology for harmonizing the data, the study also addressed specific variables that required additional harmonization. While anthropometric and demographic data were consistently collected across studies, fish consumption questions differed. Therefore, fish intake was harmonised into a three-level categorical variable representing the highest common resolution: low (<1 meal per month), moderate (1–3 meals per month), and high (>3 meals per month). It should be emphasised that this categorisation was created specifically for the purpose of this study and is not intended to represent standardised definitions of low, medium or high fish consumption in a broader nutritional context beyond this study. A standardised portion size of ~150 g was assumed. Other key variables, including the number of dental amalgam fillings, were collected comparably across studies and required no additional harmonisation.

All studies were approved by the National Medical Ethics Committee of the Republic of Slovenia (approval numbers listed in Table 1). As these were observational biomonitoring studies, clinical trial registration was not applicable.

The study population, urine collection, storage and analysis, statistical analysis (including descriptive statistics, assessment of temporal trends and determinants, and missing data and sensitivity analysis) are described in detail in the Evidence package, which is included as Appendix D of the doctoral thesis.

Chapter 4

Results and Discussion

The results from chapter 4 were published by Usenik et al. (2025; 2026), in peer-reviewed scientific journals.

4.1 Administrative/Policy Metrics: Dental Professionals Study Results

4.1.1 Respondent Demographics

The study included 171 participants, representing a diverse demographic and professional background (Figure 10). The majority of respondents were women (67%), which is consistent with the overall gender distribution in Slovenian dentistry. According to data from the Medical Chamber of Slovenia, women represented approximately 68% of active dentists in 2022 (Chamber of Slovenian Dentists, 2022), indicating that the study sample accurately reflects the current demographic structure of the dental workforce in Slovenia. Over half had more than 20 years of professional experience (52%). Age distribution leaned slightly toward older professionals, with 30% aged 51–60, followed by 25% aged 30–40 and 23% aged 41–50. Work settings were divided between 58% in the public sector and 42% in private clinics.

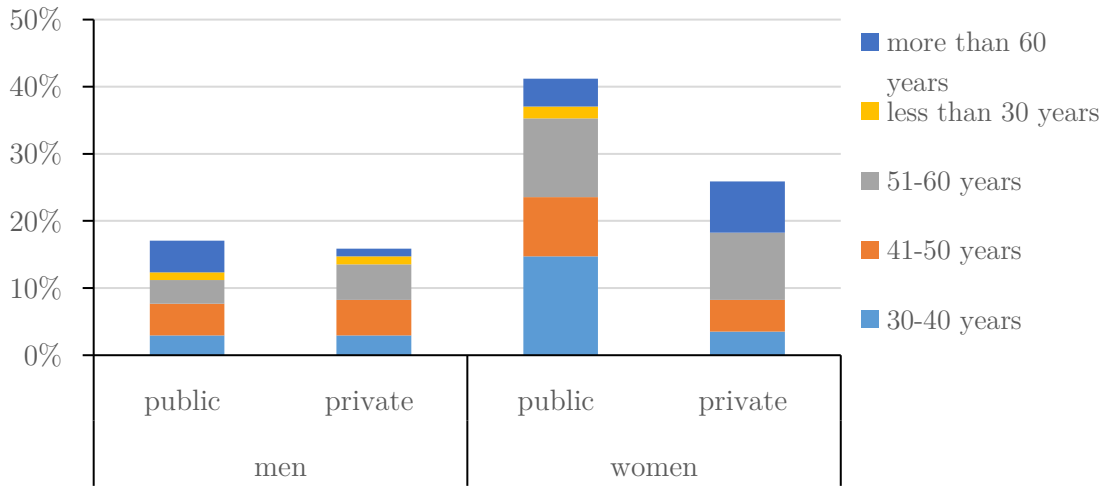


Figure 10: Study participants in Slovenia – gender, sector (public or private clinics) and age distribution.

4.1.2 Amalgam Use Patterns

The use of dental amalgam varies significantly between paediatric and adult clinics (Figure 11). The majority of dentists report never using amalgam in children aged 6–9 years (blue), 10–12 years (orange), and adolescents aged 13–17 years (grey). In contrast, amalgam use is more frequent in adults (yellow), with a small percentage reporting weekly or daily use. While rare or occasional use (monthly, weekly, or daily) is observed in adults, it remains minimal among younger age groups, reflecting a strong preference for alternative materials in paediatric dentistry. The rare instances of amalgam use in paediatric clinics (around 10%) are typically linked to specific or challenging clinical cases.

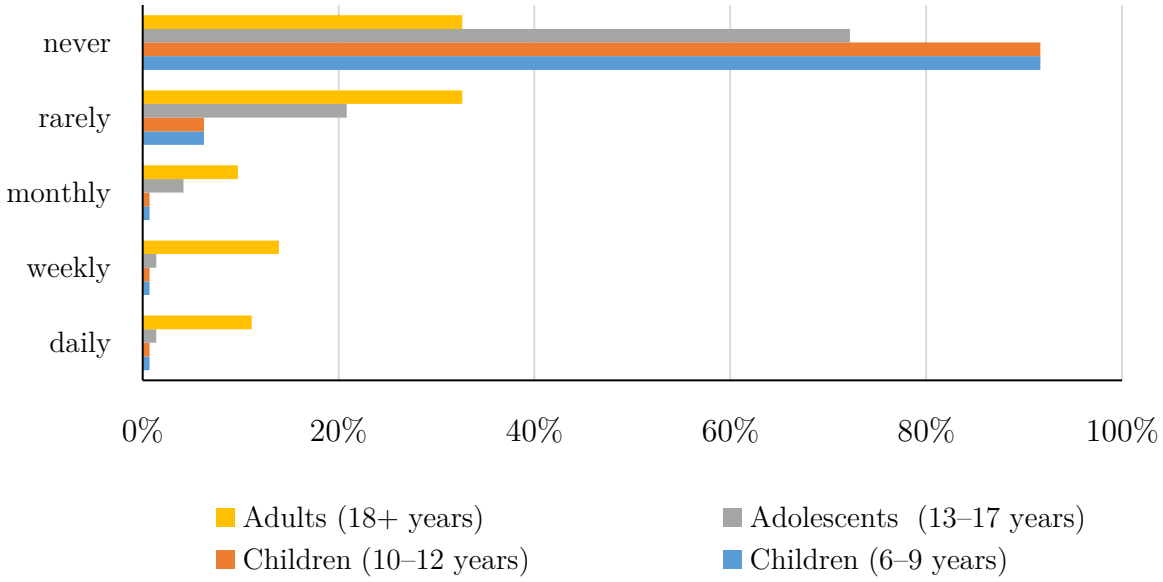


Figure 11: Frequency of amalgam use for patients in different age groups in Slovenia.

4.1.3 Differences Between Public and Private Paediatric Clinics

No significant differences were observed between public and private paediatric clinics regarding amalgam use (Figure 12). Both clinic types rarely use dental amalgam for children aged 6–12 years, with non-use rates exceeding 80%. Among adolescents (13–17 years), public clinics report slightly higher rates of non-use compared to private clinics. In contrast, among adults (aged 18 and above) treated in paediatric clinics, the non-use is lower, with private clinics reporting a higher percentage compared to public clinics.

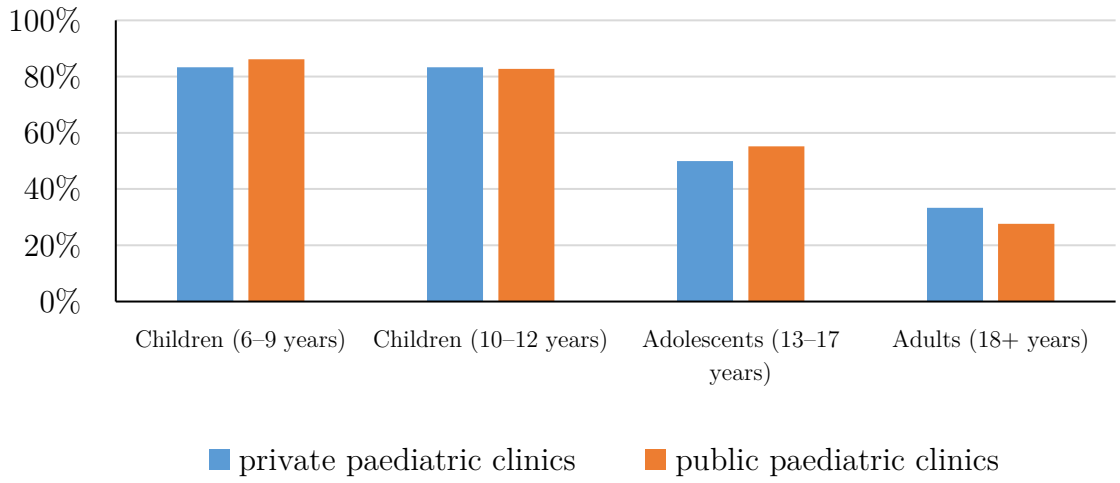


Figure 12: Percentage of non-use of dental amalgam in private and public paediatric clinics across different age groups.

4.1.4 Amalgam Use in Adult Clinics

Compared to amalgam use in paediatric clinics, its application in adult clinics (patients aged 18 and above) follows a markedly different pattern.

In private adult clinics, 51% never use amalgam when treating adult patients, whereas in public adult clinics, this percentage drops significantly to 15%. Additionally, occasional use (rarely, monthly, or weekly) is far more common in public clinics, with 69% reporting some level of use, compared to 37% in private clinics (Figure 13).

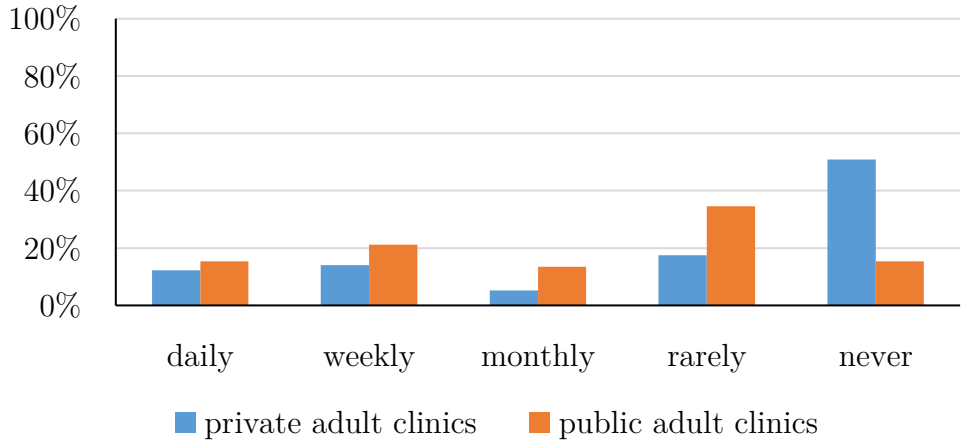


Figure 13: Percentage of amalgam use in private and public adult clinics.

4.1.5 Factors Associated with the Amalgam Use

Several factors are associated with the decision to use amalgam over alternative materials. In adult clinics, patient preferences are the most significant factor, cited by 42% of

respondents, followed by insurance coverage (37%), ease of use (25%), cost (19%), and amalgam durability (23%). Similarly, financial and systemic barriers remain important considerations, with 32% of respondents mentioning other specific reasons that are associated with their decision-making (Figure 14).

Amongst »other specific reasons«, moisture control and technical limitations were frequently mentioned as reasons for using or avoiding amalgam. Many respondents explicitly stated that they do not use amalgam at all, while others cited inability to ensure proper isolation, subgingival restorations, and poor patient hygiene as critical factors associated with material choice. A few responses indicated that amalgam is considered only in cases where absolute dryness cannot be achieved, making composite restorations impractical. Additionally, technical feasibility and existing restorations were mentioned as occasional considerations.

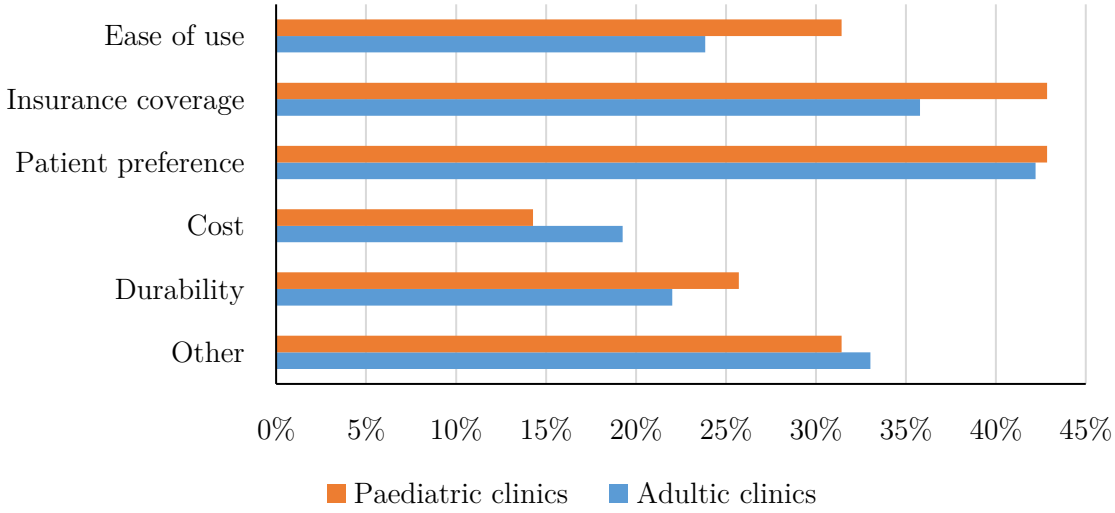
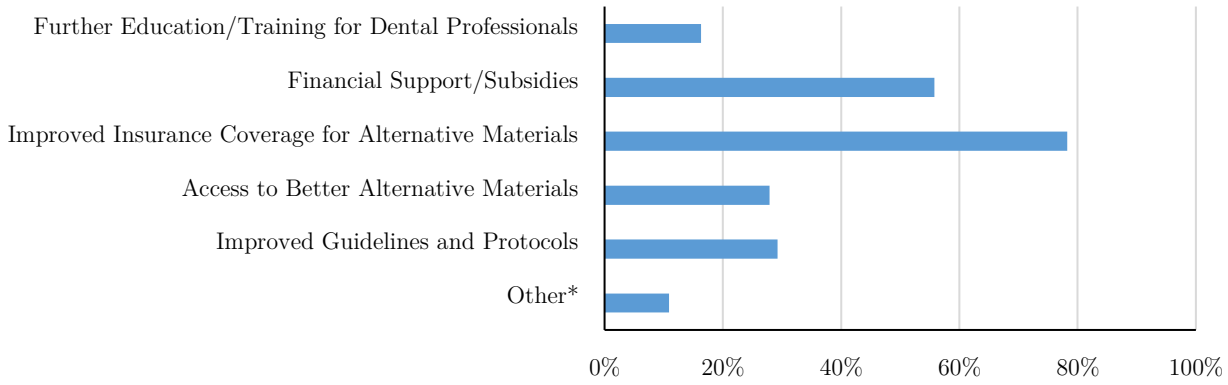


Figure 14: Factors associated with the choice of amalgam over alternative materials.

To facilitate the transition away from amalgam use, respondents emphasized several key factors that could support the process. These include improved insurance coverage for alternative materials (78%), financial support or subsidies (56%), enhanced guidelines and protocols (29%), better access to alternative materials (28%), and further education and training for dental professionals (16%) (Figure 15).



*The "Other" responses mention concerns about fair service pricing, the longer time required for composite fillings, better insurance coverage, and some respondents do not use amalgam.

Figure 15: Key factors facilitating the transition from amalgam use to alternative materials.

4.1.6 Awareness of the Minamata Convention

The study revealed varying levels of awareness regarding the Minamata Convention among Slovenian dentists. Only 9% of respondents reported a thorough understanding of the convention, while 61% were partially familiar with its provisions and 30% admitted to being entirely unaware of it, as presented in Figure 16.

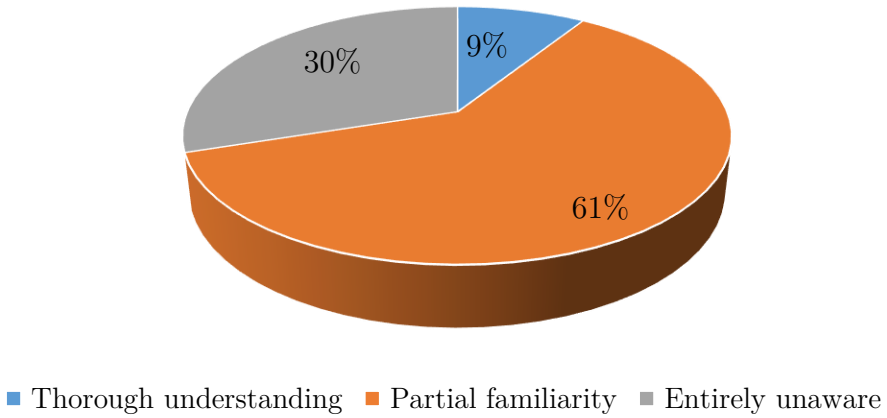


Figure 16: Awareness of the Minamata Convention among Slovenian dentists.

