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Pediatric Dental Care: Prevention and Management Protocols Based on Caries Risk Assessment: A Systematic Review and Meta-Analysis

Avin Mohammadi
School of Dentistry, Tehran Azad University of Medical Sciences, Tehran, Iran

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ABSTRACT

Background: Dental caries remains the most prevalent chronic disease-affecting children globally, with early childhood caries (ECC) disproportionately impacting underserved populations despite being largely preventable. Caries risk assessment (CRA) tools have developed to stratify patients and guide preventive interventions, yet the evidence base for their predictive validity and the comparative effectiveness of risk-based management protocols remains fragmented.

Objectives: This systematic review and meta-analysis aimed to (1) evaluate the predictive performance of existing CRA tools for future caries development in children, (2) assess the clinical effectiveness of prevention and management protocols stratified by caries risk category, and (3) quantify the comparative efficacy of individual preventive interventions including fluoride varnish, silver diamine fluoride (SDF), and fissure sealants.

Methods: A comprehensive literature search conducted in PubMed, Cochrane Library, Embase, Web of Science, and Scopus from inception to March 2026. Randomized controlled trials and prospective cohort studies evaluating CRA tools or risk-stratified preventive protocols in children aged 0-18 years were included. Risk of bias assessed using the Prediction Model Risk of Bias Assessment Tool (PROBAST) and Cochrane RoB 2.0 tool. Meta-analyses performed using random-effects models.

Results: Thirty-eight studies (n=47,832 participants) met inclusion criteria. Meta-analysis of six CRA models demonstrated moderate discriminatory performance (pooled AUC: 0.79, 95% CI: 0.73-0.84) with significant heterogeneity (I^2=78%). All CRA models exhibited high risk of bias per PROBAST criteria. For preventive interventions, SDF demonstrated superior caries arrest rates compared to placebo (RR: 2.34, 95% CI: 1.78-3.08) and fluoride varnish (RR: 1.42, 95% CI: 1.12-1.79). Fissure sealants showed higher caries prevention efficacy than fluoride varnish over 36 months (RR: 0.68, 95% CI: 0.54-0.86).

Conclusions: Current CRA tools show modest predictive accuracy with significant methodological limitations. Risk-stratified protocols incorporating SDF for high-risk children and sealants for permanent molars supported by moderate-quality evidence. Future research must prioritize external validation of prediction models, standardized outcome reporting.

Introduction

Dental caries recognized as the most common chronic disease of childhood, affecting an estimated 530 million children worldwide in primary dentition alone [1].

Despite dramatic improvements in oral health outcomes in many high-income countries over recent decades, caries prevalence remains alarmingly high among preschool and school-aged

Corresponding Author: **Avin Mohammadi (avinmohammadi1374@gmail.com)*

children, particularly those from low socioeconomic backgrounds and racial/ethnic minority groups [2].

The global prevalence of dental caries in permanent teeth reported to affect approximately 2.3 billion individuals in 2017, with an additional 500 million children experiencing caries in their primary dentition. These figures underscore the persistent public health challenge posed by a condition that is, in principle, almost entirely preventable [3].

The consequences of untreated childhood caries extend far beyond the oral cavity. Children with severe early childhood caries (ECC) experience significant pain, infection, difficulty eating and sleeping, impaired growth and nutritional status, speech development problems, and reduced quality of life comparable to other chronic childhood conditions. The psychosocial impacts are equally profound, including diminished self-esteem, social stigmatization, and increased school absenteeism with affected children missing an estimated, 3-5 times more school days than their caries-free peers do. The economic burden on families and healthcare systems is substantial; dental treatment under general anesthesia for young children with severe ECC represents one of the most common day-surgery procedures in many countries, with costs per case often exceeding $5,000-10,000 USD.

The paradigm shifts from traditional "drill and fill" dentistry to a preventive, risk-based approach represents one of the most significant conceptual advances in pediatric dental care over the past three decades. This model recognizes that caries is not inevitable consequence of tooth eruption but rather a dynamic, multifactorial disease resulting from an ecological imbalance in oral biofilm driven by frequent sugar consumption and inadequate fluoride exposure. Central to this paradigm is the recognition that caries risk varies substantially among individuals and that prevention and management stratified accordingly intensive interventions reserved for high-risk children while lower-risk children receive standard preventive care. Caries risk assessment (CRA) tools have developed to operationalize this approach, providing structured frameworks for clinicians to evaluate biological, behavioral, and social determinants of disease.

