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Review article

Water fluoridation in Australia: A systematic review

Lalantha Senevirathna [a,b], Himali Erandathie Ratnayake [c], Nadeeka Jayasinghe [a], Jinlong Gao [d,e], Xiaoyan Zhou [d,e], Shanika Nanayakkara [d,e,*]

[a] CSU Engineering, School of Computing, Mathematics and Engineering, Charles Sturt University, Bathurst, Australia
[b] Gulbali Institute for Agriculture, Water and Environment, Charles Sturt University, Albury, Australia
[c] College of Medicine and Dentistry, James Cook University, Townsville, Queensland, Australia
[d] School of Dentistry, Faculty of Medicine and Health, The University of Sydney, Sydney, Australia
[e] Institute of Dental Research, Westmead Centre for Oral health, Westmead Hospital, Westmead, Australia

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ABSTRACT

Water fluoridation is considered a safe and effective public health strategy to improve oral health. This review aimed to systematically summarize the available evidence of water fluoridation in Australia, focusing on the history, health impacts, cost effectiveness, challenges, and limitations.

A systematic search was conducted on the Ovid Medline, Web of Science, Scopus, ProQuest Central, Cinahl, and Informit databases to identify literature on water fluoridation in Australia. A grey literature search and backward snowballing were used to capture additional literature. Primary studies, reviews, letters, and opinion papers were included in the quantitative analysis and summarized based on the year of publication and geographical location. The data were extracted from primary studies and summarized under three subheadings: history, community health impacts and the limitations and challenges.

Water fluoridation in Australia was first implemented in 1953 in Tasmania. Most states and territories in Australia embraced water fluoridation by 1977 and currently, 89% of the Australian population has access to fluoridated drinking water. Studies report that water fluoridation has reduced dental caries by 26–44% in children, teenagers, and adults, benefiting everyone regardless of age, income, or access to dental care. It has been recognized as a cost-effective intervention to prevent dental caries, especially in rural and low-income areas. Water fluoridation as a public health measure has faced challenges, including political and public opposition, implementation and maintenance costs, access and equity, communication and education, and ethical concerns. Variations in research activities on water fluoridation across Australian states and territories over the last seven decades can be due to several factors, including the time of implementation, funding, and support. Ongoing monitoring and research to review and update optimal fluoride levels in drinking water in Australia is warranted to ensure sustainable benefits on oral health while preventing any adverse impacts.

1. Introduction

Fluoride is a ubiquitous element naturally occurring in water, soil, animals, and plants. Natural fluoride concentration in groundwater varies significantly in different geographical locations (Selinus et al., 2013). Fluoride enters the human body mainly through drinking water and food. Fluoride absorbed through the gut is mainly deposited in bones and teeth while unabsorbed fluoride is excreted in urine (Harrison, 2005).

Since the accidental discovery of the beneficial effects of fluoride in preventing dental caries in 1901 in Colorado, artificial fluoridation of drinking water has been considered one of the key public health strategies to improve oral health globally (Iheozor-Ejiofor et al., 2015a; Mullen, 2005). Dr. Frederick McKay was the first dentist to observe a lower prevalence of dental caries in children living in areas with naturally elevated levels of fluoride in drinking water, followed by similar reports from other places around the world (Mullen, 2005; Reid and Martin, 1946). Following these observations, drinking water fluoridation schemes were implemented in the United States with Grand Rapids in Michigan becoming the first town in the world to be artificially fluoridated in 1945 (Unde et al., 2018). Due to its significant contribution to reducing dental caries, the Centers for Disease Control and

* Corresponding author. School of Dentistry, Faculty of Medicine and Health, The University of Sydney, Sydney, NSW, 2006, Australia.
E-mail address: shanika.nanayakkara@sydney.edu.au (S. Nanayakkara).

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Prevention (CDC) announced community water fluoridation as one of the top 10 public health achievements of the twentieth century (Centers for Disease Control Prevention, 2000).

The first community water fluoridation program in Australia was started in 1953 in Beaconsfield, Tasmania (National Health and Medical Research Council, 2017b). This gradually spanned into other parts of the country, resulting in 89% of Australians having access to fluoridated drinking water by 2017 (National Health and Medical Research Council, 2017a). Since the implementation of this public health measure, there have been multiple studies to investigate the impact and challenges of drinking water fluoridation in different states of Australia (Armfield, 2008, 2010; Armfield and Spencer, 2007; Arora and Evans, 2010; Blinkhorn et al., 2015; Crocombe, 2015).

Conducting a systematic review on water fluoridation in Australia is crucial for consolidating and assessing the existing body of knowledge. This review aims to summarize the current state of research, identify any existing gaps, and provide valuable insights to enhance water fluoridation practices in Australia. Thus, this review will focus on the history, effectiveness of disease prevention, and the safety of water fluoridation in the Australian context, as well as its challenges and limitations, including ethical and economic considerations. The review is expected to provide an up-to-date and comprehensive evaluation of the available evidence on water fluoridation in Australia to inform future research and policy decisions.

The objectives of this systematic review are to (i) explore the historical development of water fluoridation, (ii) assess the effectiveness of water fluoridation in reducing dental caries and improving oral health outcomes, (iii) evaluate the safety of water fluoridation and the reported adverse health effects, (iv) identify challenges and limitations of water fluoridation and, (iv) examine ethical considerations related to water fluoridation, including consent and autonomy in Australia.

2. Methodology

This review is reported in accordance with the updated Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). A systematic search was conducted to identify peer-reviewed literature on drinking water fluoridation in Australia. The Ovid Medline, Web of Science, Scopus, ProQuest Central, Cinahl, and Informit databases were searched. A grey literature search was also conducted to capture any other relevant literature. Backward snowballing was performed by checking references listed in the review articles (Wohlin, 2014). The literature search was completed on October 31, 2022.

The search terms included were [Fluoridation OR Fluorid*] AND [Drinking water OR tap water OR water supply OR Town water OR Municipal water OR water purification OR potable water] AND [Australia OR New South Wales OR South Australia OR Western Australia OR Northern Territory OR Victoria OR Tasmania OR Queensland OR Capital territory]. A time restriction was not applied for the search. The search strategies used for each database are available in the supplementary file 1. Identified articles were transferred to the Covidence Collaboration Platform (https://www.covidence.org/) for selection and data extraction.

After removing the duplicates, the titles and abstracts of the captured articles were screened for eligibility by two independent reviewers. Primary research articles (including articles on state and national level participation), reviews and opinion papers on water fluoridation in Australia were considered eligible for further screening. Animal studies as well as *in-vitro* studies were excluded. Consensus on any discrepancies experienced during article screening was reached through discussion among the review team. The reports that were not available to retrieve were excluded. Then, the first quantitative analysis was conducted to summarize the number of articles published over the last six decades based on the year of publication and the type of article. Available full texts were assessed for eligibility for data extraction. Inclusion criteria were primary research articles reporting the findings of studies conducted in any part of Australia on water fluoridation. Review articles, letters and opinion papers were excluded at this stage. Data extraction was performed independently by two reviewers and discussed among the team when discrepancies were observed. The second quantitative analysis was performed to summarize the number of primary articles published based on the year of publication and geographical location. Data from the included studies were summarized under three subheadings: history, health impacts, and limitations and challenges of water fluoridation in Australia.