Regarding the perceived health risks of dental amalgam, 42% of respondents indicated that it does not pose significant health risks to patients and 41% considered the risks to be moderate. Similarly, when evaluating the risks of amalgam removal, 29% believed it had minimal impact on dental workers and 42% felt the risks to patients were minimal. Environmental concerns showed a comparable distribution of responses, with 30% considering the impact significant, 31% moderate and 32% minimal, while the remaining respondents believed there was no impact at all (Figure 17).

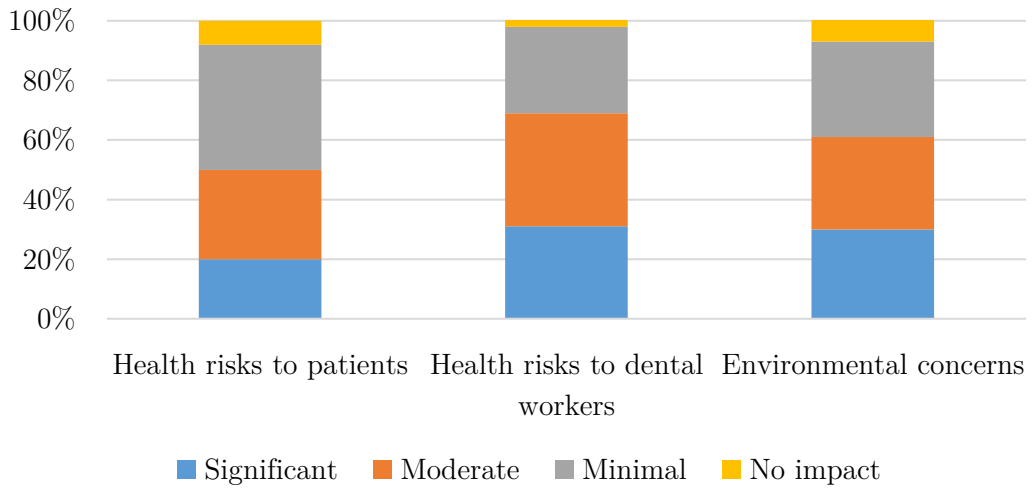


Figure 17: Perceptions of health risks and environmental concerns of dental amalgam use.

Despite these mixed perceptions, 38% of the respondents acknowledged that phasing out dental amalgam is very important, with another 38% viewing it as moderately important (Figure 18).

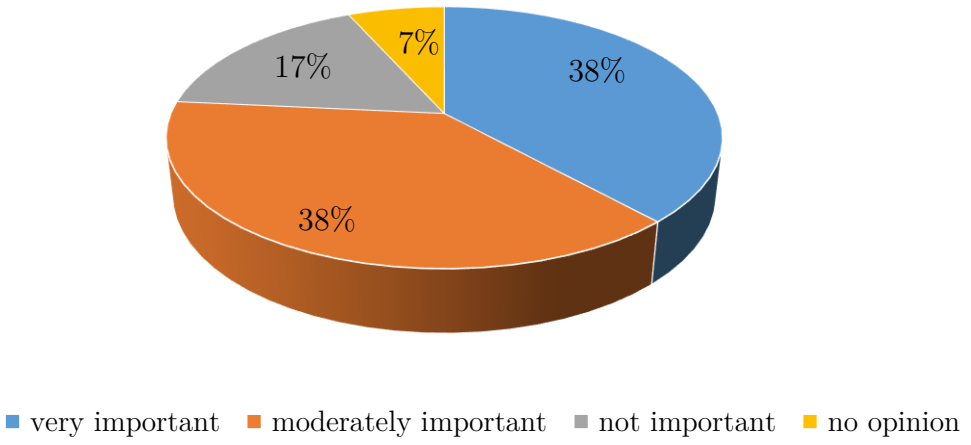


Figure 18: Perceived importance of phasing out dental amalgam.

4.1.7 Regional and Sectoral Analysis of Preparedness for the Ban on Dental Amalgam

4.1.7.1 Overall Preparedness

A majority of dental clinics across Slovenia (72%) reported being prepared for the ban on dental amalgam. However, notable differences emerged between the public and private sectors:

- Public clinics: 67% reported readiness, while 33% indicated they were not yet prepared.
- Private clinics: 78% reported being ready, while 22% stated they were not prepared.

Differences were also observed between adult and paediatric clinics, with paediatric clinics demonstrating a higher level of preparedness for the transition away from amalgam (Figure 19).

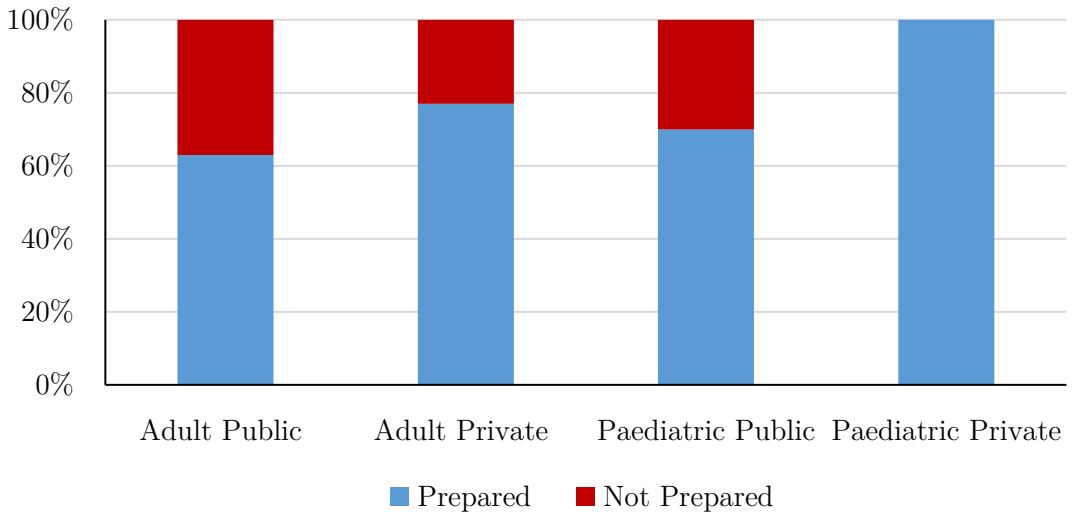


Figure 19: Preparedness for the ban on dental amalgam across different clinic types.

4.1.7.2 Regional Disparities

Significant regional variations were identified, particularly in the Savinjska region, where 63% of respondents reported that they were not yet ready for the transition (Figure 20). Public clinics in this region were particularly underprepared, with 100% of respondents working in the public sector and focused on adult dental care stating they are not prepared for the phase-out of dental amalgam.

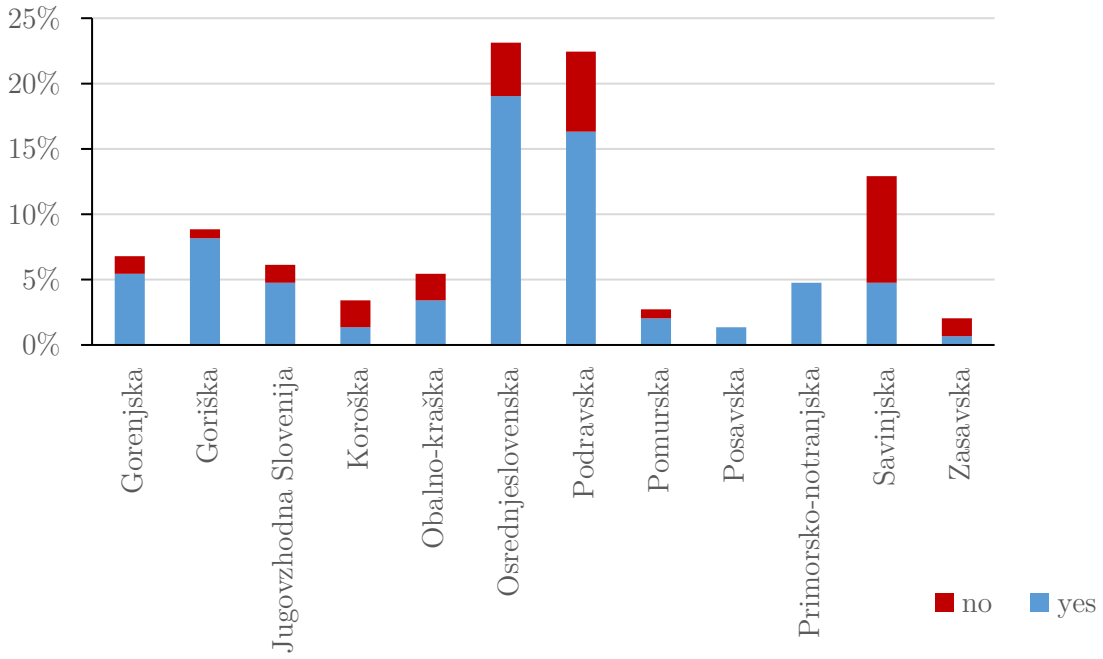


Figure 20: Preparedness for the ban on dental amalgam across regions in Slovenia.

4.1.7.3 Key Barriers to Preparedness

The greatest challenges in transitioning away from amalgam (Figure 21) were identified as:

- Financial constraints, including the high costs of alternative materials.
- Difficulties with insurance reimbursements, making the shift financially burdensome for some clinics.

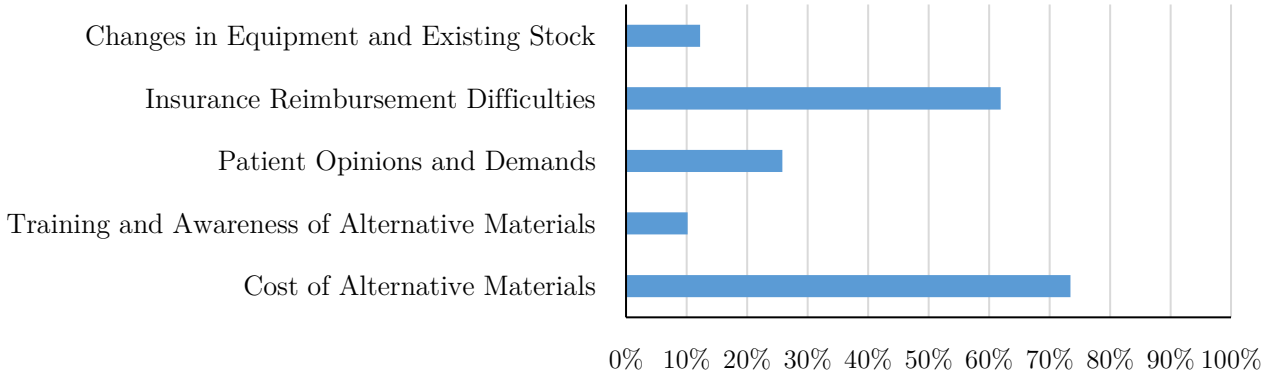


Figure 21: The greatest challenges in transitioning away from amalgam.

4.1.8 Use of Amalgam Separators and Challenges in Transition

Amalgam separators are widely adopted across all regions and types of clinics, with 97% of respondents reporting their use (Figure 22). Only three respondents indicated they do not use amalgam separators, citing reasons such as high maintenance costs, frequent breakdowns and insufficient staff training (Figure 23). Regulatory obligations under Article 4 of the Regulation on the Management of Amalgam Waste (Official Gazette of the Republic of Slovenia, No. 80/20) and the potential penalties for non-compliance may have influenced participants' willingness to provide complete answers, as reflected in some incomplete responses. This suggests that concerns about non-compliance could lead to partial or inaccurate disclosures. One respondent noted stricter oversight in private clinics, highlighting that while amalgam separators were not initially required in public health centres, their installation became mandatory upon obtaining a private concession, enforced by an inspector.

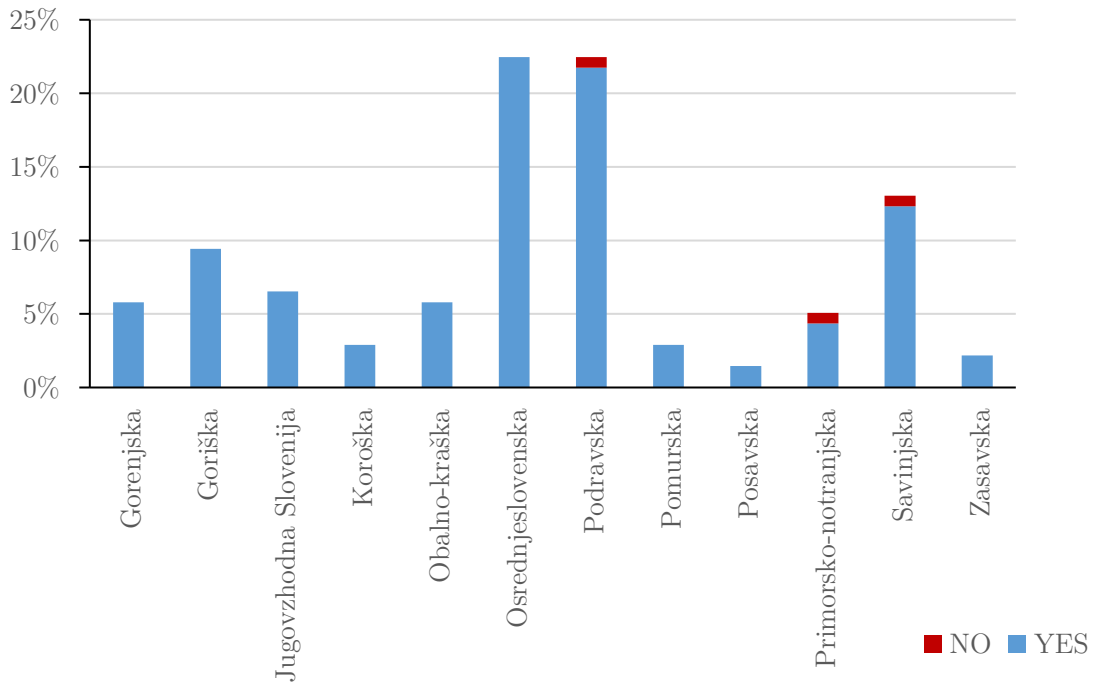
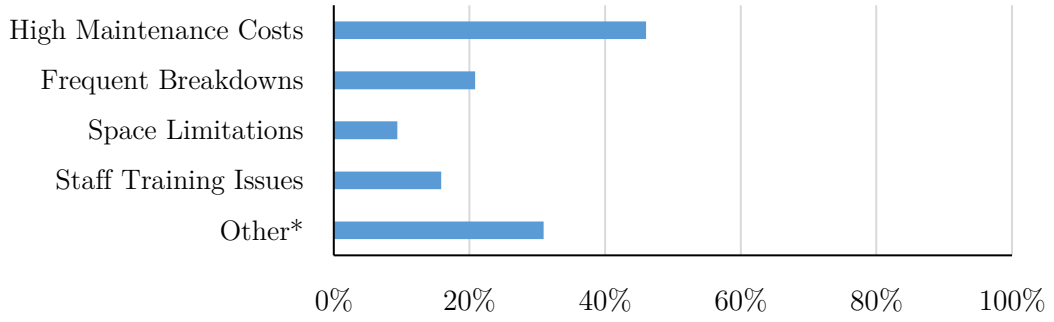


Figure 22: Use of amalgam separators across regions in Slovenia.

Despite their widespread use, respondents expressed uncertainty about the practical value of amalgam separators in protecting health and the environment. When evaluating their effectiveness in reducing environmental Hg pollution, 35% rated them as "very effective," 44% as "effective," 11% as "partially effective," and 6% as "ineffective." Similarly, in terms of health protection for patients and healthcare workers, 14% considered them "very effective," 37% "effective," 20% "partially effective," and 16% "ineffective" (Figure 24). These findings indicate mixed perceptions of the effectiveness of separators and highlight ongoing challenges in their maintenance and use.



*The 'Other' responses mostly reflect those users did not experience significant challenges with amalgam separators, with a few mentioning issues like accessibility for service technicians, sensor malfunctions, concerns over regulatory consequences, and a lack of feedback on the separators' effectiveness. Overall, respondents indicated that the separators are well integrated into dental practices and do not cause major problems.

Figure 23: The greatest challenges in the use of amalgam separators.

