SYSTEMATIC REVIEW

A Systematic Review to Inform the Development of a Population-Based Artificial Intelligence-Assisted Adult Caries Risk Assessment Tool

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ABSTRACT

Aim: To evaluate the caries risk factors in adults and identify critical predictors for developing an artificial intelligence-assisted caries risk assessment tool for population-based screening. **Design:** A systematic review was conducted in accordance with PRISMA guidelines. **Data Sources:** A comprehensive search was performed across PubMed, Google Scholar, Web of Science, and Scopus. The search was conducted on the following dates: Google Scholar (28 November 2023), PubMed (28 November 2023), Scopus (19 September 2023), and Web of Science (25 November 2023). **Review Methods:** This review included longitudinal studies that examined caries risk factors in adults. The studies were assessed using the ROBINS-E and GRADE tools, with eligibility determined by two independent reviewers. **Results:** A total of 60,042 records were screened, resulting in 12 longitudinal cohort studies that met the inclusion criteria. These studies identified eight significant risk factors for caries: smoking, systemic disease, water fluoridation, education level, fluoride toothpaste use, sugar intake, bacterial plaque, and history of caries. Quality assessments of the studies revealed that two were classified as high quality, eight as moderate quality, and two as limited quality. **Conclusion:** This review identifies essential caries risk factors that can guide the development of effective AI-assisted tools for assessing adult caries risk, thereby enhancing implementation and scalability.
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INTRODUCTION

Dental caries remains a critical global health issue, with untreated caries in permanent teeth ranking among the most prevalent conditions worldwide (1). The Global Burden of Disease Study 2021 reported a global age-standardised prevalence of 27,500 per 100,000 population, while the National Oral Health Survey of Adults (NOHSA) 2020 found that 85.1% of Malaysian adults had dental caries (2,3). The socioeconomic impact is substantial, as dental caries significantly burdens healthcare resources and adversely affects the quality of life for those affected (4). Addressing this issue requires a shift from reactive treatments to a proactive approach focusing on risk-based care and prevention to halt disease progression before irreversible damage occurs (5).

Known key risk factors for dental caries involve sociobehavioural and individual factors, as outlined in Petersen's model, which highlights distal socioeconomic determinants (e.g., low education, income disparities) and proximal behavioural risks (e.g., frequent sugar intake, poor oral hygiene) (6). Lower educational attainment is associated with a higher prevalence of dental caries, underscoring education as a key socioeconomic determinant influencing oral health outcomes (7). This association may be attributed to factors such as reduced health literacy, limited access to preventive dental services, and fewer opportunities for health-promoting behaviours among individuals with lower education levels (8). Other than risk factors like socioeconomic determinants and individual behaviours, Petersen's model also identifies additional contributors to dental caries, including environmental risk factors, access to oral health services, ethnic influences, social support networks, and lifestyle choices such as tobacco and alcohol use (6).

Dental caries generates measurable socioeconomic losses that extend well beyond the dental chair. A recent global cost of illness study estimated total worldwide economic impacts of oral conditions at $710 billion USD in 2019, of which $387 billion USD were direct treatment costs and the remainder productivity losses and informal-care costs (9). In the United States, adults forfeit approximately 92 million work hours each year to unplanned, pain driven dental visits, translating into billions of dollars in lost earnings and employer productivity (10). In addition to financial pressures, active caries negatively impacts oral health-related quality of life. Adults with untreated carious lesions report significantly higher Oral Health Impact Profile-14 (OHIP-14) handicap scores, which reflect pain, functional limitations, and psychosocial distress, compared to their caries-free counterparts (11). These converging economic and quality of life burdens provide a clear rationale for pinpointing modifiable caries determinants: by elucidating the behavioural, environmental and socioeconomic factors that concentrate disease risk, the present review lays the groundwork for precision prevention strategies and for AI enabled risk models that can triage resources toward the adults most likely to benefit.

Comprehensive Caries Risk Assessment (CRA) tools are pivotal in identifying individuals at higher risk and guiding preventive interventions that address underlying factors rather than relying solely on treatments (5). However, current CRA tools are often limited in adaptability for widespread application, especially in adult populations, highlighting the need to validate specific risk factors for practical use in diverse groups (12). Identifying risk factors specific to adults is crucial to developing screening tools that can be reliably used at a population level (13).

To overcome these limitations in traditional CRA tools, AI rapidly transforms dentistry through machine learning and data analytics advancements (14). It enhances diagnostic accuracy, treatment planning, and patient management by identifying complex patterns in large datasets (15). A systematic review by Luke et al found that AI achieves accuracy rates ranging from 73.3% to 99% in caries detection, highlighting its potential to reduce diagnostic errors compared to human assessments (16). Additionally, AI streamlines administrative processes and boosts patient education, marking a significant shift in dental practice (14).

Addressing caries risk in adults is essential due to unique factors such as diabetes, medication-induced dry mouth, and lifestyle habits like smoking and diet (17). These complexities require specific predictive variables for accurate assessment(18). While existing tools often apply to all age groups, Artificial Intelligence (AI) models tailored for adults can leverage comprehensive datasets, such as electronic health records, to improve precision (19). By developing an AI tool specifically for adults, we can respond to the World Health Organization's call for age-specific strategies to tackle the global issue of untreated caries among this population (20).