3. Results

3.1. Research activities on water fluoridation

The database and grey literature search retrieved 838 records (Ovid Medline = 202, Web of Science = 174, Scopus = 249, ProQuest = 30, Cinahl = 134, Informit = 46, grey literature search = 3). We could not identify any additional articles during the 'snowball' search. After removing the duplicates (n = 457), 381 records were screened. The title and abstract screening process excluded 210 records, leaving 171 records for retrieval. Eighteen articles were not available to be retrieved as the full texts of the articles were not accessible, and 29 records were excluded during the full-text screening. The first quantitative analysis was conducted on 124 articles, including primary articles, reviews, and other article types (opinion papers, commentaries, letters). Eighty-one articles were selected for the second quantitative analysis and data extraction (Fig. 1, supplementary file 2).

Fig. 2 illustrates the results of the first quantitative analysis summarizing the distribution of all articles, including reviews and commentaries based on the year of publication and study/article type. The first publication on water fluoridation in Australia was in 1964, almost a decade after it was introduced in Tasmania. There was a notable increase in the number of articles published in late 1960s and early 1970s, which coincides with the implementation of water fluoridation in most states. This peak demonstrates the growing interest of the research community on this public health intervention. From the mid-1970s to the mid-1980s, the number of published papers remained relatively consistent. During the first three decades, almost all primary studies were focused on the health impacts in children. However, in the 1990s, there was a noticeable decline in the number of publications. In the late 1990s, there was a significant resurgence in research activity, with a sharp increase in the number of publications related to water fluoridation in Australia. Over 60% of the papers published after 2000 are primary studies. Interestingly, health impacts on the adult population have become a focus of research interest during this period.

Fig. 3 illustrates the results of the second quantitative analysis and summarizes primary article numbers based on the year of publication and geographical distribution. The figure demonstrates the trends in research activity in different states and territories since water fluoridation was introduced. The initial publication trend in each state or territory clearly aligns with the time of implementation in different parts of Australia. For example, water fluoridation was introduced in Queensland and New South Wales (NSW) in the 1960s, whereas implementation in Victoria was only in the late 1970s. Due to this, the initiation of the research activities, as evidenced by the publications in NSW and Queensland, is much earlier than in Victoria. From the late 1990s to the present, there has been a steady increase in the number of published articles on water fluoridation in all states and territories. But the publication numbers are relatively higher in NSW and Queensland than in other states. Although Tasmania was the first state to adopt this scheme in Australia, there was a limited number of primary studies conducted.

Legend: The x-axis of each graph represents the years from 1960 to 2022, while the y-axis shows the number of publications.

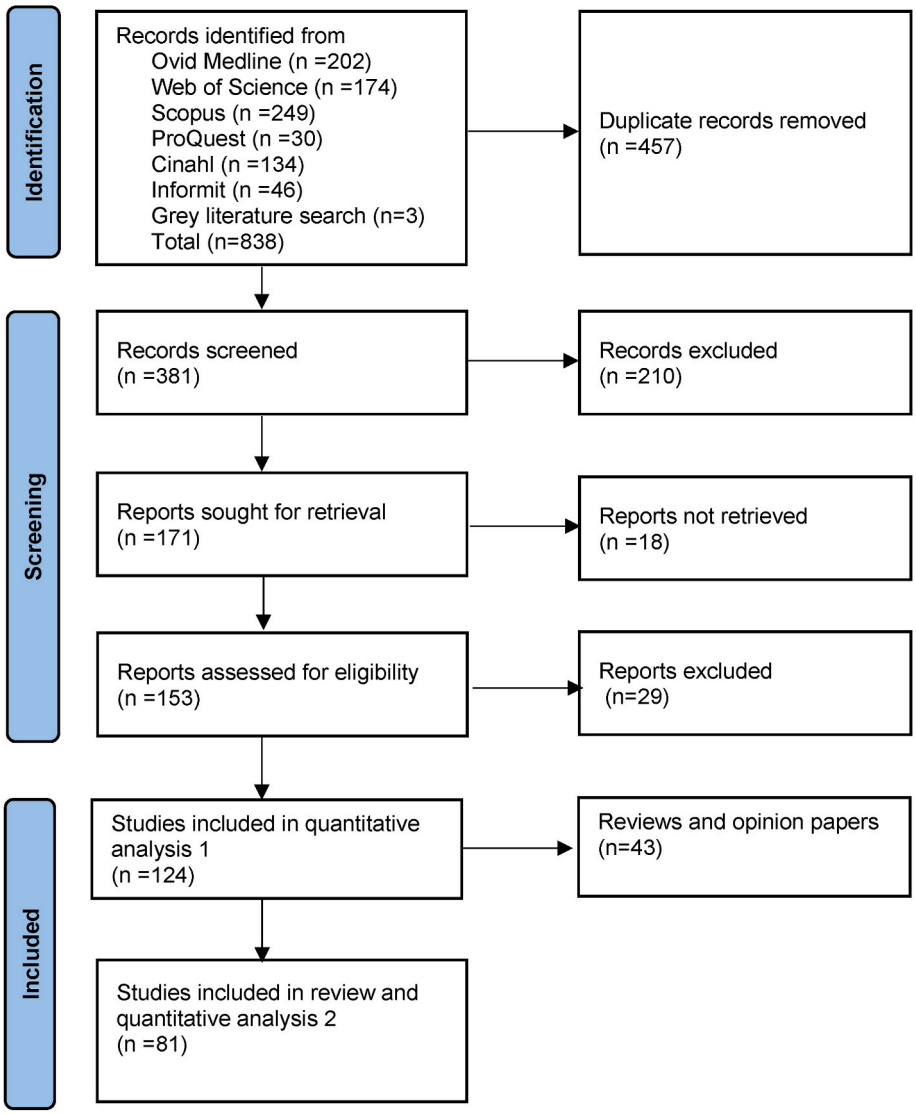

Fig. 1. PRISMA diagram illustrating the study selection process.

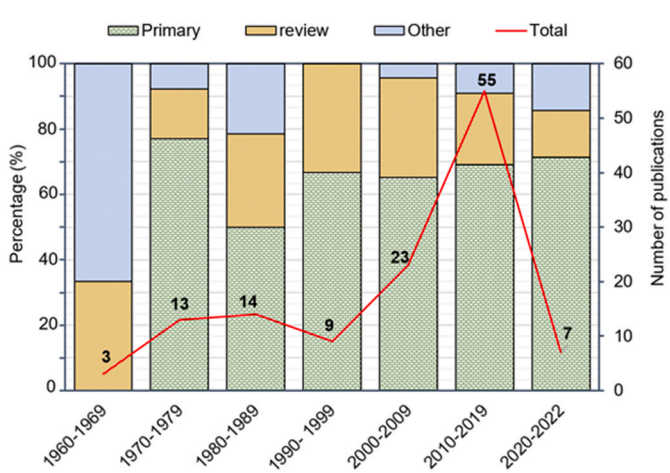

Fig. 2. Distribution of studies based on the year of publication and article type.