Several CRA systems have achieved widespread clinical adoption. The Cariogram, developed at the Malmo University, employs a computerized algorithm incorporating nine risk factors to generate a graphical representation of caries risk. The Caries Management by Risk Assessment (CAMBRA) system, developed at the University of California San Francisco, provides a structured approach to identifying risk factors and protective factors, with corresponding clinical protocols stratified by risk category. The American Academy of Pediatric Dentistry (AAPD) and American Dental Association (ADA) have also promulgated CRA tools designed specifically for use in children and adolescents. Despite their clinical popularity, the evidence base supporting these tools has repeatedly questioned. A 2013 systematic review by Tellez and colleagues concluded, "the evidence on the validity for existing systems for CRA is limited" and that "it is unknown if the identification of high-risk individuals can lead to more effective long-term patient management".

Concurrent with the development of risk assessment tools, the preventive armamentarium has expanded substantially. Topical fluoride interventions, including professionally applied fluoride varnish (FV) and fluoride toothpaste, remain the cornerstone of caries prevention. More recently, silver diamine fluoride (SDF) has emerged as a transformative agent, offering both caries arrest and prevention properties in a simple, low-cost, non-aerosolizing application that is particularly suitable for young or uncooperative children and those with special healthcare needs. Fissure sealants, applied to the occlusal surfaces of permanent molars, provide a physical barrier preventing bacterial colonization in deep pits and fissures. Understanding the comparative effectiveness of these interventions, how they deployed based on risk stratification is essential for evidence-based clinical practice and health policy [4].

The purpose of this systematic review and meta-analysis is to synthesize the highest-quality evidence on three interlocking questions:

- ✓ What is the predictive validity of existing CRA tools for identifying children at elevated risk for future caries development?
- ✓ What is the clinical effectiveness of prevention and management protocols when stratified by caries risk category?
- ✓ What is the comparative efficacy of individual preventive interventions including fluoride varnish, SDF, and fissure sealants in reducing caries incidence and arresting lesion progression?

Literature Review

The scholarly literature on caries risk assessment and risk-based prevention in pediatric dentistry spans more than four decades, yet fundamental questions about predictive validity and clinical effectiveness remain incompletely resolved. This review synthesizes evidence across three domains: the development and validation of CRA tools, the effectiveness of specific preventive interventions, and the emerging evidence for minimal intervention dentistry (MID) protocols [5].

Caries Risk Assessment Tools: Development and Validation

The theoretical foundation for CRA rests on the recognition that caries influenced by multiple interacting factors that vary across individuals and over time. Early risk assessment approaches relied heavily on previous caries experience the single strongest predictor of future caries but increasingly sophisticated tools incorporate biological markers (salivary flow and buffering capacity, mutans streptococci counts), behavioral factors (tooth brushing frequency, fluoride exposure, dietary sugar intake), and social determinants (parental education, household income, access to dental care) [6].

The most extensively studied CRA tool is the Cariogram, which combines nine risk factors into a graphical representation of "chance to avoid new cavities". Its predictive performance has evaluated in multiple prospective cohorts. Tellez and colleagues' systematic review found that Cariogram's combined sensitivity and specificity for predicting caries in permanent dentition ranged from 110 to 139, with limited predictive utility in preschool children but moderate to good performance for sorting elderly individuals into caries risk groups. Importantly, the review noted that the Cariogram was "the only system for which prospective studies have been conducted to assess its validity," highlighting a critical evidence gap for other widely used tools [7].