Traditional CRA models often include fluoride exposure, oral hygiene habits, and dietary patterns (12). Yet, these models do not always account for the temporality required for strong predictive validity, as risk factors should ideally be validated through longitudinal studies to ensure they reliably indicate future caries risk over time (21). This focus on temporality would enhance the accuracy and relevance of CRA tools for population-based screening by confirming that risk factors reflect causative, rather than merely correlative, relationships (22).

In this systematic review, we analyze caries risk factors pertinent to adults, emphasizing those crucial for developing a robust CRA tool suitable for large-scale screening. By evaluating factors for their predictive validity, which refers to their capability to reliably forecast caries risk over time, along with their practicality and scalability, this research aims to enhance CRA tools with a focus on integrating AI-assisted algorithms. AI can enhance predictive accuracy and personalize risk assessments by processing large datasets, identifying complex patterns, and adjusting risk models based on individual characteristics (5). These AI-driven tools could enable a more precise, real-time, and scalable population-based CRA tool (22).

This study aims to identify the key risk factors for caries, which are essential for developing AI-assisted CRA tools. These tools would enhance dental public health by promoting AI-driven preventive strategies that account for the complex and multifactorial nature of caries.

METHODOLOGY

Design

This systematic review adheres to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) guidelines and is registered with the International Prospective Register of Systematic Reviews (PROSPERO) at the University of York (CRD42023460116), ensuring transparency and methodological rigor. Using PICOC criteria, we focused on: Population: adults aged 18 years and above; Intervention: factors contributing to caries development; Comparison: no specific comparison group; Outcome: caries incidence and progression; Context: population-based screening tools. The primary objective is to identify caries risk factors to support the development of AI-assisted population-based screening tools.

Search methods

To identify relevant studies, an extensive search was conducted across PubMed (28 November 2023), Google Scholar (28 November 2023), Web of Science

(25 November 2023), and Scopus (19 September 2023) databases, with no restrictions on publication date to ensure comprehensive coverage. Keywords were chosen based on specific terminologies, including "Adults," "Caries risk factors," "Dental caries risk," "Population based screening tools," and "Caries risk assessment tools," among others. Boolean operators 'AND' and 'OR' were applied to refine search queries for precision and to expand the breadth of relevant literature. Additionally, reference lists from selected papers were reviewed for further relevant studies, ensuring thorough coverage of available data. Mendeley and Microsoft Excel software were utilized to organize, deduplicate, and screen the identified studies.

Search outcome

Study selection followed rigorous inclusion and exclusion criteria. This review included prospective/longitudinal cohort studies and randomised controlled trials (RCTs) with adult participants (aged 18 and above) focused on caries risk factors, without restricting by publication year to capture historical and contemporary evidence. Studies had to involve at least one risk factor. Following recommendations by Mejare et al.,(13) included studies were required to provide clear definitions of study sample and population while excluding those with unclear methodologies or populations under 18. Specific criteria were set to identify factors that are cost-effective, minimally invasive, and practical for large-scale population screening, following guidelines by Cheryl Herman (23).

Quality appraisal

Two reviewers independently assessed each study's risk of bias using the ROBINS-E tool (Risk of Bias in Non-Randomized Studies – of Exposure), which evaluates seven domains: confounding, exposure measurement, participant selection, post-exposure interventions, missing data, outcome measurement, and selection of reported results. Discrepancies were resolved through discussion and consultation with additional reviewers to ensure a thorough evaluation. To assess evidence quality, we applied the GRADE (Grading of Recommendations Assessment, Development and Evaluation) framework, categorizing evidence into High (⊕⊕⊕⊕), Moderate (⊕⊕⊕O), Limited (⊕⊕OO), and Insufficient (⊕OOO) levels. This structured approach enabled a systematic, transparent assessment of evidence reliability for each outcome, ensuring consistency in evaluating study findings.

Data extraction

Data extraction was conducted systematically by two independent reviewers using standardized Excel spreadsheet forms (kappa = 0.88). Information collected included study characteristics (e.g., title, authors, publication year, country of origin), methodology (study design, sample size, age groups), as well as risk factors assessed, main findings, and response rates. To ensure consistency and accuracy, the abstraction process was verified through secondary checks by all reviewers.

Data synthesis

The data synthesis involved reviewing the findings from all included studies to identify patterns and draw conclusions regarding caries risk factors suitable for population-based screening tools. The synthesis followed a transparent and methodical approach to ensure the study's outcomes were clearly reported. The synthesis involved combining thematic analysis with evidence prioritisation to identify risk factors for caries relevant to AI-assisted screening tools. Initially, findings from cohort studies were categorised into four themes: behavioural, environmental, socioeconomic and biological, in accordance with Petersen's distal-proximal risk framework. Consistent factors, such as sugar intake and low income, were prioritised based on their recurrence across studies, the strength of their association, and their feasibility for population-level screening (including cost effectiveness and non-invasiveness). These criteria were guided by Cheryl Herman (23) and ensured that the selected variables were measurable at scale, such as dietary habits and access to fluoridation.