3.2. History of water fluoridation in Australia

The history of water fluoridation in Australia can be traced back to the 1950s, when the first trials of water fluoridation were carried out in 1953 (National Health and Medical Research Council, 2017b). Fig. 4 illustrates the key milestones in the history of water fluoridation in Australia, including the implementation of schemes and laws. The first water fluoridation scheme was implemented in Beaconsfield, Tasmania, in 1953 and was recognized as a successful health intervention (National Health and Medical Research Council, 2017a). This led to the introduction of water fluoridation in other parts of Australia, with NSW becoming the next state to start fluoridating community water supplies in 1956 (Altree-Williams, 1972; Sivaneswaran, 2012). The NSW Fluoridation of Public Water Supplies Act (1957) was implemented immediately following the start of fluoridation in Yass, which was the first city in NSW to start fluoridation (Sivaneswaran, 2012). This Act authorizes and controls the addition of fluoride to public water supplies and rests the responsibility of water fluoridation with local government authorities (councils) (Head, 1978; Sivaneswaran, 2012). Amidst the lack of solid government policies on water fluoridation in other states at the initial stage, some local authorities expressed an interest in initiating fluoridation projects in their respective administration areas. This resulted in introducing water fluoridation to all the states and territories

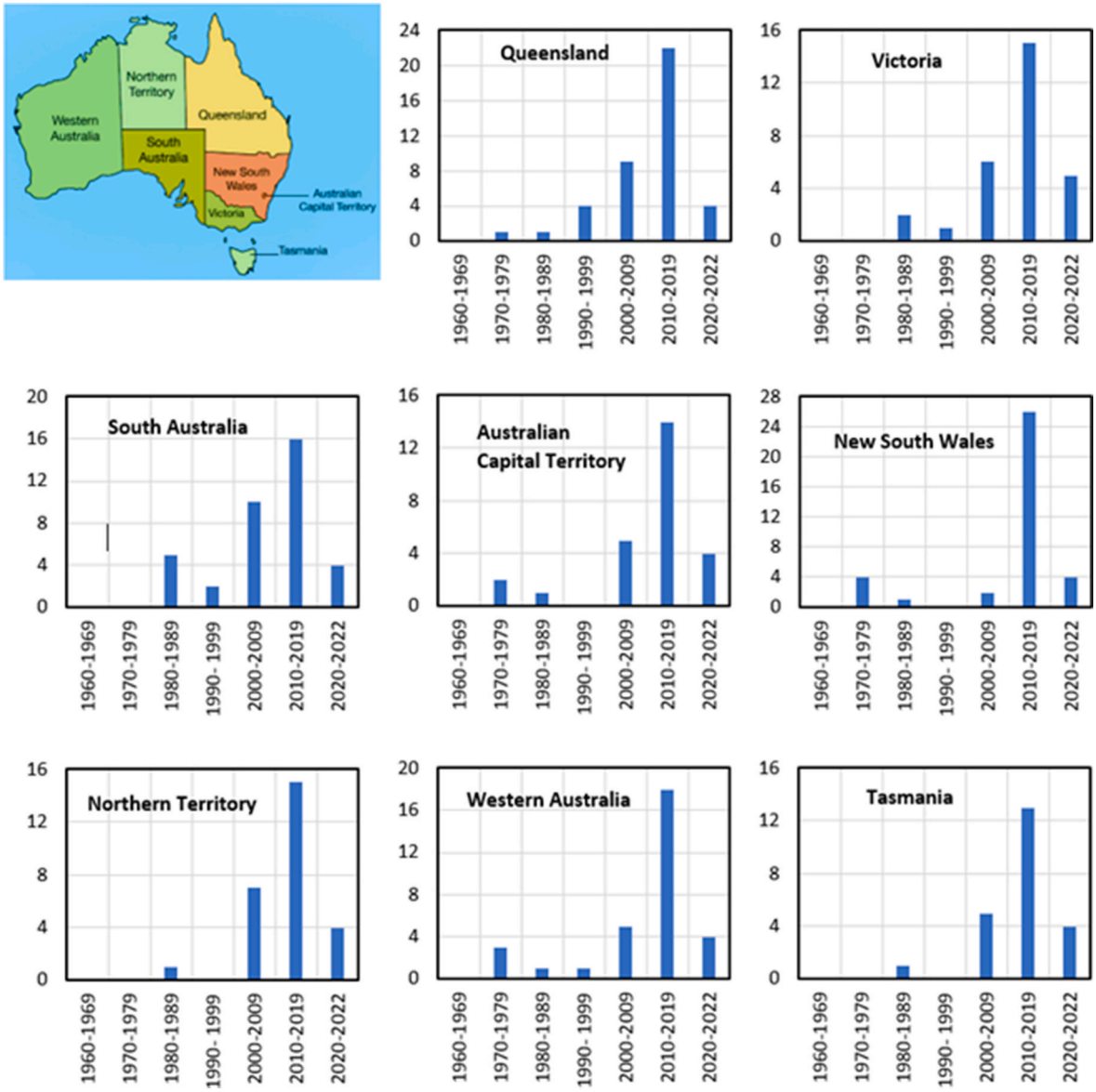

Fig. 3. Distribution of studies based on the targeted geographical location and the year of publication.

within two decades of the implementation of fluoridation in Tasmania (Akers and Porter, 2004; Altree-Williams, 1972).

Following the implementation in Yass, fluoridation was introduced to Hobart, Sydney, Newcastle and Canberra in the early 1960s (Altree-Williams, 1972; Armfield, 2005; Dawson, 1964), . Water fluoridation in Western Australia was first introduced in 1968 in Perth, followed by Adelaide (South Australia) in 1971 and Darwin (Northern Territory) in 1972 (Barnard, 1975; Fanning et al., 1980; Fanning and Somerville, 1975; Medcalf, 1978). By 1977, artificial water fluoridation was introduced in capital cities of every Australian State and territory except Brisbane (Armfield, 2005). Compared to the other states, the implementation of fluoridation was delayed in Queensland. Though fluoridation started in Townsville in 1965, which was the first city to be fluoridated in Queensland, by 2001, only 4.7% of the Queensland population had access to fluoridated water, whereas 69.1% of the Australian population had access by that time (Kroon et al., 2014). In 2008, with the introduction of the Water Fluoridation Act 2008, the Queensland Government declared that all communities with more than 1000 people should be fluoridated. Hence, 134 water supplies were identified and fluoridated (McAuliffe et al., 2020). Brisbane and Gold Coast began water fluoridation in 2008 (Kroon et al., 2014). Within four years, 90% of Queenslanders had access to fluoridated water before the coverage dropped to 76% in 2012 due to the new government decision overturning the mandatory water fluoridation in Queensland with an amendment to the Act. The legal framework in Queensland for water fluoridation comprises this Act and the Water Fluoridation Regulation 2020; Akers et al. (2005).