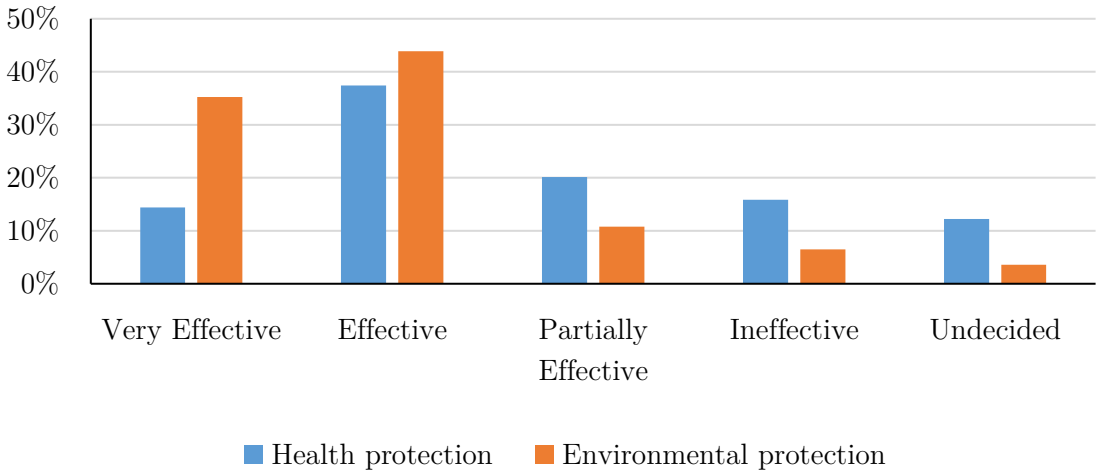
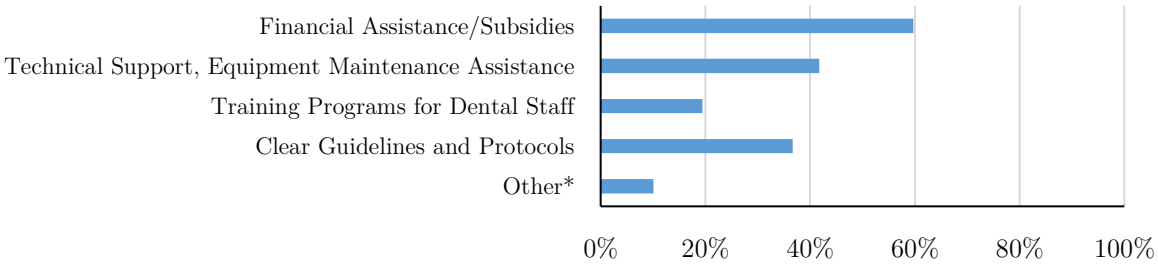


Figure 24: Perceived effectiveness of amalgam separators in protecting human health and the environment.

To address these issues, respondents emphasized the need for financial incentives (60%), technical support and equipment maintenance assistance (42%), improved guidelines and protocols (37%), and better training for dental professionals (19%) (Figure 25).



*The "Other" responses indicate that most users already have amalgam separators, with some mentioning long-term use, automated maintenance, and the inclusion of costs in service prices, all without significant issues.

Figure 25: Essential measures needed for facilitating the implementation of amalgam separators.

4.1.9 Overall Preferences for Alternative Materials

The study revealed that 90% of respondents preferred using alternative materials over dental amalgam (Figure 26), primarily citing improved aesthetics, less invasive preparation techniques, and the Hg absence. Many respondents also highlighted the long-term benefits for patients, such as better preservation of tooth structure, biocompatibility, and alignment with patient expectations for modern and aesthetic solutions.

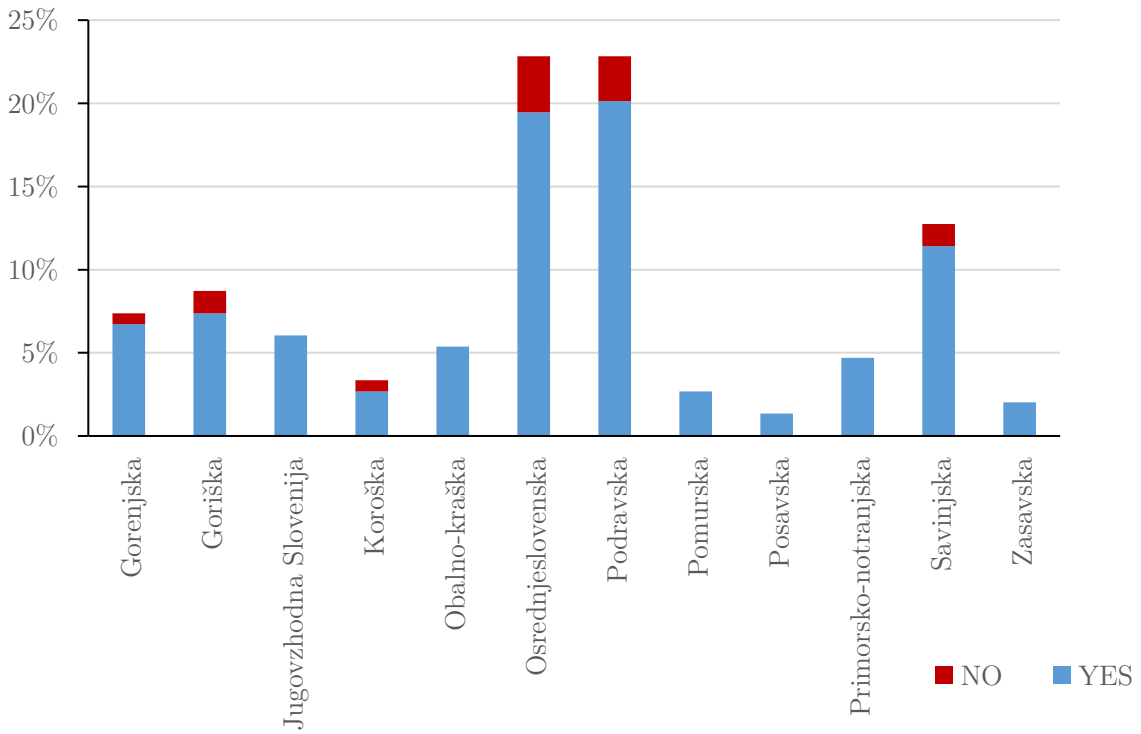


Figure 26: Overall preferences for alternative materials across regions in Slovenia.

Conversely, 10% of respondents preferred amalgam in specific cases, emphasizing its ease of use, particularly in time-constrained procedures, and its durability in challenging clinical scenarios, such as subgingival fillings or cases involving poor oral hygiene. Some respondents also expressed concerns about the lack of fully comparable alternatives, noting that composites can be more technique-sensitive and less durable in certain situations.

4.2 Environmental/Health Metrics: Results of HBM Study in Children Cohorts

Urinary Hg concentrations (both in ng mL^{-1} and µg g^{-1} creatinine) varied significantly between the four study cohorts (Kruskal-Wallis, $p < .001$; Table 1). Since urinary Hg levels are influenced by urine dilution or concentration, such as variations in fluid intake, Hg concentrations were corrected for creatinine content and expressed as µg g^{-1} creatinine to minimize this effect. Creatinine-adjusted concentrations therefore reflect Hg levels normalized to urinary creatinine, improving comparability of Hg exposure across individuals and cohorts. The highest median concentrations (both unadjusted and creatinine-adjusted) were observed in the earliest cohort (PHIME) and the lowest in the most recent, SLO-HBM-II cohort (Table 2; Table 3). When using creatinine-adjusted concentrations, the results of some pairwise comparisons shifted (Table 2). These discrepancies likely reflect variability in urinary creatinine concentrations, due to differences in physiological factors and sampling protocols (e.g., unlike other studies, CROME urine samples were not first-morning samples; Sallsten & Barregard, 2021; Barr et al., 2005; Carrieri et al., 2000; Boeniger et al., 1993). A consistent downward trend over time was evident within towns (Idrija and Ljubljana) sampled over multiple cohorts (Figure 27 and Figure 29; Table 4). Across the pooled dataset, the number of amalgam fillings showed a significant positive correlation with U-Hg concentrations (Spearman's $\rho = 0.315$ and 0.340 for U-Hg in ng mL^{-1} and in µg g^{-1} creatinine; both $p < .001$; Figure 28).

Table 1: Kruskal-Wallis rank sum test of between-study differences in urinary Hg levels (U-Hg) in ng mL^{-1} and in µg g^{-1} creatinine.

Variable	Chi squared	df	p-value
U-Hg in ng mL^{-1}	164	3	<0.001
U-Hg in µg g^{-1} creatinine	274	3	<0.001

Table 2: Post-hoc Dunn's test with Bonferroni adjustment for urinary Hg (U-Hg) in ng mL^{-1} and in µg g^{-1} creatinine.

U-Hg in ng mL^{-1}	CROME	DEMOCOPHES	HBM-II	U-Hg in µg g^{-1} creat	CROME	DEMOCOPHES	HBM-II
DEMOCOPHES	-2.08			DEMOCOPHES	6.04		
	p = 0.112				p < 0.001		
HBM-II	0.394	3.01		HBM-II	10.4	2.26	
	p = 1.00	p = 0.008			p < 0.001	p = 0.071	
PHIME	-9.58	-7.24	-12.6	PHIME	-3.28	-9.12	-14.3
	p < 0.001	p < 0.001	p < 0.001		p = 0.003	p < 0.001	p < 0.001

alpha = 0.05, reject Ho if p <= 0.025

Table 3: Summary of U-Hg concentrations (in ng mL^{-1} and in µg g^{-1} creatinine) by study and dental amalgam presence.

*Study coh*ort	Year	N[a]	Urinary Hg (ng mL^{-1})						Urinary Hg (µg g^{-1} creatinine)					
			GM	Min[b]	p25	p50	p75	Max	GM	Min	p25	p50	p75	Max
PHIME	2007	164	0.75	<LOD	0.38	0.76	1.54	12.4	0.78	0.04	0.38	0.72	1.46	10.3
DEMOCOPHES	2011	95	0.31	<LOD	0.13	0.27	0.58	4.79	0.26	0.05	0.14	0.22	0.53	3.80
	2012	60	0.34	<LOD	0.11	0.25	0.79	13.6	0.29	0.05	0.13	0.20	0.68	8.16
	Total	155	0.32	<LOD	0.13	0.25	0.59	13.6	0.27	0.05	0.13	0.22	0.56	8.16
CROME	2016	176	0.23	<LOD	0.09	0.23	0.55	5.04	0.49	0.02	0.25	0.45	0.84	11.7
SLO-HBM-II	2018	130	0.20	<LOD	0.13	0.21	0.33	3.19	0.21	0.05	0.13	0.20	0.31	3.97
	2019	233	0.18	<LOD	0.10	0.17	0.28	2.01	0.15	0.01	0.09	0.15	0.26	1.71
	2020	205	0.18	<LOD	0.11	0.18	0.32	4.07	0.18	0.01	0.10	0.18	0.29	4.05
	2021	37	0.22	<LOD	0.15	0.22	0.36	0.75	0.27	0.07	0.18	0.26	0.44	1.38
	2022	51	0.27	0.08	0.18	0.28	0.37	5.99	0.25	0.09	0.17	0.26	0.34	4.81
	2023	25	0.24	0.06	0.16	0.22	0.36	2.81	0.22	0.05	0.13	0.25	0.34	1.29
	2024	212	0.33	<LOD	0.21	0.33	0.53	2.85	0.31	0.04	0.18	0.31	0.51	2.98
	Total	893	0.22	<LOD	0.13	0.22	0.38	5.99	0.21	0.01	0.13	0.21	0.34	4.81

GM = geometric mean; Min = minimum; p25 = 25th percentile; p50 = 50th percentile (median); p75 = 75th percentile; Max = maximum.

[a]Number of individuals with available urinary Hg concentration data. Missing data in µg g^{-1} creatinine: in 2007 (n = 1); in 2016 (n = 1).

[b]The LODs for the PHIME, DEMOCOPHES, CROME, and SLO-HBM-II were: 0.1 ng mL^{-1}, 0.05ng mL^{-1} , 0.06 ng mL^{-1}, and 0.04 ng mL^{-1}, respectively.

Table 4: Results of the between-year comparisons for certain variables of interest for Idrija (2007, 2024) and Ljubljana (2007, 2011-12, 2016).

Town	BMI[a]		Fish (high)[b]		Amalgam (yes/no)[b]		U-Hg (ng mL^{-1})[a]		U-Hg (µg g^{-1} creatinine)[a]	
	Stat.	p-value	Stat.	p-value	Stat.	p-value	Stat.	p-value	Stat.	p-value
Idrija	0.113	0.737	17.7	<.001	35.3	<.001	26.0	<.001	0.292	0.589
Ljubljana	3.89	0.143	54.9	<.001	47.2	<.001	40.8	<.001	60.1	<.001

[a]Kruskal-Wallis test

[b]Pearson's Chi Squared Test with Yates' continuity correction

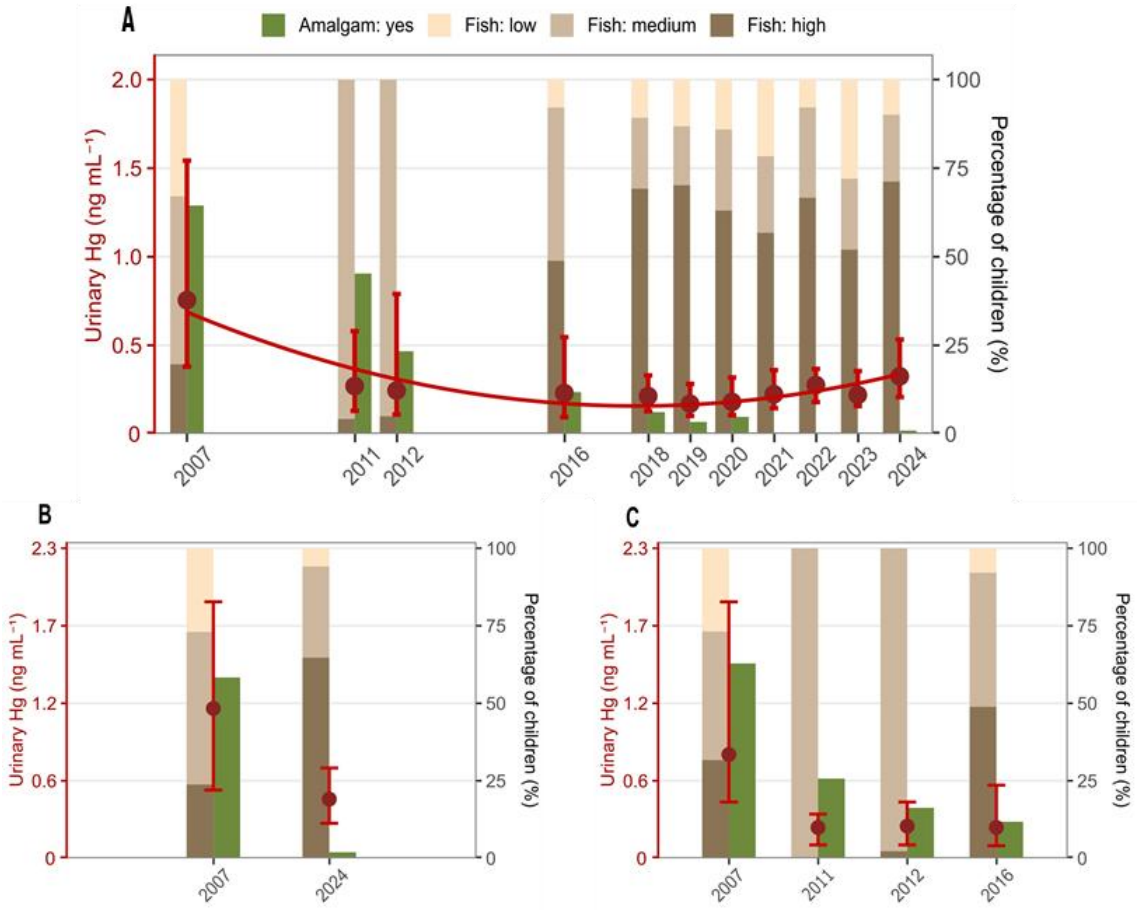


Figure 27: U-Hg concentrations and exposure-related characteristics in the recruited Slovenian children. (A) All study sites combined: urinary Hg (ng mL^{-1}; median and interquartile range, left y-axis) and, on the right y-axis, the percentage of participants with at least one dental amalgam and the percentages in low-, moderate-, and high-fish consumption groups by year (2007–2024). (B) Same metrics restricted to children from Idrija (data available for two sampling years). (C) Same metrics restricted to children from Ljubljana (data available for four sampling years).

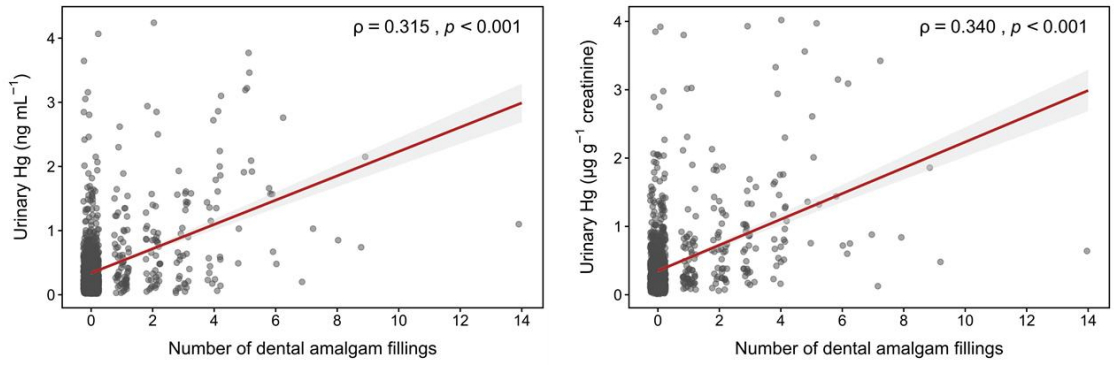


Figure 28: Correlation (Spearman's rho; p-value) between the number of amalgam fillings and the U-Hg (in ng mL^{-1} and in µg g^{-1} creatinine) in pooled data from all cohorts.