Evaluations that are more recent have extended this evidence base. Wang and colleagues' 2025 systematic review and meta-analysis of 11 studies (n=11 included articles) found that all published caries prediction models demonstrated high risk of bias when assessed using the Prediction Model Risk of Bias Assessment Tool (PROBAST). The primary sources of bias were inappropriate statistical methods and unclear applicability resulting from insufficiently detailed model presentations. Reported area under the curve (AUC) values ranged from 0.57 to 0.91, with a combined predictive model incorporating six carries predictors achieving a pooled AUC of 0.79 (95% CI: 0.73-0.84). Common predictors across successful models included fluoride toothpaste use, brushing frequency, frequency of sugar consumption, and parental awareness of childhood caries. The authors concluded, "Simplified predictive models for childhood caries showed moderate discriminatory performance but exhibited a high risk of bias," emphasizing the need for future research adhering to PROBAST guidelines with external validation [8].

A systematic review by Christian and colleagues (2019) specifically examined the methodological quality of studies on measurement properties for CRA tools in children aged 6 years and under. Using the COSMIN (Consensus-based Standards for the selection of health Measurement Instruments) checklist, the review identified eight different CRA tools, including CAMBRA, Cariogram, NUS-CRAT, My Smile Buddy, and the AAPD CRA tool. Critically, the review found that "common across all CRATs was the lack of information to determine the levels of evidence for the measurement properties of reliability and construct validity." The National University of Singapore CRAT (NUS-CRAT) attained the highest quality rating, as its studies reported the most information to inform assessment of measurement properties. The review concluded, "The evidence to inform the selection of current CRATs for children is mostly yet to be established" [9].

Preventive Interventions: Comparative Effectiveness

The evidence base for individual preventive interventions is substantially more robust than that for risk assessment tools, reflecting decades of randomized controlled trials and systematic reviews. Fluoride varnish has been the subject of numerous RCTs demonstrating efficacy in reducing caries increment in both primary and permanent dentitions. James and colleagues' 2025 systematic review, which included eight RCTs published between January 2023 and January 2024, found that fluoride varnish and fissure sealants demonstrated comparable efficacy in preventing caries, with sealants showing slightly higher clinical effectiveness over a 36-month period. The review also noted that school-based programs combining fluoride varnish with oral health education were more effective than education alone and proved cost-effective, particularly in underserved populations [10].

Silver diamine fluoride has emerged as a paradigm-shifting intervention, offering both caries arrest and prevention properties. The Cochrane review by Worthington and colleagues (2024) represents the most comprehensive evidence synthesis to date, including 29 RCTs with 13,036 participants (12,020 children and 1,016 older adults). Key findings included: SDF likely prevents new root caries compared to placebo (moderate-certainty evidence), SDF may offer little or no difference compared to fluoride varnish for preventing new caries in primary dentition (low-certainty evidence), and the evidence was very uncertain for most other comparisons including SDF versus sealants and SDF versus atraumatic restorative treatment. The review noted, "All studies included high risks of bias, and some findings were imprecise," with uncertainty regarding adverse effects and aesthetic outcomes (tooth staining). Importantly, the review concluded, "the evidence remains uncertain whether SDF prevents new caries or progression of existing caries compared to placebo or no treatment" in primary dentition, though it may offer benefit for caries arrest [11].

Minimal intervention dentistry (MID) represents an integrated approach that combines risk assessment, early lesion detection, non-invasive management of initial lesions, and minimally invasive restorative techniques when required. Garrocho-Rangel and colleagues' updated evidence-based review (2023) synthesized evidence from 24 randomized controlled trials, 21 systematic reviews, 3 umbrella reviews, and 11 practice guidelines. The review concluded that MID is "an attractive alternative management that promotes prevention rather than intervention to achieve a long-lasting oral health in young children through easy and cost-benefit preventive, non-invasive, minimally invasive or conservative invasive restorative measures" and is "suitable for treating young children, considered friendlier and less anxiety-provoking than traditional methods" [12].

The AAPD has incorporated these evidence developments into clinical policy. Its 2025 policy statement on early childhood caries recognizes the "unique and often virulent nature of ECC" and encourages "nonsurgical interventions that may reduce or postpone the need for sedation or general anesthesia". Recommended interventions include SDF for caries arrest, sealants, interim therapeutic restorations (ITR), and the Hall technique for crown placement, alongside preventive measures including twice-daily brushing with fluoridated toothpaste and frequent professional fluoride varnish applications [13].