Legend. NSW; New South Wales, TAS; Tasmania, Vic; Victoria, ACT; Australian Capital Territory, QLD; Queensland, WA; Western Australia, SA; South Australia, NT; Northern Territory.

Three decades after the initial implementation, only about two-thirds of Australians had exposure to fluoridated water (Do and Spencer, 2015). Around 66.7% of the Australian population consumed naturally or artificially fluoridated water in 1984, according to the Commonwealth Department of Health figures (Armfield, 2006). With NSW and Victoria expanding their water fluoridation and with the decision to mandate fluoridation in Queensland in 2008, water fluoridation coverage gradually improved in Australia reaching 89% based on the data published in 2017 (Do and Spencer, 2015; National Health and Medical Research Council, 2017b; Stormon et al., 2019). While the Australian Capital Territory (100%) and NSW (96%) had the highest fluoridation coverage, the Northern Territory (78%) and Queensland

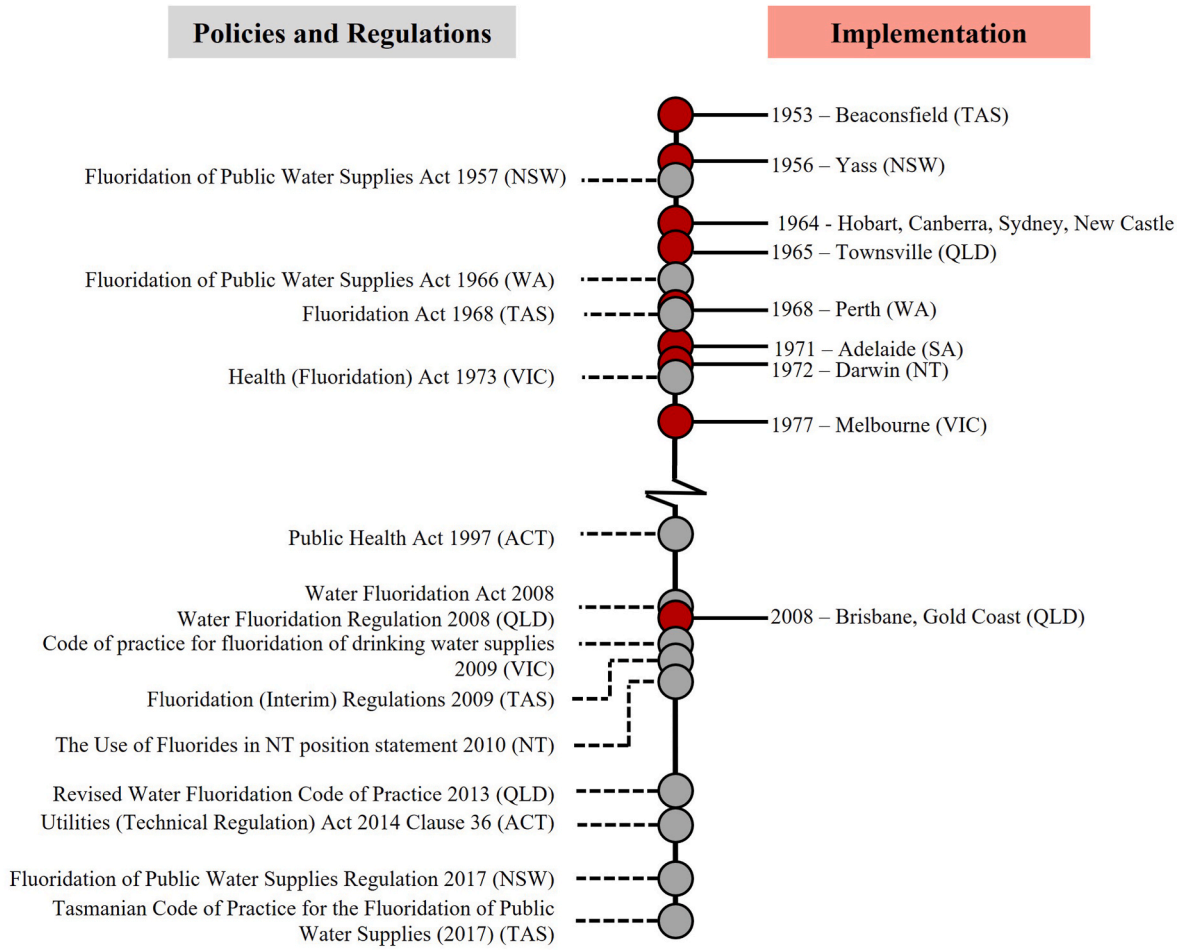

Fig. 4. Milestones in water fluoridation in Australia.

(71%) reported the lowest. All the other states had a coverage of above 90% (National Health and Medical Research Council, 2017b; NSW Health; Stormon & Lalloo, 2020; The University of Queensland, 2022). It is also noteworthy that as most indigenous communities are in areas with no fluoridation, only 50% of Indigenous Australians had access to fluoridated water based on a report published in 2020 (McAuliffe et al., 2020).

3.3. Opposition to water fluoridation

The adoption of water fluoridation in Australia was initially slow, with many communities expressing concerns about the safety and effectiveness of the practice. There has been a lot of opposition to the practice from various groups, including medical professionals, administrators, and anti-fluoride activists (Armfield and Akers, 2010, 2011). During this period, some opponents have argued that fluoridation is a form of forced medication, it could have negative health impacts, and the mass fluoridation of water supplies is a violation of individual rights (Block, 2009; Dark, 1964; M. G. Gussy et al., 2008; Head, 1978). However, as more research reported the benefits of water fluoridation, and as oral health outcomes improved in fluoridated communities, public support for water fluoridation eventually popularised (Burl and Beltran, 1988; M. Gussy et al., 2008). For example, water fluoridation in Victoria has been eventful and has faced significant opposition to implementation (Neil, 2012). Despite these disputes, some local authorities continued implementing fluoridation in their areas. In the 1960s, The State Rivers and Water Supply Commission (SRWSC) urged the Minister of Water Supply to permit local authorities to initiate fluoridation. As a result, The Public Water Supplies (Fluoridation) Bill was introduced into the Legislative Assembly in 1964 (Head, 1978). However, due to an argument on the votes on the bill and disputes from different parties, the bill was deferred and a new bill was introduced in 1973 (The Health Bill), after which the fluoridation of Melbourne's water supplies began in 1977 (Block, 2009; Head, 1978). However, the fluoridation of the rest of the state was discontinued in 1979 when the then Premier requested an expert committee to inquire and consider novel evidence on water fluoridation to decide the necessity of reviewing the Health Act 1973. The committee decided not to recommend any amendments to the Act. Thus, in 1980 it was declared that the fluoridation process should be continued throughout Victoria (Neil, 2012).