RESULTS

The final analysis encompasses a total of 12 studies. Of these, eight (66.7%) were published between 2010 and 2019 (1,24–30), and a smaller proportion (16.7%) before 1999 (31,32). Geographically, Europe (1,25–27,29–31,33) contributed the majority (66.7%), with North (32,34) and South America (24,28) each representing 16.7%. Nearly half of the studies (41.7%) included over 1,000 participants at baseline (1,25,26,28,30), and 75% focused on exposure periods of less than and equal to nine years (1,24,27–30,32–34). This systematic review offers a comprehensive analysis of adult caries risk factors, crucial for developing a population-based CRA tool.

Figure 1 outlines the study selection process using a PRISMA flow diagram. A total of 60,042 records were identified across multiple databases, with 67 duplicates removed. After screening titles and abstracts, 59,855 records were excluded by human reviewers, leaving 187 reports for full text retrieval. Fourteen reports were inaccessible, and 173 were assessed for eligibility. Of these, 117 were excluded for non-prospective designs, 22 for underage populations, 9 for factors unsuitable for population-based screening, and 13 for lacking caries risk factor analysis. Ultimately, 12 studies met all the inclusion criteria and were included in the review.

Characteristics of the included studies

Table I summarizes the characteristics of 12 included studies examining risk factors for dental caries in adults. The studies, comprising prospective cohort designs only without randomized controlled trials, evaluated

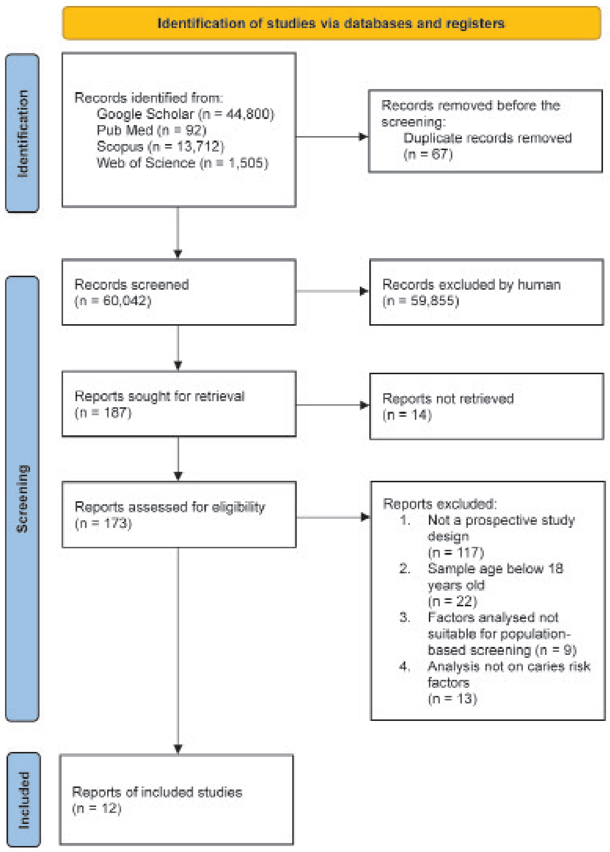

Figure 1: PRISMA flow chart displaying the selection process.

predictors such as smoking, diabetes status, fluoride access, education level, sugar intake, bacterial plaque, and socioeconomic factors, with observation periods ranging from 1.5 to 15 years. Key outcomes included statistically significant associations, such as smoking increasing caries risk by 1.5 times, poorly controlled diabetes elevating DMFS progression rates (0.716 surfaces/year), and low education increasing caries incidence (IRR 1.41). The quality of evidence varied, with most studies rated moderate (□□□O) due to robust methodologies but limitations like residual confounding or small sample sizes, while others scored high (□□□□) or limited (□□OO).
Table I. Characteristics of the included studies

Behavioural Risk Factors

Behavioral factors emerged as key contributors to caries risk, underscoring the impact of modifiable lifestyle choices. Daily smoking and sugar sweetened beverage (SSB) consumption, in particular, demonstrated a strong dose response relationship with caries increment (1,27). Smoking is associated with elevated risk ratios (RR), particularly in those smoking over 20 cigarettes daily, due to its impact on saliva production, microbial environment, and immune response all contributing to higher caries susceptibility (27). SSB consumption was also significantly impacted, with frequent consumers facing a 30-33% increased caries risk (1). The acidic environment fostered by high sugar intake promotes

Table I. Characteristics of the included studies.