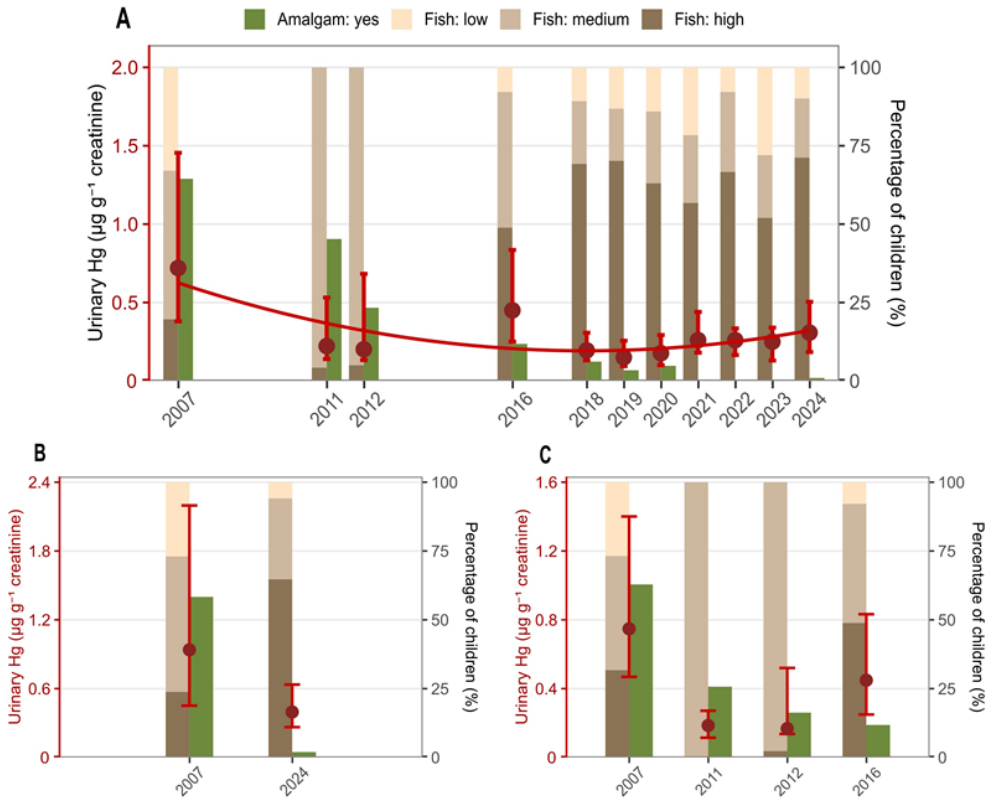


Figure 29: U-Hg concentrations and exposure-related characteristics in the recruited Slovenian children. (A) All study sites combined: urinary Hg (µg g^{-1} creatinine; median and interquartile range, left y-axis) and, on the right y-axis, the percentage of participants with at least one dental amalgam and the percentages in low-, medium-, and high-fish consumption groups by year (2007–2024). (B) Same metrics restricted to children from Idrija (data available for sampling years). (C) Same metrics restricted to children from Ljubljana (data available for four sampling years).

The observed decline in U-Hg levels from the earliest to the latest cohort closely paralleled the reduction in amalgam prevalence in children. The proportion of children with at least one amalgam filling decreased over time, from 65% in PHIME, 37% in DEMOCOPHES, 12% in CROME, to only 3% in SLO-HBM-II. Moreover, even among amalgam carriers, the average number of fillings decreased across successive cohorts (Table 5; Figure 27; Figure 30). In contrast, the overall prevalence of fish consumption remained consistently high across cohorts, while the proportion of children classified as 'high' consumers (> 3 fish meals per month) increased markedly in recent cohorts from 19.7% in PHIME, 48.9% in CROME, to 67.5% in SLO-HBM-II. Similar trends were observed in Idrija and Ljubljana over the years (Figure 27; Figure 29; Table 4).

Table 5: Summary of basic participant characteristics by study cohort and year.

Study cohort	Year	N[a]	Age[b]	Male	BMI[c]	Amalgam[d]		Fish consumption[e]		
			($\bar{x} \pm SD$)	(%)	($\bar{x} \pm SD$)	Yes (%)	N ($\bar{x} \pm SD$)	Low (%)	Moderate (%)	High (%)
PHIME	2007	180	9.2 ± 1.2	50.6	17.5 ± 3.39	64.5	3.02 ± 2.21	32.9	47.4	19.7
DEMOCOPHES	2011	95	8.6 ± 1.7	44.2	17.1 ± 2.71	45.3	2.33 ± 1.61	0.00	95.8	4.20
	2012	60	9.2 ± 2.0	53.3	16.9 ± 3.04	23.3	2.57 ± 1.70	0.00	95.0	5.00
	Total	155	8.8 ± 1.8	47.7	17.1 ± 2.83	36.8	2.39 ± 1.62	0.00	95.5	4.50
CROME	2016	178	7.7 ± 0.5	50.0	16.6 ± 6.93	11.8	2.19 ± 1.29	7.90	43.3	48.9
SLO-HBM-II	2018	130	8.2 ± 0.9	41.5	17.3 ± 3.68	6.15	2.62 ± 1.30	10.8	20.0	69.2
	2019	236	7.9 ± 0.9	50.0	16.6 ± 2.78	3.39	1.57 ± 0.79	13.2	16.6	70.2
	2020	208	8.1 ± 0.9	60.1	16.7 ± 2.65	4.81	1.56 ± 0.73	14.1	22.9	63.0
	2021	37	8.1 ± 0.9	45.9	16.3 ± 1.94	0.00	-	21.6	21.6	56.8
	2022	51	8.0 ± 0.9	43.1	16.3 ± 2.24	0.00	-	7.80	25.5	66.7
	2023	25	8.3 ± 0.8	52.0	16.6 ± 2.57	0.00	-	28.0	20.0	52.0
	2024	212	8.1 ± 0.8	44.8	17.4 ± 2.78	0.94	1.0 ± 0.00	9.90	18.9	71.2
	Total	899	8.1 ± 0.9	49.4	16.9 ± 2.86	3.11	1.85 ± 1.05	12.7	19.8	67.5

$\bar{x}$ = arithmetic mean; SD = standard deviation; BMI = body mass index; Amalgam Yes = indicator that child has dental amalgam filling(s); fish consumption: low = < 1 fish meal per month; moderate = 1-3 fish meals per month; high = > 3 fish meals per month.

[a] Total number of recruited individuals.

[b] Missing data on age: in 2016 (n = 1).

[c] Missing data on BMI: in 2007 (n = 12); in 2016 (n = 1); in 2020 (n = 1).

[d] Missing data on amalgam presence/number: in 2007 (n = 28).

[e] Missing data on fish consumption: in 2007 (n = 7); in 2019 (n = 1); in 2020 (n = 16).

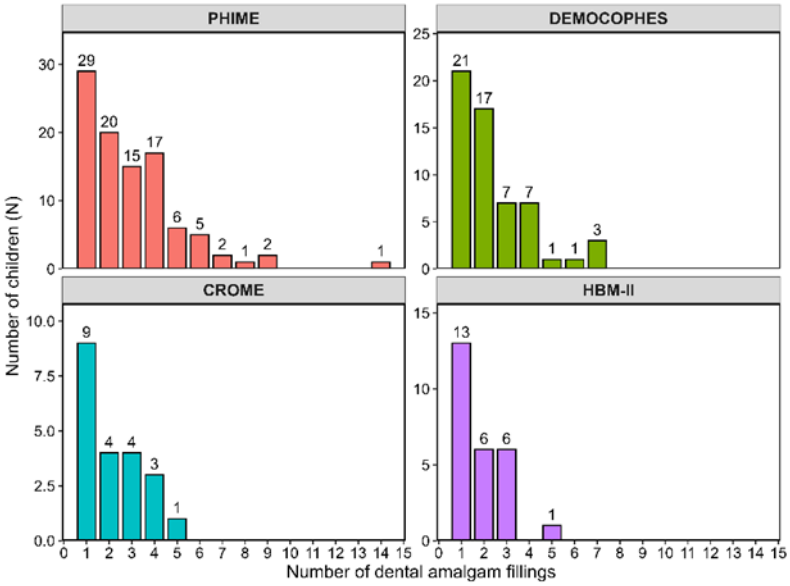


Figure 30: Distribution of the number of dental amalgam fillings among amalgam carriers, stratified by study.

Table 6: Multilevel modelling of the temporal trend in urinary Hg concentrations (2007–2024). Year effect reduction (%) represents the percentage of the temporal decline explained by the inclusion of the dental amalgam number relative to the base model (Model 1).

	Model 1		**Model 2**		**Model 3**	
	Estimate (SE)[a]	p-value	Estimate (SE)[a]	p-value	Estimate (SE)[a]	p-value
Fixed effects						
Intercept	0.301 (0.031)	<.001	0.224 (0.027)	<.001	0.220 (0.024)	<.001
Year (ratio of change per 1 year)	0.945 (0.008)	<.001	0.947 (0.008)	<.001	0.977 (0.008)	0.008
Amalgam number (per filling)					1.256 (0.029)	<.001
Fish: moderate vs low			1.058 (0.084)	0.479	1.032 (0.079)	0.680
Fish: high vs low			1.395 (0.104)	<.001	1.365 (0.098)	<.001
Age (per 1 year)			0.998 (0.023)	0.915	1.018 (0.022)	0.406
Sex: F vs M			0.916 (0.043)	0.059	0.927 (0.042)	0.090
BMI z-score (per 1 unit)			0.960 (0.015)	0.010	0.961 (0.015)	0.009
Urinary creatinine						
Rural vs urban			0.985 (0.195)	0.938	1.014 (0.184)	0.942
Potentially contaminated vs urban			1.986 (0.410)	0.004	1.803 (0.342)	0.006
Random effects						
Variance within towns (Residual)	0.870		0.700		0.652	
Variance between towns	0.135		0.068		0.055	
Model fit						
AIC	3624		3346		3251	
BIC	3645		3409		3319	
ICC	0.135		0.088		0.078	
Year effect reduction (%)	Ref.		2.40		59.0	

[a]The regression coefficients (β) from models with ln(U-Hg) as the outcome were exponentiated to obtain multiplicative effects (ratios) for U-Hg. For continuous predictors, an estimate < 1 indicates a decrease, and an estimate > 1 an increase, in U-Hg associated with a one-unit increase in the predictor. For categorical predictors, estimates represent the ratio of U-Hg in each category relative to the reference category (estimate < 1 indicates lower uHg and estimate > 1 higher U-Hg compared with the reference).

To formally assess temporal trends, a multilevel modelling approach with random intercepts for town was applied to the pooled dataset (2007-2024). The results of the models are presented in Tables 6 and 7. In the base model, Model 1, a significant decreasing trend in U-Hg was observed, with a geometric mean ratio (GMR) of 0.945 per year (95% CI: 0.929, 0.962; $p < .001$), indicating an average annual decline of approximately 5.5%. To ensure that this trend was not driven by changes in population characteristics, demographic and dietary confounders (urinary creatinine, age, sex, BMI z-score, residence area type) were added in Model 2. The time trend observed in the base model remained virtually unchanged after adjustment (GMR = 0.947). Regarding covariates, residence in potentially contaminated towns was associated with significantly higher U-Hg compared to urban areas (GMR = 1.986, $p = 0.004$). U-Hg was positively associated with urinary creatinine (GMR = 1.937, $p <.001$) and negatively associated with BMI z-score (GMR = 0.960, $p = 0.010$). Finally, to test the mediating role of dental amalgams, the number of amalgam fillings was added in Model 3. The addition of the number of dental amalgams substantially reduced the year effect, increasing the GMR to 0.977 (95% CI: 0.961, 0.994; $p = 0.008$). This corresponds to a 59% reduction in the magnitude of the temporal trend relative to the base

model. It further implies that a large portion of the decline in U-Hg in children over time can be explained by the concurrent reduction in the prevalence and/or number of dental amalgams they had.

To further characterize the temporal trend and evaluate whether it differed across population subgroups, interaction terms were introduced in Models 4-6 (Table 7). Across all models, there was a significant interaction between year and fish consumption (Table 7). The interaction terms for moderate and high fish consumption were consistently > 1.0 (1.053-1.055 in Models 4 6 for high vs. low, all p < .001), indicating that, after adjustment for amalgam status and other covariates, the annual decline in U-Hg was substantially slower among children with higher fish intake. This further implies that, as dental amalgam prevalence decreases, the relative contribution of dietary sources to U-Hg becomes more prominent.

Table 7: Multilevel mixed-effects models assessing effect modification of the temporal trend in urinary Hg (2007–2024). Models include interaction terms (year × predictor) to test if temporal trends differ across subgroups.

	Model 4		**Model 5**		**Model 6**	
	Estimate	p-value	Estimate	p-value	Estimate	p-value
Fixed effects						
Intercept	0.199 (0.021)	< .001	0.192 (0.020)	< .001	0.219 (0.024)	< .001
Year (ratio of change per 1 year)	0.937 (0.012)	< .001	0.949 (0.012)	< .001	0.940 (0.012)	< .001
Amalgam number (per filling)					1.277 (0.060)	< .001
Amalgam (Yes vs No)	2.187 (0.173)	< .001	1.642 (0.176)	< .001		
Fish: moderate vs low	1.049 (0.081)	0.535	1.049 (0.081)	0.535	1.058 (0.082)	0.462
Fish: high vs low	1.336 (0.099)	< .001	1.336 (0.099)	< .001	1.333 (0.099)	< .001
Age (per 1 year)	1.016 (0.022)	0.469	1.020 (0.022)	0.360	1.017 (0.022)	0.436
Sex: F vs M	0.937 (0.042)	0.146	0.935 (0.042)	0.129	0.930 (0.041)	0.103
BMI z-score (per 1 unit)	0.958 (0.015)	0.005	0.957 (0.015)	0.004	0.960 (0.015)	0.007
Urinary creatinine	1.939 (0.073)	<.001	1.934 (0.073)	<.001	1.935 (0.073)	<.001
Rural vs urban area	0.909 (0.157)	0.590	0.931 (0.158)	0.680	0.995 (0.175)	0.980
Pot. contaminated vs urban	1.763 (0.320)	0.005	1.707 (0.305)	0.007	1.743 (0.321)	0.007
Year × Fish (moderate vs low)	1.051 (0.014)	< .001	1.056 (0.014)	< .001	1.050 (0.014)	<.001
Year x Fish (high vs low)	1.053 (0.015)	< .001	1.053 (0.015)	< .001	1.055 (0.015)	<.001
Year × Amalgam (Yes vs No)			0.938 (0.015)	< .001		
Year × Amalgam number					1.001 (0.006)	0.800
Random effects						
Variance within towns (resid.)	0.648		0.641		0.643	
Variance between towns	0.049		0.047		0.050	
Model fit						
AIC	3247		3233		3240	
BIC	3325		3316		3323	
ICC	0.070		0.068		0.072	

[a]The regression coefficients (β) from models with ln(U-Hg) as the outcome were exponentiated to obtain multiplicative effects (ratios) for U-Hg. For continuous predictors, an estimate < 1 indicates a decrease, and an estimate > 1 an increase, in U-Hg associated with a one-unit increase in the predictor. For categorical predictors, estimates represent the ratio of U-Hg in each category relative to the reference category (estimate < 1 indicates lower uHg and estimate > 1 higher U-Hg compared with the reference).

Regarding the interaction between dental amalgams effect and time, the results depended on whether amalgams were modelled as a binary or numerical variable. In Model

5, where amalgam status was included as a binary indicator (yes/no), the interaction of amalgam and time indicated a reduction in the difference between children with and without fillings over time (GMR = 0.938, p <.001). In other words, the difference in U-Hg levels between children with and without fillings narrowed significantly over time. However, when the exact number of fillings was used in the model instead (Model 6), the interaction term was not significant (p = 0.800), which suggests that the Hg contribution per individual filling remained essentially stable over time. Consequently, the narrowing difference observed in the binary model is consistent with a reduction in the number of amalgam fillings per child in more recent cohorts (rather than, for example, a change in the amount of Hg released per filling).

The findings from multilevel modelling were confirmed by the multiple regression model fitted on the pooled PHIME and HBM-II datasets. In both the binary- and numeric-amalgam models, HBM-II children showed significantly stronger associations between fish intake and U-Hg compared with PHIME, as indicated by significant positive interaction terms for HBM-II × fish consumption (Tables 8 and 9), indicating that fish consumption played a larger role in later years. In contrast, the interaction between study and amalgam status (yes/no) was negative and borderline significant ($\beta \approx$ -0.37, p = 0.085), suggesting a weaker difference between amalgam carriers and non-carriers in HBM-II than in PHIME, but with confidence intervals including no effect. When the actual number of fillings was used instead of the binary amalgam variable, the interaction with study was small and not statistically significant, indicating that the per-filling contribution to U-Hg was stable across cohorts.

Table 8: Results of the multiple regression models fitted on pooled PHIME and HBM-II datasets. Amalgam is a binary variable (“Yes” or “No”).