3.4. National guidelines on optimal fluoride concentration in drinking water

Today, water fluoridation is widely accepted as a safe and effective way to improve dental health and is endorsed by the Australian government and major health organisations, including the Australian Dental Association and the National Health and Medical Research Council (NHMRC) (Do, 2020; National Health and Medical Research Council, 2017a; Stormon and Lalloo, 2020). It is expected that the optimal level of fluoride in drinking water provides sufficient levels of fluoride to prevent dental caries while minimizing the risk of dental fluorosis (Centers for Disease Control and Prevention, 2020; Fawell, 2006; US Department of Health, 2015). Water fluoridation recommendations have also considered the average maximum daily air

temperature because individuals residing in cooler climates tend to consume less fluid than those in warmer climates (Galagan, 1953; Galagan et al., 1957; Health, U. D. o., & Fluoridation, H. S. F. P. o. C. W, 2015; Heller et al., 1999). The temperature -related recommendations on optimal fluoride concentration were based on studies conducted in the early 1950's in United States (Donald and Lamson, 1953; Galagan and Vermillion, 1957; Spencer et al., 2018).

In Australia, the first workshop to develop national guidelines on the use of fluoride was convened in 2005 followed by the second workshop in 2012 to update the existing guidelines (Do, 2020). The third workshop that was conducted in 2019 to review the NHMRC guidelines supported continuation of water fluoridation at the existing recommended levels (Do, 2020). The current NHMRC guidelines recommend fluoridation of drinking water supplies within the range of 0.6–1.1 mg/L, depending on the average temperature of the area (National Health and Medical Research Council, 2017b). Table 1 summarizes state- or territory-specific water fluoridation recommendations in Australia.

Temperature-related recommendations have been revised in the United States considering additional fluoride exposures like toothpastes, mouth rinses, and supplements, as well as new evidence indicating no association between water intake in children and outdoor air temperature (Beltrán-Aguilar et al., 2015; Heller et al., 1999; United States Department of Health and Human Services, 2015). In 1962, temperature-based optimal fluoride recommendations were implemented in the United States, which specified a fluoride concentration of 0.7–1.2 mg/L in community water supplies. (United States Department of Health and Human Services, 2015). However, a review conducted by the Department of Health and Human Services in 2010 recommended a new guideline of 0.7 mg/L regardless of temperature which was implemented in 2015.

The NHMRC also recommends that the responsibility for water fluoridation be placed with the relevant state or territory health authority (National Health and Medical Research Council, 2017a). In addition, it also recommends regular monitoring and testing be conducted to ensure that fluoride levels in the water supply remain within the recommended range. In Australia, the regulation of water fluoridation is managed by state and territory governments rather than the federal government (Table 1). As a result, the specific legislation and regulations governing water fluoridation can vary between jurisdictions. Most states and territories in Australia have passed laws covering the regulation and monitoring of water fluoridation. For example, in NSW, the Fluoridation of Public Water Supplies Act (1957) provides the legal framework for water fluoridation, while in Queensland, the Water Fluoridation Act 2008 governs water fluoridation practices (Fig. 4).

Table 1
Recommended levels of fluoride in water in Australian states.

State/ Territory	Recommended levels of fluoride in drinking water	
Victoria	1 mg/L (Victoria Department of Health)	
New South Wales	1 mg/L (NSW Health)	
Queensland	0.6–0.8 mg/L (Queensland Health)	
Western Australia	The optimum level for the Perth metropolitan area is 0.9 mg/L, with a range of 0.7–1.0 mg/L (Government of Western Australia)	
Northern Territory	Average Maximum Air temperature (°C)	Fluoride concentration (mg/L) (Nothern Territory Government, 2010)
	32.6 and over	0.5–0.6
	26.3–32.5	0.6–0.7
	21.5–26.2	0.7–0.8
	17.7–21.4	0.7–0.9
Tasmania	0.8–1.1 mg/L (Tasmanian Government)	

There is no region-specific recommendation published for Australian Capital Territory.

3.5. Community impacts of water fluoridation: improved oral health

Despite the progress in understanding oral diseases, untreated dental caries is still the most prevalent health condition globally (Peres et al., 2019) and the most common oral disease in Australia, affecting children and adults (https://www.aihw.gov.au). Identified major risk factors for dental caries include poor oral hygiene, diet, lower socioeconomic status, and extended intervals between dental check-ups (Arrow, 2016; Do et al., 2018). Since its implementation, water fluoridation has been identified as a safe and effective way to improve oral health and prevent dental caries in communities regardless of age, income, or access to dental care. This has been especially important for those more likely to suffer from dental caries and related health problems, such as low-income and disadvantaged communities and people without access to regular dental care (Armfield and Akers, 2010).

Multiple community-level investigations have been carried out in all states and territories in Australia to evaluate the effectiveness of water fluoridation in reducing dental caries. These studies have commonly used two outcome measures, including DMFT/DMFS (decayed, missing, filled, teeth or tooth surfaces) and percentage/proportion of teeth/children without caries. The first studies on the effectiveness of water fluoridation in Australia were mostly conducted in the 1970s. One of the earliest studies was conducted in Western Australia in early 1971, two-and-a-half years after fluoridation was introduced in Perth. This study compared the prevalence of dental caries in first permanent molars in 6-year-old children with no history of pre-natal or post-natal fluoride supplement reporting a reduction in dental caries, 32 months after fluoridation introduced in 1967 (Medcalf, 1971). Another study carried out in Canberra six years after fluoridation was introduced, reported a progressive improvement of DMF index scores in children aged 6–12 years (Carr, 1972). Studies mainly focusing on children aged 6–14 years were conducted in the 1970s to investigate the effects on dental health (Carr, 1972, 1976; Lawson et al., 1978; Medcalf, 1975). These early studies provided important evidence on the effectiveness of water fluoridation in preventing dental caries in Australia and contributed to the promotion and expansion of water fluoridation programs throughout the country.

With the expansion of fluoridation coverage in all states and territories, further studies were conducted to assess the oral health effects of water fluoridation in children, adolescents, and adults (Armfield, 2005; Burton et al., 1984; Do and Spencer, 2015; Do et al., 2015; Hopcraft and Morgan, 2006; Mahoney et al., 2008; Skinner et al., 2014; Spencer et al., 2017). These studies have demonstrated decreased dental caries after water fluoridation was introduced in respective geographical locations. A cross-sectional study that analysed data on around 250,000 children in NSW found a consistent association between the reduction of dental caries and access to fluoridated water (Armfield, 2005). The observed dental caries reduction in the deciduous dentition of younger children (aged 5 and 6) was more prominent compared to the permanent dentition of older pre-teen children (aged 11 and 12). The Logan-Beaudesert district in Queensland is one of the areas fluoridated in 2008. After 36 months of fluoridation, Koh et al. reported a 19% reduction in caries experience on the primary dentition of children aged 4–9 years in a high caries risk community (Koh et al., 2015). In addition, a study conducted in Western Australia reported that children in fluoridated areas had, on average, 49% fewer fillings and 67% fewer extractions than children in non-fluoridated areas (Spencer et al., 2008). Similar observations have been reported in other locations (Campain et al., 2010; Carr et al., 1980; Ciketic et al., 2010; Cobiac and Vos, 2012; Doessel, 1985).