No.	Study	Observation time (Years)	Possible predictors of risk assessed	The outcome of the final model	Quality of evidence
1	Tobacco use and caries increment in young adults: a prospective observational study (29)	3	Impact of smoking and snuffing	Smoking, but not snuffing, displayed a statistically significant relationship with caries. For smoking, the relative risk was 1.5 (95% CI 1.2—1.7), and the number needed to harm was 6.8 (95% CI 4.5—14.2).	Moderate (⊕⊕⊕O) The study's longitudinal design and large sample size support the association between smoking and caries, but a lack of control over confounding variables could weaken the evidence. The study's concentration on Swedish young adults may limit its generalizability, and the observed effect size of 1.5 may lessen the significance of the evidence.
2	Diabetes status affects long-term changes in coronal caries - The SHIP Study (25)	11	Diabetes status (well-controlled diabetes, poorly controlled diabetes, no diabetes)	Only subjects with poorly controlled diabetes exhibited statistically significantly higher DMFS progression rates, at 0.716 surfaces per year for the DMFS index (95% CI 0.552 to 0.880), compared to subjects without diabetes.	High (⊕⊕⊕⊕) Evidence of a dose-response relationship between higher levels of fasting blood glucose and HbA1c and an increase in untreated caries further solidifies the impact of diabetes. The study's robust design and methodology, including a sizable population base, long-term follow-up, and rigorous statistical analysis, underscore the reliability of these findings, confirming the strong link between diabetes control and dental health.
3	Access to Fluoridated Water and Adult Dental Caries (28)	3	Access to fluoridated water is 50% to 75% and <50% of a participant's lifetime.	Specifically, individuals living less than 50% of their lifetime exposed to water fluoridation had a higher DMFT rate ratio, 1.39 (95% CI: 1.05–1.85).	Moderate (⊕⊕⊕O) The study finds a strong link between lifetime exposure to fluoridated water and adult dental caries. It shows that longer exposure is associated with lower rates of dental caries. Study limitations include a small sample size, the use of residential access as a proxy for individual exposure, and reliance on self-reported data for residential history. More extensive research with larger sample sizes and more precise measures is necessary to increase confidence in the findings.

CONTINUE

Table I. Characteristics of the included studies (continued)

No.	Study	Observation time (Years)	Possible predictors of risk assessed	The outcome of the final model	Quality of evidence
4	The Role of Behaviour in Inequality in Increments of Dental Caries among Finnish Adults (30) a nationally representative survey of 8,028 individuals aged 30 years or older living in mainland Finland. Four years later, 1,248 subjects were invited for oral re-examination, and 1,049 agreed to participate (84% response rate	4	Education level: -primary education, secondary education, and higher education.	The Incidence Rate Ratio (IRR) for net DMFT increment in the primary education group was 1.41 compared to the higher education group, 1.41 (95% CI: 1.07–1.85).	Limited (⊕⊕OO) Specific behaviours, such as tooth brushing with fluoride, frequency of sugar intake, dental attendance pattern, and daily smoking, were found to partially account for the association between education and the net DMFT increment. Notably, the association between education and DMFT increment became statistically non-significant when considering all behavioural variables together
5	The Shape of the Dose-Response Relationship between Sugars and Caries in Adults (26)as sugars are essential in the caries process. However, some gaps in knowledge about the sugars-caries relationship still need addressing. This longitudinal study aimed to explore 1	11	The amount of sugar intake (in grams per day)	The DMFT throughout the follow-up period increased by 0.15 (95% CI: 0.04 to 0.25) and 0.10 units (95% CI: 0.04 to 0.15) for every additional occasion of sugar consumption and every 10 g of sugars consumed, respectively.	Moderate (⊕⊕⊕O) The study found a linear dose-response relationship between sugar consumption and dental caries in adults. It used linear mixed effects models and a longitudinal design to minimise measurement errors. The research also considered fluoride toothpaste usage, reducing residual bias and confounding. This comprehensive methodology provides a reliable assessment of the relationship between sugar intake and adult dental caries.
6	Daily smoking and 4-year caries increment in Finnish adults (27)its effect on dental caries is less well known. This study assessed whether daily smoking predicts caries increment in adults over 4 years. Methods Data from 955 adults who participated in both the Health 2000 Survey and the Follow-Up Study of Finnish Adults' Oral Health were analysed. At baseline, participants provided information on demographic characteristics, education and dental behaviours. The 4-year net increment in the numbers of decayed (DT	4	Daily smoking status (categorised as 0, 1-19, and 20+ cigarettes per day)	Daily smokers had a rate 1.70 times (95% Cl: 1.07— 2.70) greater for the 4-year net DT increment than nonsmokers. In the fully adjusted model, consuming 20+ cigarettes/day had a rate of 2.00 times (95% Cl: 1.09—3.70) greater for the 4-year net DT increment than nondaily smokers. However, there were no differences between those consuming 1—19 cigarettes/day and nondaily smokers.	Moderate (⊕⊕⊕O) The study found that daily smokers had a 1.70 times greater rate of 4-year net decayed tooth increment compared to nonsmokers, and those consuming 20 or more cigarettes per day had a 2.00 times greater rate. The study also identified a dose-response relationship between tobacco consumption levels and the net increment in decayed teeth. The study aimed to address potential residual bias and confounding factors to enhance the internal validity of the findings.
7	Risk Score to Predict Dental Caries in Adult Patients for Use in the Clinical Setting (24)	1.5	Bacterial plaque/calculus) restorations with more than five years > eight teeth restored, presence of a systemic condition.	The presence of bacterial plaque/calculus (RR 4.1), the presence of restorations with more than five years (RR = 2.3), the presence of >8 teeth restored (RR = 2.0), history/active periodontitis (RR = 1.7) and the presence of a systemic condition (RR = 1.4).	Moderate (⊕⊕⊕O) The study has a moderate quality of evidence, with a C-statistic of 0.78, indicating its ability to distinguish high and low-risk individuals, and its design, control for confounders, transparency, and external validation.
8	Risk Indicators for Third Molar Caries and Periodontal Disease in Senior Adults (34)	3	Level of education and smoking status.	Odds for third molar caries experience were more than doubled if subjects were Caucasian (OR 2.5; 95% C', 1.4, 4.3), at least a high school graduate (OR 2.1; 95% Cl, 1.2, 3.8) or denied tobacco use (OR 2.3; 95% Cl, 1.1, 4.4).	Limited (⊕⊕OO) The study's GRADE score is limited due to the absence of a dose-response relationship between risk factors and third molar caries in senior adults. Despite attempts to address biases, the study faces challenges in countering residual bias and confounding factors due to the complexity of oral health conditions for the elderly. The findings are also contrary to the common understanding.
9	Factors of importance for changes in dental caries among adults: A follow-up study of Oslo citizens from the age of 35 to 50 years (31)	15	Use of fluoride and tooth cleaning frequency.	Psychological status (Beta Coefficient: 0.340), fluoride use (Beta Coefficient: 0.282), and tooth cleaning frequency (Beta Coefficient: 0.263) are the key predictors of caries progression in adults. Poor psychological health increases the risk of dental caries, while regular fluoride use and good oral hygiene support stable or improved dental health.	Moderate (⊕⊕⊕O) The study explores factors influencing dental caries among adults, revealing significant reductions in various surfaces over 15 years. Behavioural factors significantly impact dental health. However, the study acknowledges that not all significant variables have been disclosed, suggesting unaccounted variables could impact the accurate effect estimate. Due to the need for further research, overall confidence in the evidence is moderate.