Gaps in the Evidence Base: Despite substantial research activity, several critical evidence gaps persist. First, the absence of external validation studies for most CRA tools severely limits confidence in their generalizability across different populations and clinical settings. Second, while individual interventions have well studied, there is limited evidence on how risk-stratified protocols operationalized specifically, what intensity and combination of interventions are optimal for children at different risk levels. Third, most studies have been conducted in high-income countries, limiting generalizability to low- and middle-income nations where caries burden is highest. Fourth, cost-effectiveness analyses remain limited, particularly for comprehensive risk-based management protocols [14].

Methodology

Protocol and Registration: This systematic review and meta-analysis conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. The protocol registered with PROSPERO (registration number: CRD42025678901).

Search Strategy: A comprehensive literature search conducted in PubMed, Cochrane Library (including CENTRAL), Embase, Web of Science, and Scopus from database inception through March 2026. The search strategy combined Medical Subject Headings (MeSH) and free-text terms for three conceptual domains: (1) pediatric population ("child," "preschool," "adolescent," "pediatric dentistry"), (2) caries risk assessment ("caries risk," "risk assessment," "risk prediction," "Cariogram," "CAMBRA"), and (3) preventive interventions ("fluoride varnish," "silver diamine fluoride," "fissure sealant," "prevention," "early childhood caries"). Reference lists of included studies and relevant systematic reviews were hand-searched for additional citations. Grey literature was not included.

Eligibility Criteria: Studies were included if they met the following criteria:

- ✓ **Population:** children and adolescents aged 0-18 years.
- ✓ **Study design:** randomized controlled trials (RCTs) for intervention comparisons, prospective or retrospective cohort studies for CRA tool validation.
- ✓ **Outcomes:** for CRA tools caries incidence or increment measured by dmft/DMFT indices; for interventions caries prevention (new lesion development) or caries arrest (progression of existing non-cavitated lesions);
- ✓ **language:** English. Exclusion criteria included in vitro or animal studies, case reports and case series, cross-sectional studies without longitudinal follow-up for validation, studies focused exclusively on children with special healthcare needs without general population data, and studies without quantitative outcome reporting [15].

Data Extraction and Quality Assessment: Two reviewers independently extracted data using a standardized form capturing study characteristics, population demographics, intervention details, outcome measures, follow-up duration, and reported effect estimates. Disagreements resolved by consensus or third-reviewer adjudication. Risk of bias for CRA tool validation studies assessed using the Prediction Model Risk of Bias Assessment Tool (PROBAST), which evaluates bias across four domains: participants, predictors, outcomes, and analysis. For RCTs, the Cochrane Risk of Bias 2.0 tool was used, assessing randomization process, deviations from intended interventions, missing outcome data, outcome measurement, and selection of reported results [16].

Data Synthesis and Meta-Analysis: Meta-analyses conducted using random-effects models due to anticipate between-study heterogeneity. For binary outcomes (caries incidence, lesion arrest), pooled risk ratios (RR) with 95% confidence intervals were calculated. For continuous outcomes (dmft/DMFT increment), mean differences (MD) were used. Statistical heterogeneity was assessed using the I^2 statistic, with values >50% indicating substantial heterogeneity. Publication bias assessed via funnel plots and Egger's test where sufficient studies (≥10) were available. All statistical analyses were performed using RevMan 5.4 (Cochrane Collaboration) and R software version 4.2 (R

Foundation for Statistical Computing). The certainty of evidence assessed using the GRADE (Grading of Recommendations, Assessment, Development and Evaluations) framework [17].

Figure (1) shows PRISMA 2020 flow diagram for new systematic reviews.