Nationwide studies to evaluate the oral health impacts of water fluoridation have been conducted at different time points. Most of the studies on adult populations have been conducted during the last two decades. Slade et al. used data of a nationally representative sample of Australian adults from 2004 to 2006 to compare pre-fluoridation and post-fluoridation cohorts and reported the caries preventive effect of fluoride (Slade et al., 2013). Another nationwide study on 973 army

recruits aged 17–51 reported lower caries prevalence in subjects with lifetime exposure to fluoride compared to those from non-fluoridated areas (Hopcraft and Morgan, 2006). Multiple studies analysing National Child Oral Health Survey data have also repeatedly reported favourable oral health impacts of water fluoridation. For example, a causal association between longer lifetime exposure to fluoridated water and lower childhood dental caries was reported based on the 2012–2014 National Child Oral Health Survey data of 24,664 children aged 5–14 years (Foley et al., 2021). In 2017, the NHMRC reported that water fluoridation reduced tooth decay by 26%–44% in children and adolescents and 27% in adults in Australia (National Health and Medical Research Council, 2017a). In summary, these studies have consistently demonstrated the positive impact of water fluoridation in improving oral health by effectively reducing dental caries within the Australian population. Since water fluoridation was introduced, studies to assess the effectiveness of water fluoridation have been conducted in many other countries and have reported similar beneficial impacts on oral health. A Cochrane review published in 2015 summarizing global evidence on the effectiveness of water fluoridation in preventing caries reported a 26% reduction in DMFT in permanent dentition and a 35% reduction in primary dentition (Iheozor-Ejiofor et al., 2015a). The Centers for Disease Prevention and Control reports that in the United States, water fluoridation has resulted in a 25% reduction in dental caries in children and adults (Centers for Disease Control and Prevention, 2020). Singapore, which introduced water fluoridation in 1956was the first country in Asia to adopt this measure. Thirty-eight years after the implementation, a study conducted in Singapore on 7–9-year-old children reported a 52.3% reduction in caries prevalence for Chinese children and 31% for Malays (Loh, 1996). Based on these reports, it is evident that the levels of caries reduction observed in Australia are comparable to the levels reported in other parts of the world (Centers for Disease Control and Prevention, 2020; Iheozor-Ejiofor et al., 2015a; Loh, 1996).

Dental caries is relatively more prevalent among indigenous communities (Bailie et al., 2009; Green and Blinkhorn, 2010; Kroon et al., 2019; Lalloo et al., 2015; McAuliffe et al., 2020). Thus, introducing fluoridated water to these communities has been considered an important measure to prevent caries. Supporting this, a study assessed the dental caries rate among 18,067 indigenous South Australian school children. It revealed that children living in fluoridated areas had lower caries experience than those living in non-fluoridated areas, although this difference was not statistically significant (Ha et al., 2016). A discussion paper on inequalities in the oral health of Australian Aboriginal people also highlighted installing fluoridation plants in small communities as one of three main strategies to improve the oral health of the indigenous population (Green and Blinkhorn, 2010).

While studies have consistently demonstrated improved dental health following water fluoridation, research has also been conducted to compare the specific contribution of water fluoridation to caries reduction, as opposed to other factors like behavioural or societal changes (Schamschula et al., 1979). For example, a study examined children from three cities in NSW with similar racial, socioeconomic, nutritional, and dietary backgrounds but varying levels of fluoride exposure through water and reported a significant reduction in caries experience among those exposed to fluoridated water (Schamschula et al., 1979). However, there has been criticism that the decline in caries was unrelated to fluoridation, citing changes in dietary patterns, socioeconomic conditions, and the immune system as significant contributing factors (Burl and Beltran, 1988). It is also important to note that after introducing additional fluoride vehicles such as toothpastes in the 1970s, the prevalence of caries between fluoridated and non-fluoridated areas narrowed (Armfield, 2010; Burl and Beltran, 1988). This indicates that these additional fluoride exposures, such as toothpastes and professional fluoride treatments, have also contributed to reducing dental caries. Overall, it is evident that while debates persist regarding the independent impact of water fluoridation on caries reduction, fluoride has demonstrated a positive impact on the prevention of dental caries in the Australian community, irrespective of the vehicle by which fluoride is introduced (Burl and Beltran, 1988; Spencer, 1986). Responses to critics of water fluoridation have highlighted that the benefits of water fluoridation in preventing dental caries outweigh the potential risks of excessive fluoride intake (Burl and Beltran, 1988; Spencer, 1998).

3.6. Safety of water fluoridation

The safety of water fluoridation has been extensively researched all over the world, aiding in the implementation of guidelines to improve dental health and prevent dental caries (Centers for Disease Control and Prevention, 2020; Horowitz, 1996; McDonagh et al., 2000; Parnell et al., 2009; UK Department of Health and Social Care; US Department of Health, 2015). It is worth noting that the optimum fluoride levels recommended for water fluoridation have been carefully established to balance the benefits of preventing dental caries with the potential risks of excessive fluoride intake (Galagan and Vermillion, 1957). In the United States, the Public Health Service recommends an optimal fluoride concentration of 0.7 mg/L to maintain caries prevention benefits while reducing the risk of dental fluorosis (Health, U. D. o., & Fluoridation, H. S. F. P. o. C. W, 2015). In Australia, the NHMRC acts as the governing body in decision-making related to recommendations on the dietary intake of nutrients including fluoride. These recommendations consist of Nutrient Reference Values (NRV) for the nutrients including Adequate Intake (AI) and Tolerable Upper Intake (UI) levels for different age groups (National Health and Medical Research Council). AI provides information on the recommended intake for fluoride to prevent dental caries while UI informs the upper level of intake above which there is a risk of severe dental fluorosis (National Health and Medical Research Council). There has been a series of revisions to the NRV recommendation for fluoride with the growth of scientific evidence. The latest revisions in 2017 also included revised AI and UI for fluoride intake for 0–8-year-olds (National Health and Medical Research Council). The supplementary file 3 summarizes the current AI and UI recommendation for fluoride in Australia (National Health and Medical Research Council).

Even though multiple studies have confirmed the beneficial health impacts of water fluoridation, there has been criticism and debate on the health safety of fluoridation since its inception (Block, 2009; Burl and Beltran, 1988; Colquhoun, 1990; Dark, 1964). Previous studies have reported that excessive fluoride ingestion can cause acute and chronic toxicity (Augenstein et al., 1991; Whitford, 2011). Chronic excessive exposure to fluoride is known to cause dental fluorosis (DenBesten and Li, 2011), skeletal fluorosis (Srivastava and Flora, 2020), thyroid dysfunction (Singh et al., 2014), kidney disease (Dharmaratne, 2019) and neurological symptoms such as headaches, tremors, and cognitive impairment (Ren et al., 2022).