CONTINUE

Table I. Characteristics of the included studies (continued)

No.	Study	Observation time (Years)	Possible predictors of risk assessed	The outcome of the final model	Quality of evidence
10	Effect of Residence in a Fluoridated Community on the Incidence of Coronal and Root Caries in an Older Adult Population (32)	1.5	Time spent in fluoridated communities	The relative risk for people who lived in fluoridated communities for 30 years or more was 0.80 or less.	Moderate (⊕⊕⊕O) The study found that residents of fluoridated communities with extended residence periods have a reduced risk of developing new coronal caries compared to nonfluorinated communities. This is due to the protective effect of prolonged exposure to fluoridated water. The study's moderate quality of evidence is supported by the homogeneity of the population and similar baseline characteristics between fluoridated and nonfluorinated communities. Using statistical analyses and the dose-response relationship between residence duration and caries risk further supports this causal link.
11	Classification of a patient's caries activity based on lesion activity assessment among adults: findings from a prospective cohort study (33)	4	Caries-active	Caries-active individuals were 26% more likely to present DMFS increment than caries-inactive ones when migrations among DMFS components were considered (IRR [incidence risk ratio] = 1.26, 95%Cl [confidence interval] = 1.01—1.58). Additionally, the risk for coronal Caries progression on filled surfaces was 90% higher among caries-active patients IRR = 1.9 (95% CI: 1.4–2.6).	Moderate (⊕⊕⊕O) The study's overall quality is moderate, with a large sample size and rigorous sampling strategy enhancing its representativeness. The study's clinical examination protocol ensures reproducibility, improving reliability. The effect sizes show moderate to significant effects, indicating a strong association. However, the absence of detailed information on a dose-response relationship and potential confounders introduces uncertainty. The actual effect is likely close to the estimate but may differ substantially due to these limitations.
12	Sugar-sweetened beverages and dental caries in adults A 4-year prospective study (1)participants provided information on demographic characteristics, education and dental behaviours, including two questions on frequency of SSB consumption. The 4-year net DMFT increment was calculated using data from baseline and follow-up clinical oral examinations. The association was tested in negative binomial regression models and the moderating role of sex, age, education and use of fluoride toothpaste was examined by adding their two-way interaction with SSB consumption to the main effects model. Results A positive association was found between frequency of SBS consumption and 4-year net DMFT increment, regardless of participants' socio-demographic and behavioural characteristics. Adults drinking 1-2 and 3+ SSB daily had, respectively, 31% (Incidence Rate Ratio: 1.31; 95%CI: 1.02-1.67	4	Frequency of consumption of sugar-sweetened beverages (SSB)	Adults who consumed 1-2 SSB daily showed a 1.31 times higher rate (95%CI: 1.02–1.67) of 4-year net DMFT increment compared to non-SSB drinkers. Similarly, those who consumed 3+ SSB daily had a 1.33 times higher rate (95%CI: 1.03–1.72) of 4-year net DMFT increment than individuals who did not consume SSB at baseline.	High (⊕⊕⊕⊕) The study on sugar-sweetened beverage (SSB) consumption and adult dental caries provides high-quality evidence. The research used a prospective study design to establish temporal relationships. It controlled for confounding variables, ensured reliable outcome assessments through standardised measurements, and employed rigorous data analysis. Identifying a dose-response relationship between SSB consumption frequency and dental caries further strengthens the evidence. Overall, the study offers valuable insights into the impact of SSB consumption on adult dental health.

acidogenic bacterial growth, leading to enamel demineralization (1). Together, these findings underscore the importance of focusing on lifestyle modifications in AI-assisted CRA tools, particularly in communities with high smoking or sugary beverage consumption.