	Estimate	SE	p-value
Intercept	-0.973	0.154	0.000
Study: HBM-II	-0.984	0.168	0.000
Amalgam number	0.941	0.151	0.000
Fish: medium	-0.272	0.160	0.090
Fish: high	-0.074	0.208	0.723
Age	0.018	0.027	0.516
Sex: F vs M	-0.011	0.049	0.818
Urinary creatinine	0.628	0.050	0.000
BMI (z-score)	-0.057	0.019	0.003
Town type: rural	-0.087	0.069	0.209
Town type: potentially contaminated	0.615	0.081	0.000
HBM-II x Amalgam: Yes	-0.365	0.212	0.085
HBM-II x Fish: medium	0.500	0.186	0.007
HBM-II x Fish: high	0.572	0.223	0.010

Table 9: Results of the multiple regression model fitted on pooled PHIME and HBM-II datasets. Amalgam number is the actual number of amalgam fillings the child has.

	Estimate	SE	p-value
Intercept	-0.762	0.141	0.000
Study: HBM-II	-1.185	0.156	0.000
Amalgam number	0.188	0.030	0.000
Fish: medium	-0.211	0.158	0.182
Fish: high	-0.159	0.208	0.444
Age	0.020	0.027	0.466
Sex: F vs M	-0.028	0.049	0.576
Urinary creatinine	0.613	0.050	0.000
BMI (z-score)	-0.052	0.019	0.006
Town type: rural	-0.062	0.069	0.367
Town type: potentially contaminated	0.592	0.081	0.000
HBM-II x Amalgam: Yes	0.116	0.079	0.146
HBM-II x Fish: medium	0.433	0.184	0.019
HBM-II x Fish: high	0.656	0.223	0.003

4.3 Discussion

This study provides a comprehensive assessment of dental amalgam use in Slovenia, highlighting a substantial progress in the transition to Hg-free dentistry. Paediatric clinics demonstrate high compliance with up-to-date guidelines and regulations. Slovenia's efforts are closely aligned with broader European initiatives under the EU Regulation (EU) 2017/852, its 2024 amendment (Regulation (EU) 2024/1849), and the Minamata Convention on Mercury, all of which aim to minimize Hg exposure and promote safer alternatives (Fisher et al., 2018; European Parliament & Council, 2017). However, despite this progress, notable challenges remain, particularly regional disparities in resources, awareness, and financial support, which require targeted policy intervention.

4.3.1 Variability in Amalgam Use and Readiness for the Phase-Out

While paediatric clinics have largely eliminated amalgam use, adult clinics exhibit greater variability, where clinical needs, patient preferences, and systemic barriers (related to the reimbursement of costs for alternative materials that were not covered by health insurance until recently) significantly influence decision-making. Although 72% of Slovenian clinics report being prepared for the upcoming amalgam ban, regional differences persist, with the Savinjska region reporting the highest proportion (63%) of unprepared clinics. Similarly, public sector clinics (67%) report lower readiness than private clinics (78%), indicating resource and financial constraints in the public system.

Experience from countries such as Norway and Sweden demonstrate that a phased transition, supported by financial incentives, public education, and targeted training, is key to a successful phase-out (Fisher et al., 2018; HCWH Europe, 2018; Norwegian Ministry of the Environment, 2012). Sweden, for instance, discontinued amalgam on environmental grounds in 2009, supported by strong public awareness campaigns. Norway followed a

similar approach, implementing a general Hg ban in 2008 while providing time for industry adaptation and dentist training. Slovenia could benefit from adopting comparable strategies, ensuring a gradual yet effective transition while addressing regional disparities (HCWH Europe, 2018; Norwegian Ministry of the Environment, 2012).

Future studies should assess the impact of these measures on actual Hg exposure levels, through HBM programmes, particularly among populations at greater risk, such as dental workers, children and pregnant women.

4.3.2 Role of Dentists and Professional Training in Transition

Dentists play a crucial role in this transition, both individually and as a part of professional associations. Their responsibility extends beyond clinical care for minimizing the environmental impact of their practices. While some studies suggest that older dentists tend to rely on amalgam due to a lack of training in posterior composite placement (Norwegian Ministry of the Environment, 2012; Jebur et al., 2023), our findings show a balanced preference for alternative materials across all age groups, except in cases where achieving absolute dryness is not possible or when treating extensive caries in patients with poor oral hygiene.

Educational initiatives are vital to bridging gaps in awareness. The limited awareness regarding the Minamata Convention among Slovenian dentists suggests a gap in understanding the environmental and health issues associated with Hg, which is further reflected in responses to related questions. Our study found that only 9% of Slovenian dentists are fully familiar with the Minamata Convention, while 30% have no familiarity at all. This aligns with our finding that 38% of respondents consider phasing out amalgam very important, while another 38% find it moderately important. This lack of awareness underscores the need for targeted educational programs to equip dental professionals with the knowledge and skills required for the effective adoption of Hg-free practices. Dental education programmes are playing a key role in this effort by incorporating Hg-free alternatives into their curricula, offering continuous education for clinicians, as well as raising awareness of the environmental and health impacts of amalgam (Al-Rabab'ah et al., 2016; Spaveras & Antoniadou, 2023; Bakhurji et al., 2017; Al-Nahedh et al., 2020; Alkhudhairy, 2016; Ercin et al., 2021; Hayes et al., 2020). Success stories from countries such as Sweden, Denmark, the Netherlands and Japan highlight the effectiveness of these approaches, with many dental educational programmes abandoning amalgam training and focusing on Hg-free techniques to promote sustainable dental practices (UNEP, 2016). Future assessments should measure the effectiveness of educational interventions by tracking changes in knowledge and attitudes among dental professionals regarding Hg-free dentistry.

4.3.3 Financial Barriers and the Role of Health Insurance

While patient preferences for composite resins and Hg-free alternatives are increasing, financial barriers remain a key challenge. Public and private health insurance policies must adapt to fully reimburse composite fillings, which remain cost-prohibitive for some patients. Evidence from Sweden suggests that removing financial coverage for Hg amalgam fillings in national insurance programs led to their near-complete phase-out, as composite restorations became equally or more affordable (HCWH Europe, 2017; UNEP, 2016).

Therefore, reforming health insurance policies to favour Hg-free alternatives is another critical area for development. Both public and private insurance systems in Slovenia must adapt to fully reimburse composite fillings, which remain cost-prohibitive for many

patients. Recent findings indicate that private dentists are already more likely to replace existing amalgam restorations with composite resins, reflecting a market-driven approach (Al-Nahedh et al., 2020). Our findings show that private clinics report higher preparedness for the transition (78%) compared to public clinics (67%), suggesting that financial barriers disproportionately affect the public sector.

The observed reduction in amalgam use across both paediatric and adult clinics reflects broader trends driven by patient preferences, regulatory changes, and the availability of alternative materials. However, this trend often excludes lower-income patients who cannot afford the higher out-of-pocket costs associated with Hg-free restorations. While 51% of private adult clinics report never using amalgam for their adult patients, the figure drops significantly to 15% in public adult clinics, where its occasional use remains more prevalent. These differences indicate that financial and systemic factors continue to shape treatment decisions, with public clinics relying more on amalgam use due to cost-related concerns.

Without comprehensive health insurance coverage, patients with lower socioeconomic status may be left with fewer treatment options, perpetuating inequalities in access to dental care. Slovenia should monitor disparities in access to Hg-free materials and evaluate the impact of insurance policy reforms on dental care equity.

4.3.4 Waste Management and Environmental Impact

Waste management practices are equally critical. The safe removal of amalgam fillings, with appropriate measures to minimize Hg release, is a necessary step in this transition. Amalgam separators are widely used in Slovenia, with 97% of respondents reporting their use, yet concerns about their effectiveness remain. Amalgam separators can effectively remove up to 98.7% of Hg from wastewater, however, their efficiency depends on proper maintenance and timely removal of collected Hg. Processed Hg must be sent to specialized processing facilities, which can be challenging in countries with limited hazardous waste management infrastructure (UNEP, 2016). High maintenance costs and doubts about their effectiveness add to the financial and operational difficulties faced by clinics in the region. These issues are closely tied to broader challenges in transitioning away from dental amalgam.

Establishing centralized clinics equipped with amalgam separators, as outlined in Slovenia's National Plan on Measures for the Gradual Phase-Out of Dental Amalgam Use by 2030 (Slovenian Ministry of Health, 2024b), could alleviate the financial and operational burdens faced by individual practitioners. Such centralized systems would streamline compliance with waste regulations and improve Hg collection, particularly in regions with limited resources, such as Savinjska (Chamber of Slovenian Dentists, 2022; HCWH Europe, 2018; Norwegian Ministry of the Environment, 2012). Despite these measures, dental amalgam can still enter wastewater via human waste and sewage, causing soil, landfill and air pollution through waste incineration processes. Crematoria are also an important source of Hg emissions, which are expected to increase due to the increasing frequency of cremations and the prevalence of amalgam fillings in the deceased. Strengthening waste treatment infrastructure and adopting environmentally friendly disposal methods are therefore essential to support preventive and centralized efforts (Tibau & Grube, 2019; UNEP, 2016; Štamfelj et al., 2025).

Slovenia must improve its waste treatment infrastructure and increase monitoring of Hg levels in wastewater and cremation emissions to ensure compliance with environmental standards. While Slovenia has a functioning waste management system, gaps remain, particularly in the final disposal of hazardous waste, which is currently exported due to the absence of a dedicated disposal facility. Additionally, the lack of comprehensive

quantitative data on amalgam consumption, waste generation, and disposal pathways (Deloitte INERIS, 2020) limits the ability to accurately assess environmental releases and human exposure. Crematoria, though contributing less to overall Hg emissions, may underestimate local exposure due to their proximity to residential areas and lower emission release points, further highlighting gaps in regulatory and monitoring frameworks (Štamfelj et al., 2025).

4.3.5 Future Directions and Policy Recommendations

To ensure a successful and equitable transition, Slovenia must adopt a comprehensive, multi-stakeholder approach that integrates regulatory enforcement, financial incentives, and public awareness campaigns. The National Plan emphasizes collaboration among key institutions (Kocman et al., 2018; Slovenian Ministry of Health, 2024b), including:

- Ministry of Health – oversight of awareness campaigns and professional development programs, particularly through the Chemical Office of the Republic of Slovenia (Urad Republike Slovenije za kemikalije, URSK), which is responsible for regulating chemical safety and implementing related policies.
- Slovenian Environmental Agency (Agencija Republike Slovenije za okolje, ARSO) – monitoring Hg emissions and enforcing waste regulations.
- National Institute of Public Health (Nacionalni inštitut za javni zdravje, NIJZ) – preventive strategies and public health initiative and the regional health authorities addressing regional disparities in preparedness and access to resources.
- Jožef Stefan Institute (JSI) & Slovenian Research and Innovation Agency (ARIS) – research and innovation in Hg-free materials.
- Jožef Stefan Institute, National Institute of Public Health & Chemical Office of the Republic of Slovenia – continuous HBM to track long-term trends in internal Hg exposure, policy-driven shifts in dominant sources, and residual exposure pathways.
- Dental Associations and Medical Chamber of Slovenia – advocacy, training, and implementation of best practices.

Preventive strategies remain a crucial component of Hg-free dentistry, reducing the need for both amalgam and composite restorations. Public health campaigns must encourage better oral hygiene practices and provide accessible preventive care, particularly for vulnerable populations who face financial barriers to dental treatment (Slovenian Ministry of Health, 2024b; HCWH Europe, 2018).

Investing in research and development will also be key to overcoming remaining barriers, including concerns about composite resin toxicity and the need for more durable Hg-free alternatives (Spaveras et al., 2023). International examples, particularly from Denmark, Norway, Sweden, and Finland, highlight the value of engaging dental associations and industry stakeholders in policy development, ensuring gradual adaptation to new regulations (UNEP, 2016).

By building upon international best practices and by fostering collaboration among various stakeholders (policy makers, academia, regulative bodies, practitioners, public), Slovenia can address these challenges effectively. Enhanced education, robust financial incentives and continued innovation will enable the country to meet its commitments under the Minamata Convention. This collective effort will not only contribute to sustainable and equitable dental practices but also position Slovenia as a leader in Hg-free dentistry and environmental health.

4.3.6 Human Biomonitoring Findings and Implications for Exposure Trends

This study represents the first investigation in Slovenia to assess the relationship between U-Hg concentrations in children and their exposure to Hg via dental amalgam fillings. Overall, U-Hg concentrations observed in Slovenian children were low and comparable to those reported in other European countries, with most values below 3 ng mL^{-1}, typical for general background populations (Basu et al., 2018). The highest median U-Hg concentration was recorded in the earliest cohort, PHIME (0.76 ng mL^{-1} or 0.72 µg g^{-1} creatinine), and the lowest in the latest, SLO-HBM-II (0.22 ng mL^{-1} or 0.21 µg g^{-1} creatinine). Within the broader framework of health risk assessment, the German Human Biomonitoring Commission has established an HBM-I value of 7 ng mL^{-1} for U-Hg in children, below which no adverse effects are expected (Apel et al., 2017). In our pooled dataset, only six children exceeded this value, five of those in PHIME and one in DEMOCOPHES.

Consistent with international evidence, our findings confirm that dental amalgams are a major determinant of U-Hg in children. We observed a significant positive correlation between the number of dental amalgam fillings and U-Hg (Figure 28), in agreement with previous reports of a dose-dependent relationship between amalgam burden and U-Hg (Maserejian et al., 2008; Varkey et al., 2014; Dutton et al., 2013).

A clear downward trend in U-Hg was observed from 2007 to 2024. Our results suggest that much of this decline can be attributable to the reduction of amalgam use in children. The proportion of children with at least one dental amalgam filling decreased from 65% in PHIME to only 3% in SLO-HBM-II, and the mean number of fillings among amalgam carriers also decreased from an average of 3.02 in 2007, to 1.00 in 2024 (Table 2). When the amalgam number was added to the time trend model (Table 4, Model 3), the estimated year effect was substantially decreased, indicating that reduced amalgam use appears to account for a large share of the observed time trend. Moreover, the interaction results showed that the difference between children with and without amalgams narrowed over time when amalgam was modelled as a binary (yes/no) variable (Table 5, Model 5), but not when modelled as the actual number of fillings (Table 5, Model 6). This suggests that the Hg contribution per filling remained stable, and the difference between the groups (amalgam carriers and non-carriers) shrank because children in more recent cohorts had fewer fillings.

On the other hand, the relative importance of fish consumption increased over time. Although the overall fish consumption prevalence (i.e., number of children eating at least one fish meal per month) remained high across cohorts, the proportion of children reporting frequent consumption ($>$ 3 fish meals per month) increased from $\sim$ 20% in 2007 to 71% in 2024, with similar observations in the two towns sampled multiple times over the years (Idrija and Ljubljana). Interaction analyses suggest that the decreasing trend of U-Hg was slower among frequent fish consumers (Table 5, Models 4-6, interactions of fish x year), indicating increasing relative contribution of dietary Hg as exposure from amalgams decreased. Multiple regression models comparing PHIME and SLO-HBM-II confirmed stronger fish consumption and U-Hg associations in the recent cohort (Tables 8-9). This, however, does not imply increased absolute dietary exposure, but rather a redistribution of sources as one major source of exposure (amalgam) decreases. Similar patterns have been reported in other HBM datasets (Nicolae et al., 2013; Astolfi et al., 2020; Sherman et al., 2013; Hrubá et al., 2023; Basu et al., 2018).

The environmental context also contributed to variability in exposure. Children living in historically Hg-contaminated areas, such as Idrija (a former Hg-mining town), and in

certain industrial zones had higher U-Hg levels (Tables 4-5, Models 2-6), consistent with previous work demonstrating persistent impacts of legacy pollution on local populations (Kobal et al., 2017; Astolfi et al., 2020). These findings underline the importance of interpreting HBM data within both environmental and policy contexts, and they support the need for ongoing environmental surveillance and targeted remediation. This is in line with recommendations from European HBM coordination initiatives to systematically include legacy contamination sites in national monitoring frameworks (Den Hond et al., 2015; Schindler et al., 2014).

An important methodological consideration concerns creatinine adjustment. Although creatinine correction is widely used to account for urine dilution, differences in sampling time and inter-individual variability in creatinine excretion (e.g. due to age, sex, muscle mass, hydration, and diet) can introduce bias (Barr et al., 2005; Sallsten & Barregard, 2021). In our dataset, the afternoon sampling protocol used in CROME likely contributed to discrepancies between unadjusted and creatinine-corrected U-Hg results. This highlights the need to carefully consider sampling protocols and creatinine variability when comparing U-Hg across studies, as these factors may influence the conclusions.

4.3.7 Relevance to the Minamata Convention Effectiveness Evaluation

Article 22 of the Minamata Convention establishes a framework for the global evaluation of the treaty's effectiveness, relying on indicators such as environmental monitoring, HBM, and information on regulatory implementation. These evaluations occur at the international level, nonetheless, national HBM programs represent a key source of evidence for tracking exposure trends and understanding changes in dominant exposure pathways. In this context, our study provides insight into how a major Hg^0 exposure source, dental amalgam, declined in Slovenia over nearly two decades, and how this decline was reflected in biomarker concentrations in children.