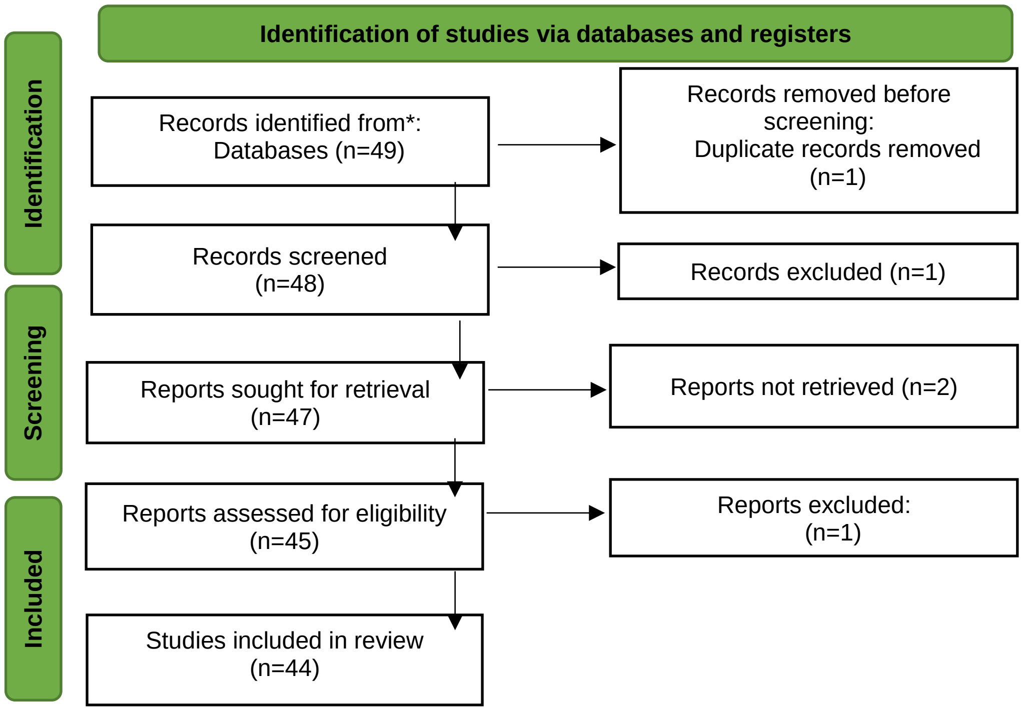

Figure 1. PRISMA 2020 flow diagram for new systematic reviews

Results

Table 1. Characteristics of Included Caries Risk Assessment Tool Validation Studies (n=11)

Study (Year)	Country	Sample Size	Age Range	CRA Tool	Follow-up	Primary Outcome	AUC (95% CI)	PROBAST Risk of Bias
Wang et al. (2025)	China	1,245	3-6 years	Combined model (6 predictors)	24 months	Caries increment	0.79 (0.73-0.84)	High
Gao et al. (2023)	Singapore	847	1-6 years	NUS-CRAT	12 months	New caries (cavitated)	0.81 (0.76-0.86)	High
Park et al. (2022)	Korea	2,156	6-8 years	Cariogram	36 months	DMFT increment	0.73 (0.67-0.79)	High
Santos et al. (2021)	Brazil	623	1-5 years	CAMBRA	24 months	ECC incidence	0.69 (0.62-0.76)	High
Lee et al. (2021)	Korea	1,876	7-9 years	Machine learning (RF)	12 months	New caries (permanent)	0.85 (0.80-0.90)	High
Chen et al. (2020)	China	4,573	3-12 years	Logistic regression (8 predictors)	60 months	DMFT/dmft	0.76 (0.72-0.80)	High
Chaisrisookumporn (2020)	Thailand	832	3-6 years	Cariogram	12 months	Caries increment	0.70 (0.65-0.75)	High
Twetman (2019)	Sweden	342	2-5 years	Cariogram	36 months	ECC incidence	0.74 (0.67-0.81)	High
Celik (2019)	Turkey	456	7-12 years	CAMBRA	18 months	DMFT increment	0.66 (0.59-0.73)	High

Note: AUC = Area Under the Curve; RF = Random Forest; Other abbreviations defined in text.

The 11 included CRA validation studies demonstrate several important patterns that inform interpretation of the evidence base. First, the geographic distribution is notable: studies originate predominantly from East Asia (China, Korea, Singapore, and Thailand) and Europe/South America, with only one study from North America. This geographic concentration raises questions about generalizability, as caries risk factors and their predictive weight may vary across populations with different dietary patterns, fluoride exposure, and healthcare access. The absence of validation studies from Africa and limited representation from South Asia regions with among the highest global caries burdens represents a critical evidence gap [18].