Environmental Risk Factors

Environmental exposure to fluoride stood out as a highly protective factor, affirming its critical role in public health interventions. Individuals with less than 50% lifetime exposure to fluoridated water exhibited higher caries rates, with a risk ratio of 1.39 for decayed, missing, and filled teeth (DMFT) increments (28). Fluoride enhances enamel resistance to acid attack, reducing caries susceptibility over time (28). Higher lifetime fluoride exposure correlated with fewer coronal and root caries, strongly supporting public health initiatives for water fluoridation (32). Integrating fluoride exposure as a factor in CRA tools allows clinicians to account for this preventive measure in CRA, especially in regions with varied access to fluoridated water (35).

Socioeconomic Risk Factors

Socioeconomic factors, significantly correlate with caries risk, primarily through their influence on health behaviors (30). Lower socioeconomic status (SES) and limited education correlate with higher rates of smoking, poorer oral hygiene practices, and less access to regular dental care, all of which contribute to increased caries risk (30). While SES itself is not a direct causative factor, it plays an essential role in shaping behaviors that elevate caries susceptibility (30). Including SES indicators as predictors in CRA tools is therefore valuable, as they provide a comprehensive understanding of an individual's risk profile (22). By incorporating SES into CRA models, we can better identify individuals at higher risk and direct preventive resources more effectively, addressing the social determinants of health that impact dental outcomes (36).

Biological Risk Factors

Biological factors, particularly poorly controlled diabetes, were significant predictors of caries progression (25). Poor glycemic control exacerbates caries risk through multiple mechanisms, such as compromised immune response, altered saliva composition, and heightened bacterial proliferation (25). Annual DMFS (decayed, missing, and filled surfaces) increments were substantially higher among adults with uncontrolled diabetes, indicating a need for integrated diabetes and dental care management (25). Including diabetes as a risk factor in CRA tools enables clinicians to identify high risk individuals who may benefit from enhanced preventive strategies targeting both metabolic and dental health (24).

Periodontal history and psychological status were excluded from the final AI-assisted CRA tools despite their potential influence on caries risk (24,31). Periodontitis and caries, though often coexisting, involve distinct pathological processes; periodontitis arises from inflammatory responses in tooth supporting structures, while caries is driven by bacterial demineralization of tooth surfaces (34). Furthermore, assessing periodontal disease requires resource intensive clinical evaluation, making it impractical for population level screening (23). Similarly, while psychological factors impact oral health behaviors indirectly through diet, oral hygiene, and dental visit frequency, measuring these factors consistently at a population level is challenging (31). Excluding these variables enhances the AI-assisted CRA tool's practicality for broad scale screening initiatives (23).

Moss et al., 2007 (34) present with contrasting findings, highlighting how race, education, and tobacco use influence caries risk. They found that Caucasians, highly educated individuals, and non-smokers were more likely to develop caries in their third molars, a trend that diverges from the broader patterns observed here (34). This discrepancy may be due to differences in study populations and factors affecting older adults, such as higher education correlating with greater retention of third molars, increasing caries risk (37). Additionally, smoking may reduce caries risk by accelerating tooth loss due to periodontal issues, thereby reducing the likelihood of caries in retained molars (38).

Figures 2 highlight the variability and strength of associations across caries risk factors, as reflected in their effect sizes and confidence intervals. Notably, the confidence intervals (CIs) for most risk factors are relatively narrow, indicating a high level of precision in the estimates. For instance, daily smoking (IRR 1.70 [1.07–2.70]) and high tobacco consumption (IRR 2.00 [1.09–3.70]) show well defined, significant associations with increased caries risk, albeit with slightly wider CIs due to variability in study populations. The consistent direction of the associations across all factors indicated by all IRRs being above 1 enhances the validity of the identified risk factors. These findings highlight the robustness of the analysis and emphasize the balance between precision and variability in synthesizing evidence for predicting caries risk.

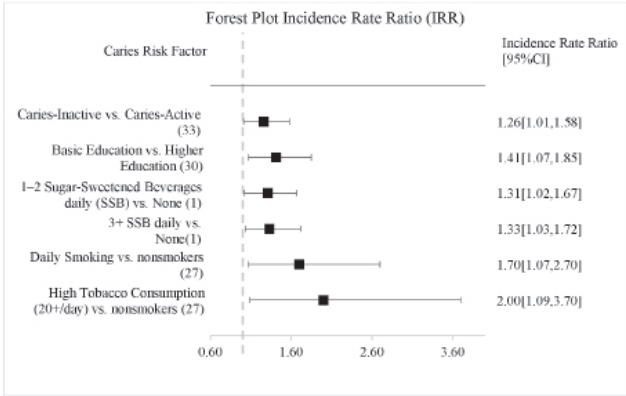

Figure 2: Forest plot incidence rate ratio (IRR)

Risk of Bias

Figures 3 summarise the risk of bias assessments for the studies included. Information for individual studies is provided in the supplementary document. Overall, three studies were rated as having a low risk of bias (1,24,25) and nine studies had some concerns (26–33,39).

Most studies exhibit a mix of low and some concerns across various domains. Notably, Moss et al. (34) reveal a high risk of bias in the domain of missing data (D5).