Slovenia ratified the Minamata Convention in 2018, however, our data demonstrates that the reduction in dental amalgam use among children began well before the Convention entered into force (Figure 31), with only 12% of the sampled children reporting having dental amalgams in 2016, compared to over 64% in 2007. This pattern likely reflects evolving clinical guidelines, improved preventive oral health programs, increased availability of composite restorative materials, and changing preferences among both clinicians and patients (Usenik et al., 2025). Slovenia is not unique in this regard, as several countries had already phased down or banned dental amalgam independently of Minamata, including Norway (2008), Sweden (2009), and others with partial or full restrictions (e.g., Japan, Switzerland, France, Germany, Finland, Austria, Canada) (HCWH Europe, 2017; HCWH Europe, 2018; UNEP, 2016; EnvMed Network, 2025).

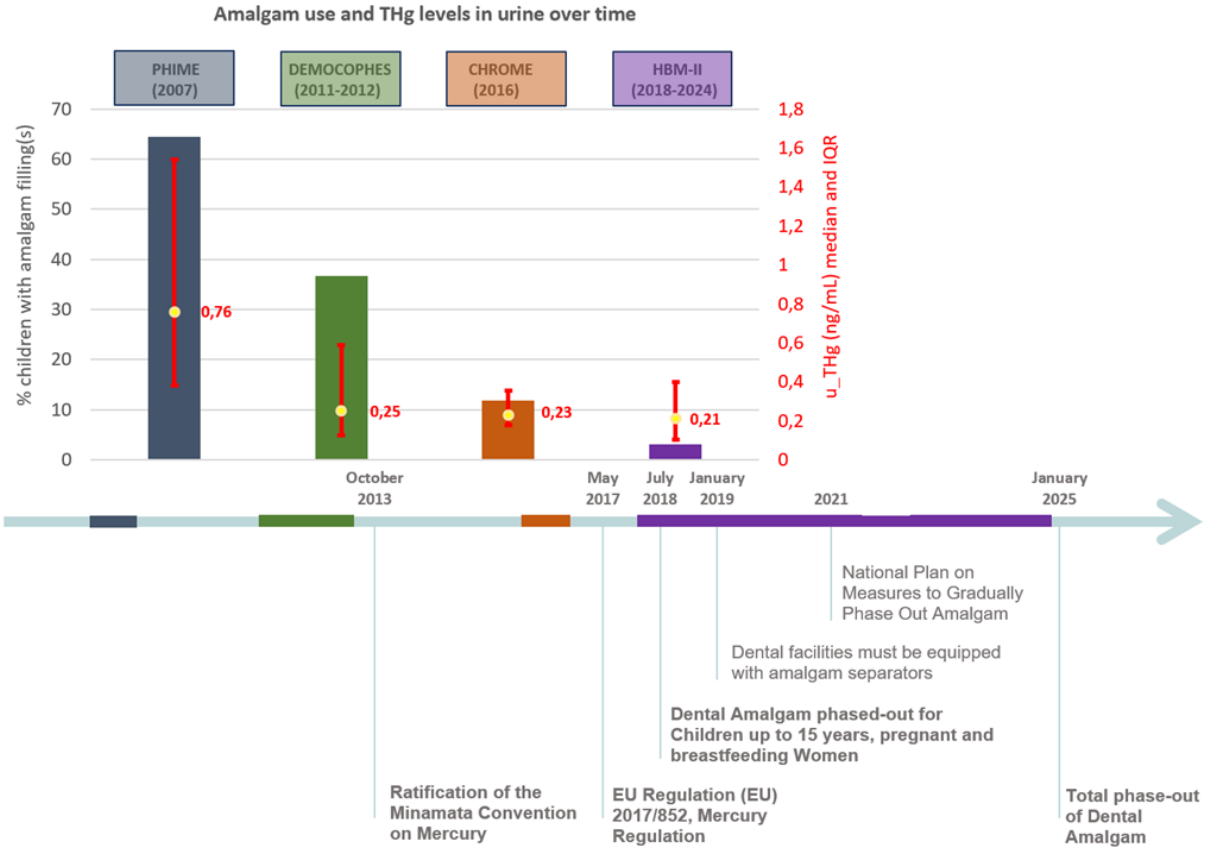


Figure 31: Amalgam use and THg levels in urine over time, with timeline highlighting the adopted Slovenian legal measures on the use of amalgam.

Because the major decline in amalgam use in Slovenian children occurred before Minamata implementation, our findings cannot be interpreted as a direct assessment of Convention effectiveness in Slovenia. However, they provide an example of how HBM data can support effectiveness evaluations elsewhere by illustrating the type of evidence directly relevant for Article 22: long-term trends in internal exposure, shifts in dominant sources linked to policy or practice changes, quantification of how specific reductions relate to biomarker declines, and identification of residual exposure pathways (e.g., dietary, or environmental factors). By linking long-term trends in U-Hg to changes in dental amalgam prevalence and burden, and by quantifying how much of the temporal decline is explained by reduced amalgam use, our results suggest that declining dental amalgam use likely contributed to lower internal Hg levels in children. At the same time, as amalgam use decreases, dietary and other sources account for an increasing share of the residual exposure. This type of combined information on exposure trends, sources and determinants is directly relevant for the effectiveness evaluation framework.

Even though the use of dental amalgams in Slovenian children at the present moment is no longer concerning, amalgam-related exposure is still relevant in adults, especially among socioeconomically vulnerable groups, as it remains the only restorative material fully reimbursed by the national health insurance system (Usenik et al., 2025; Perharič, 2014; Deloitte INERIS, 2020). Dental professionals are also directly exposed to Hg vapor during amalgam handling, making them an additional group that would benefit from the full transition to amalgam-free dentistry (Picard et al., 2025).

It is also worth noting that an important value of HBM is its participatory dimension. By involving citizens directly in the monitoring process, HBM raises awareness of exposure sources and empowers individuals to make informed decisions to reduce their personal risks.

4.3.8 Study Limitations

The HBM study has several limitations. First, the analyses are based on repeated cross-sectional, observational data rather than longitudinal follow-up, so the temporal patterns in U-Hg reflect population-level changes and cannot be interpreted as causal at the individual level. The samples of children included in the present study were not designed to be fully nationally representative, therefore, the findings reflect the characteristics of the sampled populations rather than the entire national child population. Next, although we adjusted for key covariates (age, sex, BMI, creatinine, residence area type, fish intake), residual confounding by unmeasured factors such as oral health practices, socioeconomic status, and interindividual differences in Hg metabolism cannot be excluded. It also relies on self-reported amalgam and dietary data, and lacks detailed fish species information. Moreover, most towns were sampled only once, and only two were repeatedly sampled across cohorts, which limits the ability to fully disentangle temporal from spatial variability. This further means that, while the direction of the amalgam–U-Hg association and its contribution to the temporal decline appear robust, the precise magnitude of effect should be interpreted with caution.

A key limitation of the administrative/policy assessment is its reliance on self-reported data, which may introduce response bias, particularly in sensitive areas such as compliance with waste regulations. The legal obligations under Article 4 of the Regulation on the Management of Amalgam Waste (Official Gazette of the Republic of Slovenia, No. 80/20) and the potential penalties for non-compliance may have influenced participants' willingness to provide complete and accurate responses. An additional limitation is the relatively low response rate to the dentist questionnaire (approximately 10% of all Slovenian dentists). Although this may introduce selection bias, the survey was distributed to more than 600 verified e-mail addresses. Due to GDPR restrictions, direct access to comprehensive contact lists was not possible. Alternative recruitment strategies, such as distribution at dental conferences, were considered but would likely have been less effective, as such events in Slovenia are typically hybrid, with fewer than 200 participants and limited opportunities for survey dissemination. Under these constraints, the number of responses obtained is considered acceptable and reasonably representative of the target population.

Overall, while these limitations do not undermine the main findings, they highlight the need for cautious interpretation of effect sizes and for future studies to incorporate longitudinal designs, more detailed exposure assessment, and improved representativeness to strengthen causal inference and generalizability.

Chapter 5

Conclusions

This study provides the first nationally representative evidence in Slovenia linking children's Hg body burden to exposure from dental amalgam fillings, using HBM as a policy evaluation tool. By combining administrative and policy metrics with environmental and health metrics derived from long-term HBM, the study addresses the main requirement of Article 22 of the Minamata Convention to evaluate its effectiveness and assess how regulatory actions translate into real-world outcomes relevant to human health.

The environmental component of the research demonstrates a clear and sustained decline in U-Hg concentrations among Slovenian children in the last 17 years. The median U-Hg levels declined from 0.76 ng mL^{-1} (0.72 µg g^{-1} creatinine) in 2007 to 0.22 ng mL^{-1} (0.21 µg g^{-1} creatinine) in 2024. Over the same period, the prevalence of dental amalgam fillings in children dropped from 64% to around 3%, with a parallel reduction in the number of fillings per child. Multilevel mixed-effects modelling confirmed that dental amalgam remains a significant determinant of U-Hg levels, and that reduced amalgam prevalence may explain part of the observed decline. These findings directly confirm the first hypothesis, showing that the gradual phase-out of dental amalgam, together with the increased availability of Hg-free alternatives, led to a measurable reduction in children's internal Hg exposure.

As the exposure from dental amalgam diminished, other sources became relatively more important. Dietary exposure, particularly fish consumption, and also the environmental exposure in historically Hg-contaminated areas, contributed to a larger share of the remaining variability in U-Hg concentrations. This finding supports the second hypothesis and highlights the dynamic nature of Hg exposure pathways. Importantly, it shows that eliminating a major source of exposure does not remove Hg exposure entirely, but rather shifts its relative determinants. This underlines the continued need for HBM and for comprehensive assessment of multiple exposure sources.

The administrative and policy analysis provides essential context for interpreting these exposure trends. Slovenia has achieved substantial progress in phasing out dental amalgam, particularly in paediatric dentistry, where compliance with regulatory restrictions is high. However, adult clinics still face challenges related to clinical needs, insurance coverage, and material costs. In addition, limited awareness of the Minamata Convention among dental professionals indicates that formal regulation alone is not sufficient to ensure consistent implementation. Targeted education and training, financial incentives and improved insurance policies could ease the transition. Centralized waste management systems with amalgam separators, alongside public health campaigns and research collaborations would support environmental compliance and further sustain Hg-free practices.

These findings provide strong support for fourth hypothesis, that gaps in enforcement, education, and financial support can moderate the effectiveness of regulatory measures and

slow the pace of transition to Hg-free dentistry. However, the third hypothesis is supported more cautiously. The results indicate that implementation measures are reflected in reduced amalgam use and related exposure decline, although the available data allow only limited inference on the direct relationship between the degree of implementation effectiveness and exposure outcomes.

A key contribution of this study lies in demonstrating the added value of combining administrative and policy metrics with environmental and health metrics with long-term HBM data. Environmental trends alone cannot be reliably attributed to specific policy interventions without understanding how regulations are implemented and experienced in practice. On the other hand, administrative indicators cannot reveal whether regulatory measures lead to meaningful reductions in internal exposure. By linking policy implementation with exposure outcomes, the integrated assessment framework used in this study allows for stronger causal interpretation and provides a more robust basis for evaluating effectiveness.

However, the success of such measures cannot be fully understood without examining how they were implemented. Understanding the administrative and policy processes behind Hg reduction strategies has proven equally vital. Without detailed knowledge on how interventions were introduced, monitored, and enforced, the exposure reductions could not be confidently attributed solely to those actions, nor could similar outcomes be ensured elsewhere. To address this, the broader scope of the research focused on key questions related to administrative/ regulatory actions and the sufficiency of implemented measures. Evaluating these components through a tailored set of tools and indicators, as well as strong stakeholder engagement, revealed essential insights into the effectiveness, challenges, and implementation gaps associated with the dental amalgam phase-out. This multidimensional evaluation allowed us to link observed reductions in Hg exposure with specific administrative and policy efforts, providing a more robust understanding of cause and effect.

Although the major decline in dental amalgam use among Slovenian children occurred prior to the formal ratification of the Minamata Convention, the findings presented here exemplify the type of evidence directly relevant for effectiveness evaluation under Article 22. Long-term HBM data, combined with detailed information on regulatory implementation and professional practices, allow changes in exposure sources to be tracked, quantified, and interpreted in relation to policy measures. In this respect, Slovenia represents a valuable case study for how national data can contribute to the broader international evaluation of the Convention's effectiveness. Our findings show that the phase-out of dental amalgam in Slovenia has been successful, with children's Hg levels steadily declining over the past 17 years. Looking ahead, maintaining HBM as part of national health surveillance will be crucial, not only in children but also in adults and groups with higher fish consumption.

While the dissertation identifies patterns consistent with a relationship between regulatory implementation and reduced exposure, this relationship is observed primarily through differences in amalgam use rather than through a direct measure of implementation effectiveness itself. Because variability in implementation intensity was limited and unevenly captured across settings, the evidence is stronger for the association between amalgam use and U-Hg outcomes than for a fully quantified implementation–outcome gradient.

In conclusion, this thesis demonstrates that sustained reductions in Hg exposure are achievable when regulatory measures are supported by effective implementation, professional engagement, and continuous monitoring. The integration of administrative and policy evaluation with environmental and health (HBM) data is essential for interpreting exposure trends, sustaining long-term success, and informing evidence-based decision-

making. This combined approach provides a robust basis for concluding that the reduction in Hg exposure observed in Slovenia is not an isolated achievement, but a replicable model for other countries aiming to protect human health and the environment under the framework of the Minamata Convention.

Appendix A

Dentist Questionnaire (English Version)

Dentist Questionnaire on the Use and Gradual Phase-Out of Dental Amalgam

Introduction

Dental amalgam is an alloy of mercury and other metals (copper, silver, tin, zinc) used as a filling material to restore tooth surfaces and represents the largest remaining intentional use of mercury in the EU. The use of dental amalgam can result in mercury emissions during placement/removal by dental professionals, as well as through excretion, cremation, or burial of individuals with dental amalgam fillings. These emissions can lead to mercury exposure for dental professionals and the general population, potentially causing harmful effects on human health. Limited exposure can also occur due to the presence of fillings in the oral cavity of the user. The use of dental amalgam varies significantly among EU member states, influenced by professional, socio-economic, and environmental factors.

Following the signing of the Minamata Convention on Mercury in 2013, the EU adopted Regulation (EU) 2017/852 on mercury, which imposes restrictions on the use of mercury in various products and bans the export of metallic mercury from the EU. As of July 2018, the EU implemented a ban on the use of amalgam fillings for children under 15 years old, pregnant women, and breastfeeding mothers. By July 2019, the regulation required EU member states to develop plans for the gradual yet complete phase-out of amalgam use. As of January 1, 2025, the EU will enforce a complete ban on the use and export of dental amalgam fillings (with rare exceptions). With this updated regulation, the EU will become the first economic area to eliminate the use of mercury entirely.

The survey on the use and gradual phase-out of dental amalgam is intended for all general dentists and specialists, in both private and public practices. Completing the survey takes 10–15 minutes. Participation is voluntary, and your responses are anonymous. Please ensure that your answers do not include personal data or company names.

Your responses will help improve our understanding of the challenges faced by healthcare professionals in phasing out the use of dental amalgam and implementing amalgam separators. This will enable us to identify how legislative measures can contribute to safer working environments and address challenges encountered in the development of relevant legislation and guidelines.

If you have any questions or need clarification, or if you would prefer to discuss this with a member of the research team, please contact Vanja Usenik at vanja.usenik@ijs.si or 041 639 471.

The survey is open until 30.09.2024.
Thank you for your effort and participation!