It is worth noting that though a limited number of studies have been conducted in Australia to investigate possible adverse impacts of fluoridation, these studies have concluded that water fluoridation at optimal levels is not associated with any adverse health effects in any age group (Do et al., 2023; McCoomb, 2017). For example, Laurence et al. (2012) conducted a cross-sectional study in the NSW Central Coast region and reported that dental fluorosis levels in children were not significantly varied across fluoridated and non-fluoridated regions. Interestingly, two studies have reported an increased prevalence of enamel defects in children with lifelong or near lifelong exposure to water fluoride levels at 1 ppm in South Australia (Dooland and Carr, 1985; Dooland and Wylie, 1989). However, further studies have revealed that dental fluorosis among South Australian children is very mild to mild (Do and Spencer, 2007). This was supported by another study conducted in Western Australia assessing dental fluorosis in 12-year-olds in fluoridated and non-fluoridated areas, which also reported similar observations (Riordan, 1991). Researchers have also investigated potential associations between cancer and water fluoridation. For example, the

standardized cancer mortality ratios in fluoridated and non-fluoridated regions in NSW were compared and it was reported that there was no association between the two (Richards and Ford, 1979). In addition to the research activities on dental fluorosis and cancer mortality, a recent population-based longitudinal study using data from Australia's National Child Oral Health Study 2012–14 reported the absence of an association between exposure to fluoridated water during the first five years of life and altered measures of executive functioning and emotional and behavioural development of children (Do et al., 2023). The absence of evidence to support associations between negative health impacts and water fluoridation (Do et al., 2023; Dooland and Carr, 1985; Dooland and Wylie, 1989; Laurence et al., 2012; Richards and Ford, 1979; Riordan, 1991) has supported the further expansion of water fluoridation in Australia (Sivaneswaran, 2012). However, there have been concerns about potential excessive fluoride exposure in individuals exposed to multiple sources, including water, dental products, and dietary sources (Centers for Disease Control and Prevention, 2020).

3.7. Cost effectiveness

According to a report by the NHMRC, water fluoridation is one of the most effective and cost-efficient public health measures for preventing dental caries (National Health and Medical Research Council, 2017a). Studies have highlighted that the cost of water fluoridation is relatively low compared to the cost of treating dental caries (Ciketic et al., 2010; Cobiac and Vos, 2012). Water fluoridation can also help to improve overall oral health and reduce the need for costly dental procedures, such as fillings, root canals, and extractions (Carr et al., 1980; Ciketic et al., 2010; Cobiac and Vos, 2012). Cost evaluations concluded that in Australia, for each $1 spent on water fluoridation, there is a saving of $7–18 from the decrease in costs of dental treatments (National Health and Medical Research Council, 2017b).

3.8. Limitations and challenges

Although water fluoridation is widely accepted globally as an effective public health measure (Centers for Disease Control and Prevention, 2020), implementing and maintaining community water fluoridation have posed significant challenges in many countries. These challenges include public and political opposition, costs associated with implementation and maintenance, and insufficient attention given to dental caries as a public health problem by responsible authorities (Botchey et al., 2015; Zokaie and Pollick, 2022). These challenges are not unique to any geographical region. Major limitations and challenges experienced and reported in Australia are discussed below.

3.8.1. Political and public opposition

Since water fluoridation was introduced, there has been public opposition in some communities (Armfield and Akers, 2010, 2011). Some reasons for opposition to water fluoridation include concerns about potential health risks and concerns about individual rights and freedom of choice (Head, 1978). Even though previous studies evaluating possible adverse effects of fluoridation have concluded that water fluoridation at optimum recommended levels is not associated with any such effects (Do et al., 2023; Dooland and Carr, 1985; Dooland and Wylie, 1989; Laurence et al., 2012; Richards and Ford, 1979; Riordan, 1991), some people continue to express concerns about the safety of fluoride (Block, 2009; Foley, 2015; Sivaneswaran, 2012). The presence of political will is critical to the success of implementing and maintaining public health interventions. Unfortunately, unfavourable political support has also contributed to delayed decision-making related to implementing water fluoridation in Australia (Akers and Armfield, 2010; Akers and Foley, 2012; Foley, 2015).

3.8.2. Implementation, maintenance and monitoring cost

The cost of implementing and maintaining water fluoridation programs can be divided into one-time investment costs, recurrent fixed costs for maintenance, and variable recurrent costs that depend on the amount of water being fluoridated (Ran et al., 2016). Though community water fluoridation is recognized as the most cost-effective method of delivering fluoride (Centers for Disease Control Prevention, 2000), fluoridating small, geographically dispersed communities is not considered cost-effective (Ran et al., 2016). Water fluoridation programs require infrastructure modifications and ongoing monitoring to ensure the safe delivery of fluoride to target communities (de Freitas, 1981; Desai et al., 2015). For small communities, it is challenging to afford the cost of the resources necessary to maintain a successful fluoridation project (Patel et al., 2017).

3.8.3. Access and equity

Currently, most Australians have access to fluoridated water. However, some regions, particularly indigenous and rural communities, still have limited access to this important public health intervention (Dickson-Swift and Crocombe, 2022). Thus, these communities are considered disadvantaged in regard to their access to fluoridated water (M. Gussy et al., 2008; Neil, 2011; Ran et al., 2016). Though a policy decision was taken in the early 2000s to fluoridate water supplies in indigenous communities, implementation of fluoridation is challenging due to the small and highly dispersed nature of indigenous communities (Spencer et al., 2010). Australia's National Oral Health Action Plan 2015–2024 states that communities with populations over 1000 should have access to a reticulated fluoridated water supply, considering the high cost of implementing and maintaining fluoridation plants in smaller communities (Oral Health Monitoring Group, 2015). However, this approach may result in health disparities and unequal access to this preventive oral health measure. The same report highlights the importance of introducing other forms of fluoride to optimize oral health in these communities (Oral Health Monitoring Group, 2015). Extending fluoridation coverage to include small communities has also been suggested, considering the substantial benefits of water fluoridation (Cobiac and Vos, 2012).

3.8.4. Communication and education

Effective communication and education play a pivotal role in ensuring the public is well-informed about the multitude of benefits and the safety of water fluoridation. Studies have evaluated the level of public knowledge and gauged opinions regarding water fluoridation (Mummery et al., 2007). Public surveys have demonstrated that a negative attitude towards fluoridation in Australia is associated with low educational attainment (Armfield and Akers, 2011; Kroon et al., 2014). It has also been stated that misinformation on water fluoridation may lead to a public dispute (Roberts-Thomson and Spencer, 1999) whereas the successful use of communication favours implementation of water fluoridation programs (Sivaneswaran et al., 2010). Thus, there is a need to emphasize the importance of effective communication strategies, thereby engaging the public in meaningful discussions about water fluoridation. Health education programs should also be designed to increase public knowledge and awareness of the benefits and safety. However, some research also suggests that healthcare professionals' contribution towards public advocacy is not satisfactory (Kroon et al., 2014). Thus, the importance of gaining dental professionals' support in public education has been advocated in several studies (Howat et al., 2015; Sivaneswaran and Chong, 2011).