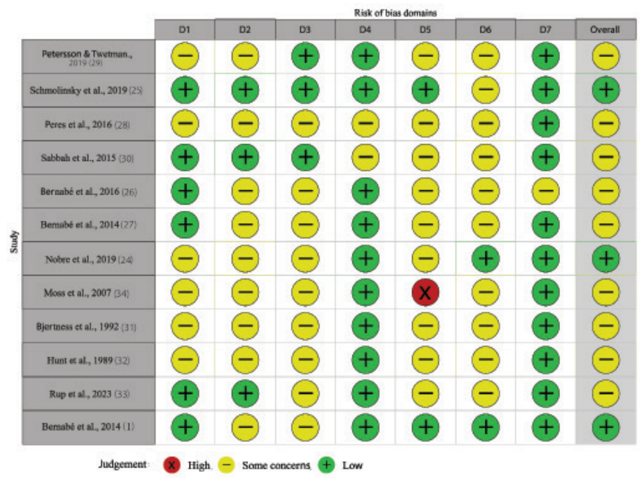

Figure 3: Traffic light plot of risk of bias assessments for 12 observational studies.

This elevated risk stems from inadequate reporting on missing data management, which may introduce bias. Their analysis considered clinical data from 810 dentate participants; however, only 340 subjects with visible third molars were evaluated for caries experience. This lack of clarity in addressing missing data could significantly affect the study's findings, thereby increasing the risk of bias in assessing the relationship between exposure and outcome.

Risk-of-bias domains:
D1: Bias due to confounding.
D2: Bias arising from measurement of the exposure.
D3: Bias in selection of participants into the study (or into the analysis).
D4: Bias due to post-exposure interventions.
D5: Bias due to missing data.
D6: Bias arising from measurement of the outcome.
D7: Bias in selection of the reported result.

DISCUSSION

This systematic review highlights critical behavioural, environmental, socioeconomic, and biological factors influencing adult caries risk, offering a valuable foundation for designing an AI-assisted CRA tool (36). The tool's emphasis on modifiable, high impact risk factors aligns with the public health focus on preventive care, facilitating proactive, large scale interventions (40). In the context of previous research, the findings are consistent with established evidence that behavioral factors like smoking and sugar consumption are central predictors of caries risk, while environmental factors such as fluoride exposure provide substantial preventive effects (17). These findings align with broader evidence indicating that systemic health, SES, and environmental determinants significantly influence oral health outcomes (41). The review further underscores the importance of integrating these factors into a robust AI-assisted CRA tool to address caries risk proactively (40).

Petersen's conceptual model offers a well-established framework for understanding the risk factors associated with dental caries by categorizing them into distal (upstream societal) and proximal (direct behavioural) influences(6). Aligning with the findings of this systematic review, this model has demonstrated robustness and wide applicability. Over the past decade, it has frequently been utilized in oral health research, underscoring its credibility. For instance, national oral health surveys and epidemiological studies in Saudi Arabia have adapted Petersen's World Health Organization (WHO) model as a foundation for analyzing population-wide dental data (42,43). The consistent use of this model in peer-reviewed studies confirms its reliability and conceptual soundness for examining caries risk across different settings.

The proposed AI-assisted CRA tool offers a significant advantage due to its scalability and feasibility, effectively addressing the resource and skill limitations of traditional CRA tools while balancing predictive accuracy and user friendliness for diverse healthcare settings with varying levels of resources (12). Unlike traditional tools, which rely on highly trained clinicians for accurate risk assessments, AI-assisted tools leverage complex algorithms to analyze risk factors, enabling dental nurses or other support staff to conduct screenings effectively (44). This redistribution of tasks reduces dependency on specialists, making large scale implementation feasible even in resource limited settings (45). Additionally, the AI component provides instant, data driven patient risk evaluations, facilitating efficient screening and early intervention (46). By emphasizing easily assessed factors that directly impact caries progression, the tool ensures preventive care can be extended to underserved communities, contributing to health equity and aligning with global public health goals (47).

Our findings support and extend prior research emphasizing the critical role of lifestyle and environmental exposures in caries prevention (41). Smoking and SSB consumption were repeatedly linked to caries progression, echoing evidence from other studies showing dose response relationships between these behaviors and oral health outcomes (21). Smoking contributes to caries risk by affecting saliva production, microbial balance, and immune responses, while frequent SSB intake fosters acidogenic bacterial growth, increasing demineralization (1,48). In line with this evidence, including these factors in CRA tools provides targeted entry points for lifestyle interventions in both clinical and public health settings (49).

Similarly, fluoride exposure consistently demonstrated protective effects, supporting established policies promoting water fluoridation (50). Individuals with lower lifetime fluoride exposure showed higher caries incidence, consistent with evidence on fluoride's role in strengthening enamel and reducing susceptibility to acid attacks (51). By incorporating fluoride exposure in CRA tools, our findings align with the global consensus on the preventive benefits of fluoride and support its inclusion in population based health strategies (52).