Q1 - Demographic Data

Q2 - Age
- Less than 30 years
- 30–40 years
- 41–50 years
- 51–60 years
- More than 60 years

Q3 - Gender
- Male
- Female
- Prefer not to say

Q4 - Work experience in dentistry
- Less than 5 years
- 5–10 years
- 11–20 years
- More than 20 years

Q5 - Sector
- Private practice
- Public dentistry

Q6 - Area of work
- Pediatric and adolescent dentistry
- Adult dentistry
- Other

Q7 - Region
- Pomurska
- Podravska
- Koroška
- Savinjska
- Zasavska
- Posavska
- Jugovzhodna Slovenija
- Osrednjeslovenska
- Gorenjska
- Primorsko-notranjska
- Goriška
- Obalno-kraška

Q8 - Current Practices

How often do you use amalgam fillings for patients in the following age groups?
- Daily
- Weekly
- Monthly
- Rarely
- Never

Children (6–9 years)
Children (10–12 years)
Teenagers (13–17 years)
Adults (18+ years)

Q9 - Have you noticed a change in the frequency of amalgam use in your practice over the last five years?
- Decreased
- Increased
- Stayed the same
- Don't know

Q10 - What factors influence your choice of amalgam over alternative materials?
(Multiple answers allowed.)
- Durability
- Cost
- Patient preference
- Insurance coverage
- Ease of use
- Other:

Q12 - How do you inform patients about available materials for dental fillings?
(Multiple answers allowed.)
- Brochures
- Oral explanation
- Visual aids (models, pictures)
- Other:

Knowledge and Attitudes

Q14 - How well do you know the Minamata Convention on Mercury and its provisions regarding the use of dental amalgam?
- Very well
- Partially
- Not at all

Q15 - Do you think dental amalgam poses significant health risks to patients?
- Yes
- No
- Partially

Q16 - What is your opinion on the health risks to dental professionals during the removal of dental amalgam?
- Significant
- Moderate
- Minimal
- No impact

Q17 - What is your opinion on the impact of dental amalgam removal on patients?
- Significant
- Moderate
- Minimal
- No impact

Q18 - What is your opinion on the environmental impact of dental amalgam removal?
- Significant
- Moderate
- Minimal
- No impact

Q19 - How important do you think it is to phase out the use of dental amalgam?
- Very important
- Moderately important
- Not important
- No opinion

Q20 - Do you prefer to use alternative materials instead of dental amalgam? Why?
Yes - Please explain:
No - Please explain:

Impact of the Phase-Out

Q21 - How many amalgam fillings do you remove on average per month?
- Less than 10
- 10–20
- 21–30
- More than 30

Q22 - Is your dental practice prepared for the complete ban on the use of dental amalgam?
- Yes
- No

Q23 - What challenges do you anticipate during the phase-out of dental amalgam?
(Multiple answers allowed.)
- Cost of alternative materials
- Training and awareness of alternative materials among dental professionals
- Patient opinions and demands
- Insurance reimbursement difficulties
- Changes in equipment and existing stock

Q24 - What incentives would help you in the process of phasing out dental amalgam?
(Multiple answers allowed.)
- Further education and training for dental professionals
- Financial support or subsidies
- Improved insurance coverage for alternative materials
- Access to better alternative materials
- Improved guidelines and protocols
- Other:

Use of Amalgam Separators

Q26 - Does your dental practice currently use amalgam separators?
- Yes
- No
- We use other protective measures:

Q27 - If yes, how long has your practice been using amalgam separators?
- Less than 1 year
- 1–3 years
- More than 3 years

Q28 - What challenges have you encountered, if any, in using amalgam separators?
(Multiple answers allowed.)
- High maintenance costs
- Frequent breakdowns
- Space limitations
- Staff training issues
- Other:

Q29 - If you do not use amalgam separators, what are the reasons for non-use?
(Multiple answers allowed.)
- Cost of installation and maintenance
- Lack of knowledge regarding use
- Perception of unnecessary use

- Technical issues
- Other:

Q30 - In your opinion, how effective is the use of amalgam separators in protecting patient health from mercury exposure and ensuring a safer working environment for dental professionals?
- Very effective
- Effective
- Partially effective
- Ineffective
- Undecided

Q31 - What supporting activities or resources would facilitate the implementation and maintenance of amalgam separators in your dental practice?
(Multiple answers allowed.)
- Financial assistance or subsidies
- Technical support, equipment maintenance assistance
- Training programs for dental staff
- Clear guidelines and protocols
- Other:

Additional Open-Ended Questions / Comments

Q33 - What obstacles (factors that hinder the implementation of measures) do you identify in the process of phasing out dental amalgam?

_____

Q34 - What drivers (factors that help implement measures) do you identify in the process of phasing out dental amalgam?

_____

Q35 - Please share your experiences, comments, or concerns regarding the gradual phase-out of dental amalgam and the implementation of amalgam separators:

_____

Q36 - In your opinion, how could awareness among dentists and patients about the impacts of dental amalgam on humans/environment and the existence of alternative materials be improved?

_____

Appendix B

Dentist Questionnaire (Original Slovene Version)

Vprašalnik za zobozdravnike o uporabi in postopnem opuščanju zobnega amalgama

Vprašalnik

Kratko ime ankete:	Vprašalnik za zobozdravnike
Število vprašanj:	39
Število spremenljivk:	74
Status:	Aktivna od: 06.09.2024 Aktivna do: 06.12.2024
Avtor:	anonimen, 05.09.2024
Spreminjal:	anonimen, 18.12.2024

Uvod

Zobni amalgam je zlitina živega srebra in drugih kovin (baker, srebro, kositer, cink), ki se uporablja kot polnilo za obnovo zobnih površin in je največja preostala namerna uporaba živega srebra v EU. Uporaba zobnega amalgama lahko povzroči emisije živega srebra med vstavljanjem/odstranjevanjem s strani zobozdravstvenih delavcev ter z izločki, upepelitvijo ali pokopom ljudi z zobno amalgamsko zalivko. Te emisije lahko vodijo do izpostavljenosti živemu srebru pri zobozdravstvenih delavcih in splošni populaciji ter potencialno povzročajo škodljive učinke na zdravje ljudi. Do omejene izpostavljenosti lahko pride tudi 'zaradi prisotnosti zalivke v ustni votlini uporabnika'. Uporaba zobnega amalgama se med državami članicami zelo razlikuje, povezano pa je tudi s strokovnimi, socialno-ekonomskimi in okoljskimi vidiki.

Po podpisu Konvencije Minamata o živem srebru leta 2013, je EU sprejela Uredbo (EU) 2017/852 o živem srebru, ki določa omejitve uporabe živega srebra v številnih proizvodih in prepoveduje izvoz kovinskega živega srebra iz EU. Že julija 2018 je v EU začela veljati prepoved amalgamskih zalivk za otroke do 15. leta starosti, nosečnice in doječe matere, do julija 2019 pa je evropska uredba vladam članic EU odredila izdelavo načrta postopne, a popolne odprave uporabe amalgamskih zalivk. S 1.1.2025 pa v Evropski uniji sledi popolna prepoved uporabe in izvoza amalgamskih zobnih zalivk (v izjemnih primerih tudi po tem datumu). S prenovljeno uredbo bo EU postalo prvo gospodarsko območje, ki živega srebra ne bo več uporabljalo.

Anketa o uporabi in postopnem opuščanju zobnega amalgama je namenjena vsem splošnim zobozdravnikom in specialistom, tako v zasebnih kot javnih ambulantah. Izpolnjevanje ankete traja 10–15 min. Odgovarjanje na anketo je prostovoljno. Vaši odgovori so anonimni. Prosimo, da v svoje odgovore ne vključite osebnih podatkov ali imen podjetij.

Vaši odgovori nam bodo pomagal izboljšati razumevanje o tem, s kakšnimi izzivi se soočajo zdravstveni delavci pri opuščanju uporabe zobnega amalgama in implementaciji amalgamskih separatorjev. Na ta način bomo ugotavljali kako lahko ukrepi na področju zakonodaje doprinesejo k zagotavljanju varnejšega delovnega okolja in k reševanju izzivov, ki se pojavijo pri razvoju zakonodaje in povezanih smernic na zadevnem področju.

Če imate kakršnakoli vprašanja ali če je karkoli nejasno oz. bi se raje pogovorili s članom raziskovalne skupine, se obrnite na Vanja Usenik, vanja.usenik@ijs.si, 041 639 471.

Anketa bo odprta do 30.9.2024

Hvala za vaš trud in sodelovanje!

Q1 - Demografski podatki

_____ **Q2 - Starost**

○ manj kot 30 let
○ 30-40 let
○ 41-50 let
○ 51-60 let
○ več kot 60 let

Q3 - Spol

○ moški
○ ženska
○ ne želim se opredeliti

Q4 - Delovne izkušnje na področju zobozdravstva

○ manj kot 5 let

◯ 5-10 let
◯ 11-20 let
◯ več kot 20 let

Q5 - Sektor
◯ zasebna ambulanta
◯ javno zobozdravstvo

Q6 - Področje dela
◯ zobozdravstveno varstvo otrok in mladine
◯ zobozdravstveno varstvo odraslih
◯ drugo

Q7 - Regija
◯ Pomurska
◯ Podravska
◯ Koroška
◯ Savinjska
◯ Zasavska
◯ Posavska
◯ Jugovzhodna Slovenija
◯ Osrednjeslovenska
◯ Gorenjska
◯ Primorsko-notranjska
◯ Goriška
◯ Obalno-kraška

Q33_2 - Trenutne prakse

_____ **Q8 - Kako pogosto uporabljate amalgamske zalivke pri pacientih v naslednjih starostnih skupinah? (Označite ustrezen odgovor za vsako starostno skupino)**

	dnevno	tedensko	mesečno	redko	nikoli
Otroci (6-9 let)	◯	◯	◯	◯	◯
Otroci (10–12 let)	◯	◯	◯	◯	◯
Najstniki (13–17 let)	◯	◯	◯	◯	◯
Odrasli (18 + let)	◯	◯	◯	◯	◯

Q9 - Ali ste v zadnjih petih letih opazili spremembo v pogostosti uporabe amalgamskih zalivk v vaši praksi?
◯ se je zmanjšala
◯ se je povečala
◯ je ostala enaka
◯ ne vem

Q10 - Kateri dejavniki vplivajo na vašo izbiro zobnega amalgama pred alternativnimi materiali?
Možnih je več odgovorov
☐ trajnost
☐ strošek

- ☐ pacientova preferenca
- ☐ zavarovalno kritje
- ☐ enostavnost uporabe
- ☐ Drugo:

Q12 - Kako obveščate paciente o razpoložljivih materialih za zobne zalivke?
Možnih je več odgovorov

- ☐ brošure
- ☐ ustna razlaga
- ☐ vizualna sredstva (modeli, slike)
- ☐ Drugo:

Q13 - Znanje in stališča

_____ **Q14 - Kako dobro poznate Minamatsko konvencijo o živem srebru in njena določila glede uporabe zobnega amalgama ?**

- ○ zelo dobro
- ○ delno
- ○ ne poznam

Q15 - Ali menite, da zobni amalgam predstavlja pomembno zdravstveno tveganje za paciente?

- ○ da
- ○ ne
- ○ delno

Q16 - Kakšen je po vašem mnenju vpliv, ki ga ima odstranjevanje zobnega amalgama na zdravstveno tveganje za zdravstvene delavce?

- ○ pomemben
- ○ zmeren
- ○ minimalen
- ○ ni vpliva

Q17 - Kakšen je po vašem mnenju vpliv, ki ga ima odstranjevanje zobnega amalgama na pacienta?

- ○ pomemben
- ○ zmeren
- ○ minimalen
- ○ ni vpliva

Q18 - Kakšen je po vašem mnenju vpliv, ki ga ima odstranjevanje zobnega amalgama na okolje?

- ○ pomemben
- ○ zmeren

○ minimalen
○ ni vpliva

Q19 - Kako je po vašem mnenju pomembno postopno opuščanje uporabe zobnega amalgama?
○ zelo pomembno
○ srednje pomembno
○ nepomembno
○ brez mnenja

Q20 - Ali raje uporabljate alternativne materiale namesto zobnega amalgama? Zakaj?
○ DA - prosimo, podajte obrazložitev

○ NE - prosimo, podajte obrazložitev

Q35_2 - Vpliv postopnega opuščanja uporabe amalgamov
_____ **Q21 - Koliko amalgamskih zalivk v povprečju odstranite pri pacientih v enem mesecu?**
○ manj kot 10
○ 10-20
○ 21-30
○ več kot 30

Q22 - Ali je vaša zobna ambulanta že pripravljena na dokončno prepoved uporabe zobnega amalgama?
○ da
○ ne

Q23 - Katere ovire pričakujete pri opuščanju zobnega amalgama?
Možnih je več odgovorov
☐ strošek alternativnih materialov
☐ usposabljanje zobozdravstvenih delavcev in seznanjenost z alternativnimi materiali
☐ mnenje in zahteve pacientov
☐ težave pri povračilu zavarovalnine
☐ spremembe opreme in zalog obstoječih materialov

Q24 - Katere vzpodbude bi vam olajšale proces opuščanja zobnega amalgama?
Možnih je več odgovorov
☐ nadaljnje izobraževanje in usposabljanje zobozdravstvenih delavcev
☐ finančne spodbude ali subvencije
☐ izboljšano zavarovalno kritje za alternativne materiale
☐ dostop do boljših alternativnih materialov
☐ izboljšane smernice in protokoli
☐ Drugo:

Q25 - Uporaba separatorjev pri odstranjevanju zobnih amalgamov
_____ **Q26 - Ali vaša zobna ambulanta trenutno uporablja amalgamske separatorje?**
○ da
○ ne
○ Uporabljamo druga zaščitna sredstva:

Q27 - Če da, koliko časa vaša ambulanta že uporablja amalgamske separatorje?
○ manj kot 1 leto
○ 1-3 leta
○ več kot 3 leta

Q28 - S katerimi izzivi ste se srečali, če sploh, pri uporabi separatorjev amalgame?
Možnih je več odgovorov
☐ visoki stroški vzdrževanja
☐ pogoste okvare
☐ prostorske omejitve
☐ usposobljenost osebja
☐ Drugo:

Q29 - Če ne uporabljate amalgamskih separatorjev, kateri so razlogi za neuporabo?
Možnih je več odgovorov
☐ strošek namestitve in vzdrževanja
☐ pomanjkljivo znanje glede uporabe
☐ percepcija o nepotrebnosti uporabe amalgamskih separatorjev
☐ tehnične težave
☐ Drugo:

Q30 - Kako učinkovita je po vašem mnenju uporaba amalgamskih separatorjev pri varovanju pacientovega zdravja pred negativnimi učinki živega srebra in zagotavljanju varnejšega delovnega okolja za zdravstvene delavce?
○ zelo učinkovita
○ učinkovita
○ delno učinkovita
○ neučinkovita
○ neodločeno

Q27_2 - Kako učinkovita je po vašem mnenju uporaba amalgamskih separatorjev na področju zmanjševanja okoljskih vplivov živega srebra oziroma zmanjševanju onesnaževanja z živim srebrom?

○ zelo učinkovita
○ učinkovita
○ delno učinkovita
○ neučinkovita
○ neodločeno

Q31 - Katere podporne dejavnosti ali viri bi vam olajšali proces implementacije in vzdrževanja amalgamskih separatorjev v vaši zobni ambulanti?
Možnih je več odgovorov
☐ finančna pomoč ali subvencije
☐ tehnična podpora, pomoč pri vzdrževanju opreme
☐ programi usposabljanja za zobozdravstveno osebje
☐ jasne smernice in protokoli
☐ Drugo:

Q32 - Odprta vprašanja / Dodatni komentarji
_____ **Q33 - Katere morebitne ovire (dejavniki, ki zavirajo uvajanje ukrepov) prepoznavate pri procesu opuščanja zobnega amalgama?**
_____

Q34 - Katere morebitne gonilnike (dejavniki, ki pomagajo pri izvedbi ukrepov) prepoznavate pri procesu opuščanja zobnega amalgama?
_____

Q35 - Prosimo delite vaše izkušnje, komentarje ali skrbi glede postopnega opuščanja uporabe zobnega amalgama in implementacije amalgamskih separatorjev:
_____

Q36 - Na kakšen način bi se po vašem mnenju lahko izboljšala ozaveščenost zobozdravnikov in pacientov o vplivih zobnega amalgama na ljudi/okolje, ter o obstoju alternativnih materialov?
_____

Appendix C

Survey Response Complete Dataset

Due to the volume and structure of the survey responses, the raw survey data are not included directly in this dissertation. The complete dataset of anonymized survey responses (original Slovene version) is available via a secure link provided below and hosted on JSI Nextcloud. The dataset includes all responses collected through the questionnaire presented in Appendices A and B and was used for the quantitative and qualitative analyses described in this thesis.

Link: https://portal.ijs.si/nextcloud/s/jBEQmFDYJyPSSgY .

Appendix D

Evidence Package

D.1 Description of the Contributing Human Biomonitoring Studies

D.1.1 PHIME

Public health impact of long-term, low-level mixed element exposure in susceptible population data (PHIME) study is a cross-sectional study conducted within the 6th EU framework program, aimed at assessing regional differences in mercury, lead and cadmium in school-age children in different European and non-European countries. Children aged 6–11 years were recruited from elementary schools in three study areas (one urban, one rural, and one potentially contaminated) between 2007 and 2009. In Slovenia, the selected study areas included Ljubljana (urban), Žužemberk (rural) and the former mercury mining town of Idrija (historically Hg-contaminated). Contact was established first with the headmaster and then with parents and their children. The study was approved by the National Ethics Committee of the Republic of Slovenia (Approval No. 98/05/06). Written informed consent was obtained from a parent or legal guardian of each child, and oral consent was obtained from the child before sampling. Only healthy children with no chronic diseases were recruited. Both sexes and all age groups were equally represented, and the participating children came from diverse socioeconomic backgrounds (Kobal et al., 2017; Hruba et al, 2012; Hruba et al., 2023; Snoj Tratnik et al., 2019b). The final sample included 64 children from Idrija, 69 from Žužemberk, and 47 from Ljubljana, all recruited and sampled in 2007. A detailed description of the biological sampling and chemical analysis procedure can be found in the work previously published by Kobal et al. (2017).

For each child, the parent (guardian) completed a questionnaire on the child's dietary habits, drinking water consumption from local sources, basic residential characteristics, residential history, basic anthropometric measures, socio-economic status, age, gender, number of amalgam fillings the child has, smoking conditions inside the home, as well as parents' occupational history.