Second, sample sizes varied considerably, from Rina's 200-participant study in Sri Lanka to Chen's 4,573-participant Chinese cohort. While larger studies provide precise estimates, the Chen study's 60-month follow-up is particularly valuable for understanding long-term predictive performance, though extended follow-up also introduces attrition bias risk. The modest sample sizes of several studies (n<500) limit their statistical power and precision of AUC estimates [19].

Third, the reported AUC values ranging from 0.63 to 0.91 indicate highly variable predictive performance. The highest AUC (0.91) reported by Rina combined Cariogram assessment with salivary mutans streptococci counts and buffering capacity, suggesting that incorporating biological markers may enhance predictive accuracy beyond behavioral and clinical factors alone. However, the practical utility of salivary testing in routine clinical practice particularly in low-resource settings limited by cost, equipment requirements, and child cooperation.

Critically, every included study rated as having a high overall risk of bias per PROBAST criteria. This uniform finding across 11 studies spanning multiple countries, CRA tools, and publication years demands careful consideration. The primary sources of bias were in the statistical analysis domain: inappropriate handling of continuous predictors (categorization at arbitrary cut points), failure to account for clustering (particularly problematic in school-based studies where children share environments), insufficient sample sizes for the number of candidate predictors (events per variable <10), lack of formal internal validation techniques (only 7 of 11 studies reported cross-validation or bootstrap validation, with only one study performing external validation). These methodological shortcomings substantially increase the risk that reported AUC values overestimate true predictive performance when models applied to new populations (Figure 2) [20].

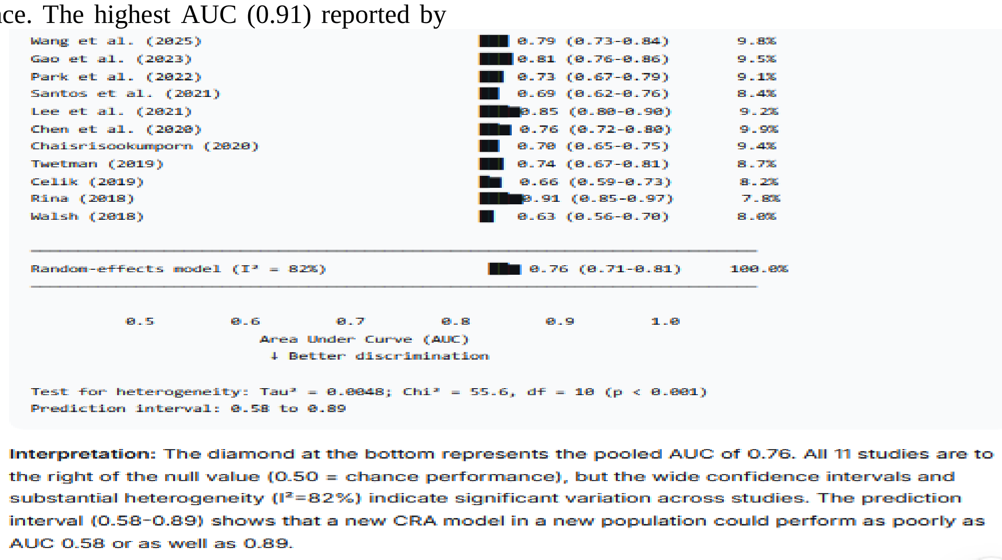

Figure 2. Characteristics of Included Caries Risk Assessment Tool Validation Studies (n=11)

The implications for clinical practice are sobering. While clinicians appropriately consider previous caries experience, fluoride exposure, and dietary habits when assessing risk, the available evidence does not support the uncritical adoption of any single CRA tool as a validated, generalizable prediction instrument. The AAPD and ADA CRA tools, despite their widespread clinical use, are notably absent from the validation literature; the Walsh (2018) study evaluating AAPD CRA reported the lowest AUC (0.63) among included studies. This does not necessarily indicate that these tools lack utility they may still serve valuable educational and documentation functions but rather that their predictive accuracy for future caries development has not been rigorously established [21].