Caries history emerged as a substantial predictor of future caries risk, underscoring its role in CRA tools for identifying high risk individuals (33). Previous studies show that past caries experience is a strong indicator of susceptibility, as individuals with a caries history are likely to have behavioral, biological, or environmental factors that persist over time, contributing to further disease progression (53). Integrating a history of caries into CRA tools emphasizes the significance of proactive dental care by enabling clinicians to monitor and intervene early, which aligns with preventive healthcare trends aimed at reducing recurrence and enhancing long-term oral health outcomes (40).

Although Moss et al. (34) demonstrated a high risk of bias in the domain of missing data (D5) due to inadequate reporting on handling missing third molar data, the overall risk of bias for this study remained "some concerns" when accounting for other domains. Although this limitation creates uncertainty regarding the caries risk relationship, the quality of evidence is limited rather than insufficient since the Moss et al. (34) study's key predictors of low education and smoking status are consistent with results from higher quality studies (27,29,30). For example, studies by Bernabй et al (27) and Petersson et al (29) similarly identified education and smoking as significant caries risk factors, reinforcing the plausibility of these associations despite methodological weaknesses of Moss et al. (34) .

Most studies exhibited mixed risk of bias profiles (low/some concerns across domains), reflecting challenges such as residual confounding or incomplete outcome data. Nevertheless, the consistency of findings across studies, especially regarding socioeconomic and behavioural (such as smoking) factors, enhances the credibility of the review's conclusions. These predictors were repeatedly identified as impactful across diverse populations and study designs, mitigating concerns about individual study biases. Nonetheless, the limited quality of evidence for certain associations underscores the need for caution in interpreting isolated results and highlights opportunities for future research to address gaps in reporting and methodology.

Despite these findings, several limitations in the evidence are notable. Variability in study design, demographics, and outcome measures, including DMFS, DMFT, and net decayed tooth increment, introduces heterogeneity that may impact the consistency of results across diverse populations (54). Most studies were conducted in Europe, limiting the generalizability of findings to other regions with different socioeconomic and environmental contexts (55). Moreover, while education was considered, the lack of direct assessment of income level may underestimate the broader influences of SES (56). These issues highlight the need for future research to include more diverse populations and standardized outcome measures for improved clarity and comparability.

We assessed heterogeneity qualitatively, noting that the included studies varied in observation periods, predictor variables, study populations, and outcome measures. Observation periods varied from 1.5 to 15 years; shorter studies typically focused on biological factors, while longer follow ups examined behavioral factors. Predictor variables also differed, with some studies evaluating single factors (e.g., smoking, sugar intake) and others analyzing multivariate models encompassing systemic conditions, fluoride exposure, and education level. Study populations varied geographically and demographically, with age, health status, and socioeconomic backgrounds contributing to potential variability in findings. Outcome measures included DMFS, DMFT, and net decayed tooth increment, each capturing unique aspects of caries progression. This qualitative assessment provides context for interpreting pooled findings but does not quantify heterogeneity statistically.

The findings from this review offer critical insights into clinical practice, public health policy, and future research. In clinical practice, incorporating identified risk factors into AI-assisted CRA tool enables a focused approach to prevention (40). Clinicians can evaluate caries risk by addressing modifiable behaviors like smoking and SSB consumption through personalized counseling (12). This empowers health professionals to provide tailored support that motivates patients to change behaviors, ultimately enhancing oral health outcomes (17).

From a public health perspective, the review emphasizes the vital role of fluoride in prevention. By recognizing fluoride exposure as a key risk factor in CRA tool, the importance of advocating for water fluoridation policies becomes apparent (50). In areas lacking fluoridated water, CRA tool can inform community fluoride initiatives and help prioritize dental care interventions for at risk populations (40). Furthermore, addressing socioeconomic factors, particularly education level, is crucial in caries prevention (12). CRA tool that pinpoint SES related behaviors allow public health programs to direct resources toward high risk groups with targeted educational campaigns and affordable preventive options (57). This method ensures fair access to care, leading to better oral health outcomes in various communities (58).

Recommendations

In terms of future research, the findings underscore the importance of standardizing study methodologies to reduce heterogeneity. Future studies should aim to use consistent outcome measures, such as the DMFT or DMFS index, to improve comparability across studies. Additionally, further research should focus on diverse populations and explore how different socioeconomic conditions influence caries risk in varied cultural and environmental settings. Longitudinal studies that validate these risk factors over time are essential to confirm the temporal predictive value of factors such as diabetes, fluoride exposure, and smoking. Furthermore, the integration of CRA tools into digital health platforms presents a promising area of exploration, allowing real time tracking of risk factors and providing clinicians and patients with personalized preventive guidance (59).

CONCLUSION

This systematic review highlights the transformative potential of an AI-assisted CRA tool focused on validated, modifiable risk factors in adults, advancing caries management toward proactive, preventive care. Key findings emphasize the importance of behavioral modifications, particularly reducing smoking and SSB consumption, and support the inclusion of fluoride exposure in preventive strategies, reinforcing its protective role. Addressing socioeconomic barriers and incorporating systemic health factors, like diabetes, into CRA assessments allows for a more equitable and integrated approach to dental health. By prioritizing these evidence-based, actionable factors, an AI-assisted CRA tool can be widely implemented across healthcare settings, enabling clinicians, policymakers, and public health programs to target caries prevention effectively, ultimately reducing caries incidence and promoting broader health improvements.

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