3.8.5. Ethical considerations

The ethical concern of violating individual autonomy due to mandatory artificial water fluoridation has been a persistent issue in the history of water fluoridation in Australia. Some groups have opposed community water fluoridation on the grounds that it infringes on individual freedom of choice (Awofeso, 2012; Head, 1978; Knox et al., 2017). Although ethical bodies, such as the Centre for Social Ethics and Policy in the University of Manchester and the International Bioethics

Committee of UNESCO, consider community water fluoridation as ethical, the debate on this issue continues (National Health and Medical Research Council, 2017b). Despite evidence of the safety and effectiveness of water fluoridation in preventing dental caries, there is still a need for further discussion and ethical considerations regarding mandatory water fluoridation in Australia. This debate highlights the importance of balancing public health benefits with individual rights and autonomy.

4. Discussion

Important patterns in research on water fluoridation in Australia were identified in this literature review. The contribution from each state or territory to the scientific research on water fluoridation varied significantly, possibly due to the differences in the timing of implementation (Fig. 4). Providing funding and support for research is paramount in stimulating research activity and output, and it is plausible that these factors have also influenced the observed variations. The level of research activity on water fluoridation could have also been influenced by variations in interest or advocacy for this practice, as well as differences in research focus and priorities across various states and territories. A discernible decline in research activity during the 1990s (Figs. 2 and 3) can be attributed to factors such as the lack of public interest and funding, as well as a perceived absence of ground-breaking findings. It is worth noting that during this period, concerns about the ethical implications and efficacy of water fluoridation increased (Awofeso, 2012; Douglas, 1991). A spike in publications after 2010 (Fig. 3) may be due to renewed public interest in the topic, as well as advancements in research methods and technology.

Consistent observations on the reduction of dental caries following water fluoridation have been reported globally (Iheozor-Ejiofor et al., 2015b; Loh, 1996; McDonagh et al., 2000; Parnell et al., 2009). Multiple reviews have consistently demonstrated the benefits of water fluoridation in reducing dental caries in children, encompassing both deciduous and permanent teeth. These reviews have found no substantial evidence of adverse effects, aside from mild dental fluorosis at optimal levels of fluoridation (Harding and O'Mullane, 2013; Iheozor-Ejiofor et al., 2015b; McDonagh et al., 2000). Research questioning the benefits of water fluoridation is not a rare occurrence (Peckham and Awofeso, 2014) as the debate and criticism surrounding this practice have been observed in countries including the USA (Pizzo et al., 2007; Rabb--Waytowich, 2009) and Europe (Griffin et al., 2008).

The limitations and challenges associated with the implementation of water fluoridation extend beyond Australia, as supported by the existing evidence. On several occasions, these challenges have been significant enough to disrupt the already implemented fluoridation projects. For example, in countries like the Czech Republic, Sweden, Netherlands and Switzerland, water fluoridation projects were suspended due to anti-fluoride activities in the 1990s (Awofeso, 2012).

Based on the most recent Australian government report on Sustainable Development Goals indicators, 98% of Australian households have access to clean and safe drinking water sources via central supplies (Australian Government, 2017). However, it is essential to recognize that this figure primarily applies to urban areas. In contrast, approximately 8% of individuals residing in remote regions of the country accessing water from private and small supplies face challenges in accessing drinking water with a comparable quality (Wyrwoll et al., 2022). Thus, it is important to extend access to fluoridated drinking water to these disadvantaged, remote communities or introduce them to other forms of fluoridated supplies to improve oral health outcomes.

4.1. Practical implications and future research prospects

Despite achieving close to 90% water fluoridation coverage in Australia, certain communities still face barriers in accessing this preventive measure. It is imperative to aid smaller communities, ensuring equitable access to fluoridated water without imposing excessive financial burdens. In cases where water fluoridation is not feasible or is cost-prohibitive, alternative caries preventive measures should be implemented. To effectively promote public health interventions such as water fluoridation, it is crucial to address concerns, foster consensus, and improve awareness among the relevant communities. This could be achieved through community engagement and soliciting public input and feedback during program implementation to establish trust and support for initiatives. Including relevant experts and organisations in decision-making processes is vital to ensure evidence-based and scientifically grounded interventions and public health measures. The successful implementation of fluoridation programs also relies on essential collaboration with local communities including First Nations people.

Further research endeavours are warranted to regularly review and update the optimal fluoride concentration in Australia considering the potential multiple sources of exposure and temperature variations. These research activities should aim to maximize dental health benefits while minimizing the risk of dental fluorosis. Ongoing monitoring and research efforts are necessary to review and update optimum fluoride recommendations to ensure safety and efficacy. Moreover, additional studies are warranted to assess the safety of water fluoridation and explore potential health effects beyond dental health. These studies should comprehensively evaluate any potential associations between water fluoridation and systemic health conditions, such as bone health, endocrine function, and neurodevelopmental outcomes. By gaining a comprehensive understanding of the long-term impacts, evidence-based practices can be further developed and implemented. A paucity of publications exists concerning public attitudes and perceptions towards water fluoridation in Australia. By delving into public concerns and countering misinformation, researchers can devise effective communication strategies that increase acceptance and facilitate an informed decision-making process. To ensure the long-term sustainability of the water fluoridation program and maximize its health benefits for all Australians, ongoing research, advocacy, and collaboration among researchers, policymakers, and communities are imperative.

5. Conclusions

This review sheds light on the uneven distribution of research focus on water fluoridation in Australia, with certain regions taking a more proactive role in this research domain. Since 2010, there has been a notable surge in publications, indicating sustained interest from the research community. These studies consistently highlighted the positive effects of water fluoridation, particularly in reducing dental caries among both children and adults. It is vital to promote increased research efforts encompassing both the positive and negative impacts of fluoridation. Despite most Australians having access to fluoridated water, there are still regional and remote communities that lack this essential resource. Thus, enhancing access to fluoridated water across the country while monitoring and updating the existing fluoridation recommendations are vital pursuits.

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Lalantha Senevirathna: Conceptualization, Supervision, Formal analysis, Writing – original draft. Himali Erandathie Ratnayake: Data curation, Writing – original draft. Nadeeka Jayasinghe: Data curation, Writing – original draft. Jinlong Gao: Writing- Reviewing and Editing. Xiaoyan Zhou: Writing- Reviewing and Editing. Shanika Nanayakkara: Conceptualization, Supervision, Data curation, Formal analysis, Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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