D.1.2 DEMOCOPHES

The DEMOCOPHES project (Demonstration of a Study to Coordinate and Perform Human Biomonitoring on a European Scale) was a part of a coordinated European effort

to pilot a harmonised human biomonitoring protocol across multiple countries. It involved 17 European countries, applying a common protocol for recruitment, sampling, laboratory analysis, questionnaires, and data management, deployed within the twin COPHES/DEMOCOPHES initiative (Schindler et al., 2014). The goal was to demonstrate the feasibility and usefulness of collecting comparable HBM data across Europe to support evidence-based policy-making and future large-scale surveillance. The efforts were motivated by the recognition that existing HBM activities were fragmented and not sufficiently comparable between countries.

To ensure high data quality and comparability, a Quality Assurance Unit (QAU) was established, which provided standard operating procedures (SOPs), external quality assessments (EQUAS) materials, and organised inter-laboratory comparison exercises. Participating laboratories were qualified through this process to ensure reliable measurement of analytes across all countries. The harmonised study also included common fieldwork procedures and questionnaires. These questionnaires captured key determinants of chemical exposure, including socio-demographic information, residential environment, lifestyle behaviours (e.g., tobacco smoke exposure), and detailed dietary habits such as fish and seafood consumption.

Within the project, 1844 children aged 5–11 years and their mothers were recruited in the 17 implementing countries. In Slovenia, children and mothers were recruited between September 2011 and March 2012 through three primary schools in Ljubljana (urban) and two primary schools in the towns of Šmarje pri Jelšah and Bizeljsko (rural). In total, 155 children were recruited, out of which 78 were from the urban area and 77 from the rural areas. The study received ethics approval from the National Medical Ethics Committee of the Republic of Slovenia (Approval No. 64/06/11), and informed consent/assent procedures followed the DEMOCOPHES framework.

D.1.3 CROME

Cross-Mediterranean Environment and Health Network (CROME) (LIFE12 ENV/GR/001040) was an EU-funded LIFE programme project aimed at assessing the health impacts of chemical exposures originating from environmental contamination and consumer products, and integrating environmental monitoring with human biomonitoring to better relate environmental contamination to internal dose and support evidence-based policy actions. CROME operated across multiple Mediterranean countries, including Slovenia, Italy, Greece, and Spain, and focused on a range of contaminants, including metals (such as mercury and lead), persistent organic pollutants, and pesticides.

In Slovenia, the CROME study functioned as a follow-up to the PHIME birth cohort, which had originally enrolled 590 mother-child pairs at the Maternity Hospital of Ljubljana between 2007 and 2009. Eligible mothers were permanent residents of Ljubljana and the surrounding area, at least 18 years old, and free of major health issues or pregnancy complications. In 2016, when the children were 7–8 years old, these families were re-contacted to be recruited in CROME. Biological samples, including spot urine and peripheral blood/plasma, were collected from both mothers and children during scheduled clinical visits at the Paediatric Clinic of the University Medical Centre Ljubljana. A total of 175 of the original PHIME mother-child pairs were successfully resampled within CROME.

Ethical approval for Slovenian CROME was obtained from the National Ethics Committee of the Republic of Slovenia (Approval No. 65/09/14), with written consent from parents/legal guardians and oral assent from children prior to sampling. Children's

parents completed a questionnaire on the child's dietary habits, drinking water consumption from local sources, basic residential characteristics, residential history, basic anthropometric measures, socio-economic status, age, gender, number of amalgam fillings the child has, smoking conditions inside the home, as well as parents' occupational history.

D.1.4 SLO-HBM-II

The study population comprised children (age 6–9) and adolescents (age 12–15), recruited between 2018 and 2024 from multiple regions across Slovenia as part of the Second National Human Biomonitoring Programme (SLO-HBM-II). The programme was designed to capture regional variability in environmental exposure by including areas with different industrial, agricultural, geochemical, and urban characteristics.

Recruitment was conducted through primary schools, following an agreement from school principals and the distribution of study information to parents. The inclusion criteria were: continuous residence in one of the selected study areas for at least three years, age between 6-9 or 12-15 years, and absence of medication use for chronic disease. Written informed consent was obtained from parents or legal guardians, and oral consent was obtained from each child prior to sampling. The study protocol was approved by the National Medical Ethics Committee of the Republic of Slovenia (Acceptance No. 0120-431/2018-2711-10).

The programme was implemented in several consecutive sampling phases. The first phase (pilot) was carried out in 2018 within the framework of the national project "Exposure of children and adolescents to selected chemicals through their habitat environment (2016–2019)" and focused on the Prekmurje region in northeastern Slovenia. In this phase, 246 children and adolescents were recruited from three sub-regions with distinct land-use characteristics: Goričko (hilly area with dispersed farms, vineyards, and orchards), Ravensko (flat area with intensive agriculture), and Lendavske Gorice (hilly vineyard region).

Between 2019 and 2022, the sampling was extended to additional areas representing major industrial, mining, and traffic-affected environments, including Mežica Valley, Celje, Jesenice, Vrhnika, and Prestranek. The final sampling campaign, conducted in 2023–2024, further expanded geographic coverage to Zasavje, Idrija, Posočje, the Slovenian coastal area (Koper and surroundings), and Bela Krajina, bringing the total number of recruited individuals to 1849.

Across all phases, biological samples were collected at participating local primary schools, and parents completed standardized questionnaires providing information on lifestyle, dietary habits (including fish consumption), living environment, and socioeconomic status.

D.2 Urine collection, storage and analysis

Participants of the PHIME, DEMOCOPHES, and SLO-HBM-II studies provided a first-morning spot urine sample at their local primary school visit. Samples were collected into nitric-acid solution pre-cleaned vessels (or sterile vessels for PHIME) provided prior to the sampling. Participants of the CROME study provided a random spot sample (not first-morning) at their appointed visit to the Paediatric Clinic. All samples were transported to the clinical laboratory within 2 hours at 2°C, aliquoted, and stored at -20°C (PHIME, DEMOCOPHES) or -80°C (CROME, SLO-HBM-II) until analysis. In all studies, urinary

creatinine concentrations were determined at the University Medical Centre Ljubljana using the compensated Jaffé reaction (Dimension biochemical analyser, Dade Behring) to account for urine dilution.

All measurements of total Hg in urine were performed at the Jožef Stefan Institute, Department of Environmental Sciences, however, the analytical methodology evolved over the 17 years (Tables 10, 11). In the initial cohorts (PHIME, DEMOCOPHES), total Hg was analysed using cold vapor atomic absorption spectrometry (CVAAS) after acid digestion on a hot plate. The limits of detection (LODs) were 0.10 ng mL^{-1} and 0.05 ng mL^{-1}, respectively. In later cohorts (CROME, SLO-HBM-II), measurements were performed using triple quadrupole inductively coupled plasma mass spectrometry (QQQ-ICP-MS) after microwave acid digestion. The respective LODs were 0.06 ng mL^{-1} and 0.04 ng mL^{-1} for CROME and SLO-HBM-II, respectively.

Table 10: Overview of Slovenian child cohorts included in the present analysis.

	PHIME[a]	**DEMOCOPHES**[b]	**CROME**[c]	**SLO-HBM-II**[d]
Study characteristics				
Sampling year(s)	2007	2011–2012	2016	2018–2024
Study area(s)	Urban (n = 1), rural (n = 1), Hg-contaminated (n = 1)	Urban (n = 1), rural (n = 1)	Urban (n = 1)	Urban (n = 7), rural (n = 1), (potentially) Hg-contaminated (n = 3)
N of children[e]	180	155	178	899[e]
References	[1–4]	[5]	[6]	[7]
Analytical method				
Sample	Spot morning urine	Spot morning urine	Spot random urine	Spot morning urine
Sample preparation	Acid digestion (hot plate)	Acid digestion (hot plate)	Acid digestion (microwave)	Acid digestion (microwave)
THg determination	CVAAS	CVAAS	ICP-MS	ICP-MS
LOD (ng mL^{-1})	0.10	0.05	0.06	0.04
% samples <LOD	3.0	0.0	9.7	4.5
Reference materials	ClinCheck L1	ClinCheck L1	ClinCheck L1 Seronorm Urine L1, L2 SRM 3668 L1, L2	ClinCheck L1 Seronorm Urine L1, L2
References	[8–11]	[8–11]	[12]	[12]

[1] Kobal et al., 2017; [2] Hruba et al, 2012; [3] Hruba et al., 2023; [4] Snoj Tratnik et al., 2019b; [5] Den Hond et al., 2015 [6] Bravo et al., 2020; [7] Stajnko et al., 2020; [8] Akagi, 1997; [9] Horvat et al., 1991; [10] Miklavčič et al., 2011; [11] Miklavčič et al., 2013; [12] Kek et al, 2025.

[a]**Public Health Impact of Long-term, Low-level Mixed Element Exposure in Susceptible Population Strata**

[b]**Demonstration of a European Human Biomonitoring System**

[c]**Cross-Mediterranean Environment and Health Network**

[d]**Second National Human Biomonitoring Programme, Slovenia**

[e]**Refers to the total number of recruited children. For SLO-HBM-II, a subsample consisting of children aged 6-9.**

Throughout all four study cohorts, analytical reliability and long-term data comparability were ensured by rigorous, consistent Quality Assurance (QA) protocols, that required inclusion of at least one reference material in every analytical batch, monitoring reference material recoveries within the certified uncertainty range, verification that within-

batch precision met predefined targets, and repetition of batches that did not fulfil the acceptance criteria. The reference materials used over the span of 17 years include ClinCheck Urine Control for Trace Elements L1 (RECIPE), Seronorm Urine L1 and L2 (SERO AS), and SRM 3668 L1 and L2, NIST. Importantly, ClinChek Urine L1 was consistently measured across all cohorts, providing essential indirect cross-calibration between the older CVAAS method and the newer ICP-MS method. These procedures, along with continuous participation in external interlaboratory comparison schemes, such as the German External Quality Assessment Scheme (G-EQUAS), confirmed that all results consistently fell within assigned acceptance ranges.

Table 11: Summary of data completeness and availability for selected variables, by study.

	PHIME	**DEMOCOPHES**	**CROME**	**HBM-II**
Total number of recruited children	180	155	178	899
Valid U-Hg (ng mL^{-1}), N(%)	164 (91.1)	155 (100)	176 (98.9)	893 (99.3)
Valid U-Hg (µg g^{-1} creat), N(%)	163 (90.6)	155 (100)	175 (98.3)	893 (99.3)
Valid amalgam presence data, N(%)	152 (84.4)	155 (100)	178 (100)	899 (100)
Valid fish consumption data, N(%)	173 (96.11)	155 (100)	178 (100)	882 (98.1)
Valid BMI data, N(%)	168 (93.3)	155 (100)	177 (99.4)	898 (99.9)
Valid age data, N(%)	180 (100)	155 (100)	177 (99.4)	899 (100)
Complete cases, N(%)	125 (69.4)	155 (100)	173 (97.2)	876 (97.4)

D.3 Statistical Analysis

D.3.1 Descriptive Statistics

Geometric means, minimum, maximum, and percentiles for urinary Hg were calculated for each study cohort using all participants with valid U-Hg measurements. Values below the limit of detection (LOD) were replaced by LOD/2. Differences between cohorts were evaluated using the Kruskal–Wallis test, with Dunn's post-hoc comparisons (Bonferroni-adjusted). Associations between the number of dental amalgam fillings and U-Hg levels were investigated using Spearman's correlation (ρ).

D.3.2 Assessment of Temporal Trends and Determinants

Temporal trends in U-Hg levels were investigated on the pooled dataset using linear mixed-effects models (LMMs). This approach was selected to account for the hierarchical and unbalanced structure of the data, especially the nesting of individual children within towns and the repeated sampling of certain towns (Ljubljana, Idrija) across multiple years. A random intercept for town was included to capture residual spatial heterogeneity and unmeasured local context shared by children residing in the same place. The sampling year was included as a fixed effect to estimate the overall temporal trend across the entire dataset.

The outcome variable was natural log-transformed (ln(U-Hg)). Fixed-effect covariates included age, sex, body mass index (BMI), urinary creatinine, and residence area type (urban as reference; rural; potentially contaminated, including the former Hg-mining town of Idrija and two towns with potential industrial Hg contamination). The primary predictors were sampling year (continuous), dental amalgams (binary or numeric, depending on the model), and fish consumption (three frequency levels: low, moderate, high). The final model specification was chosen based on likelihood ratio tests and favoured

parsimony. For modelling purposes, BMI was standardised to BMI z-scores using the WHO growth reference for school-aged children and adolescents (de Onis et al., 2007). All continuous predictors were grand-mean centred. To characterise the temporal trend in U-Hg and identify its drivers, a two-stage modelling strategy was applied:

Stage 1: **Reduction of the year effect (Primary Analysis)**
A stepwise sequence of models was fitted to assess how much of the temporal decline in U-Hg was explained by reduced amalgam exposure. The following models were fitted:

- Model 1 (base model): sampling year as fixed effect and a random intercept for town (unadjusted time trend).
- Model 2: Model 1 additionally adjusted for demographic and contextual covariates (age, sex, BMI, urinary creatinine, residence area type, fish consumption).
- Model 3: Model 2 further adjusted for the number of amalgam fillings to test their mediating role.

The contribution of dental amalgams to the time trend was quantified by calculating the percent reduction of the year coefficient from Model 1 to Model 3, using the formula: % reduction = $(\beta_{\text{Model1}} - \beta_{\text{Model3}})/\beta_{\text{Model1}} \times 100$

Stage 2: **Effect Modification (Secondary Analysis)**
Interaction terms were added to Model 3 to assess whether the temporal trend varied across subgroups. For this purpose, additional models were fitted:

- Model 4: amalgam included as a binary variable; the year × fish consumption interaction included to test whether the temporal trend differed by fish intake.
- Model 5: Model 4 with the addition of year × binary amalgam interaction to determine whether the difference between amalgam carriers and non-carriers changed over time.
- Model 6: Model 5 but with amalgam number instead of binary amalgam, to test whether the per-filling effect changed over time.

D.3.3 Missing Data and Sensitivity Analysis

The overall data missingness was low: 94.1 % of children (N = 1329) had complete data on every model predictor and were retained in the complete-case analysis (Table 3). As a sensitivity check, the same mixed-effects models were fitted to 20 multiply imputed data sets and to complete cases only. The parallel analyses produced similar inferences, therefore, the complete-case estimates are presented.

To formally compare effects between the earliest (PHIME) and most recent (HBM-II) cohort, we fitted multiple regression models to the pooled data, including study × amalgam and study × fish consumption interaction terms. A statistically significant interaction term indicates that the corresponding effect differs between cohorts.

All analyses and plotting were performed using R Statistical Software (version 4.4.1 (2024-06-14 ucrt)). The statistical significance level was set at $p < 0.05$.

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Publications Related to the Thesis

Journal Articles

Usenik, V., Kontić, D., Kocman, D., & Horvat, M. (2025). Practices and attitudes of dentists regarding the use and phase-out of dental amalgam fillings: Compliance with EU regulations and the Minamata Convention. *Zdravniški vestnik / Slovenian Medical Journal, 94*(5–6), 119–131. https://doi.org/10.6016/ZdravVestn.3611

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In both research papers, the candidate was the first author and played a leading role in the development of the manuscripts.

For the first paper (Usenik et al., 2025), the candidate was responsible for the entire manuscript development process, including conceptualizing the research, preparing and distributing the questionnaire to dentists and medical personnel, conducting the data analysis, interpreting the results, and drafting the manuscript.

For the second paper (Usenik et al., 2026), the candidate similarly played a central role in manuscript preparation and data interpretation. The laboratory analyses, including mercury (Hg) measurements, were performed by co-authors within established human biomonitoring (HBM) programs. The candidate's primary contributions included conceptualizing the research, interpreting the findings, and writing the manuscript, with particular emphasis on the policy implications related to the Minamata Convention on Mercury and the phase-out of dental amalgam.

Other Publications

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Biography

The author of this thesis, Vanja Usenik, began her higher education at the University of Ljubljana, where she studied International Relations at the Faculty of Social Sciences, completing her Bachelor's degree in 2010. She then pursued a Master's degree in Political Science, World Studies, which she completed in 2012. Despite her formal education in the social sciences, her interest in natural sciences had been present from an early age, already during primary and secondary school. During this period, she demonstrated outstanding talent in chemistry and was a multiple recipient of the prestigious Pregl Awards, including both gold and silver Pregl Plaques, awarded at the national chemistry competitions in Slovenia. In 2015, she enrolled in the doctoral study programme in Ecotechnologies at the Jožef Stefan International Postgraduate School.

Vanja's professional career began at the Jožef Stefan Institute in 2009, when she joined the Condensed Matter Physics Department as an Administrative Assistant (student work). In 2011, she transitioned into a full-time role as Project Manager, a position she held until June 2014.

In 2014, Vanja moved to the Department of Environmental Sciences, where she continued her work as a Project Manager, overseeing a range of European projects, including Horizon 2020, Horizon Europe, Life+, and EMPIR Euramet, alongside several non-EU projects, such as ARIS and market-funded initiatives. Her involvement in the H2020 MSCA ITN project GMOS-Train (Global Mercury Observation and Training Network in Support to the Minamata Convention) allowed her to explore the complexities of mercury as a global environmental issue, which significantly influenced the direction of her doctoral research. This research integrates her foundation in political science with critical environmental challenges, fostering an innovative, interdisciplinary approach to addressing global environmental issues through a combination of policy analysis and scientific exploration.