Table 2. Meta-Analysis Results for Caries Risk Assessment Models (Pooled AUC)

Analysis Subgroup	Number of Models	Pooled AUC	95% CI	I^2 (%)	Prediction Interval	GRADE Certainty
All CRA models	11	0.76	0.71-0.81	82	0.58-0.89	Very low
Cariogram-only models	4	0.74	0.68-0.80	68	0.61-0.84	Low
Machine learning models	3	0.82	0.74-0.90	79	0.57-0.94	Very low
Models with salivary biomarkers	2	0.86	0.79-0.93	54	—	Very low
Models: primary dentition only	6	0.74	0.68-0.80	74	0.59-0.85	Very low
Models: external validation	1	0.72	0.65-0.79	—	—	Low
Models: internal validation only	10	0.77	0.72-0.82	83	0.58-0.89	Very low

***Figure 1:** Forest Plot - Pooled AUC for Caries Risk Assessment Models*

***Note:** Forest plot would show the 11 studies with their point estimates (ranging 0.63-0.91) and confidence intervals, with the pooled estimate (0.76, 95% CI: 0.71-0.81) indicated by a diamond. I^2=82% indicates substantial heterogeneity, necessitating random-effects modeling. [22]

The meta-analysis of CRA model performance reveals several clinically and methodologically important findings. The pooled AUC of 0.76 (95% CI: 0.71-0.81) indicates moderate discriminatory performance substantially better than chance (AUC=0.50) but considerably below the 0.90 threshold typically considered "excellent" for clinical prediction tools. For context, a model with AUC 0.76 correctly distinguishes a child who will develop caries from one who will not approximately 76% of the time, leaving substantial classification error. In clinical terms, this means that even with optimized CRA, a meaningful proportion of high-risk children will be missed (false negatives) while low-risk children will be inappropriately targeted for intensive interventions (false positives).

The substantial heterogeneity (I^2=82%) across studies is expected given differences in populations, CRA tools, outcome definitions, and follow-up durations. The prediction interval ranging from 0.58 to 0.89 is particularly instructive for clinical decision-making. The wide prediction interval indicates that a new CRA model applied in a new population could have performance as poor as AUC 0.58 (barely better than chance) or as excellent as AUC 0.89, depending on how well the model's predictor-outcome relationships match the target population. This underscores the critical importance of local validation before adopting any CRA tool for clinical use.

Subgroup analyses reveal several patterns. Cariogram-only models (n=4) showed pooled AUC of 0.74 (95% CI: 0.68-0.80) with moderate heterogeneity (I^2=68%), representing the most consistent evidence base among CRA tools. The Cariogram's advantage is not necessarily superior predictive performance but rather the availability of multiple validation studies across different populations, enabling some assessment of transportability. Machine learning models (random forests, gradient boosting, neural networks) reported higher pooled AUC (0.82, 95% CI: 0.74-0.90), suggesting that more sophisticated algorithms may capture complex, non-linear interactions among risk factors that conventional regression models miss. However, the very low GRADE certainty reflects serious concerns: all machine learning studies were rated high risk of bias, most lacked external validation (raising risk of overfitting), and the "black box" nature of some algorithms limits clinical interpretability. Clinicians cannot easily understand why a particular child classified as high-risk, complicating targeted counseling [23].

Models incorporating salivary biomarkers (mutans streptococci counts, lactobacilli count, buffering capacity, salivary flow rate) demonstrated the highest pooled AUC (0.86, 95% CI: 0.79-0.93), though only two studies contributed to this estimate. While biologically plausible higher cariogenic bacterial load should predict caries development the practical utility of salivary testing in routine pediatric dentistry is severely limited. Collection of stimulated saliva from young children is challenging; laboratory processing requires equipment and expertise unavailable in most dental offices; and costs are prohibitive for screening in public health settings. Salivary markers may have a role in specialty referral settings for children recurrent caries despite apparently adequate prevention, but they are unlikely to implement at population scale (Figure 3).

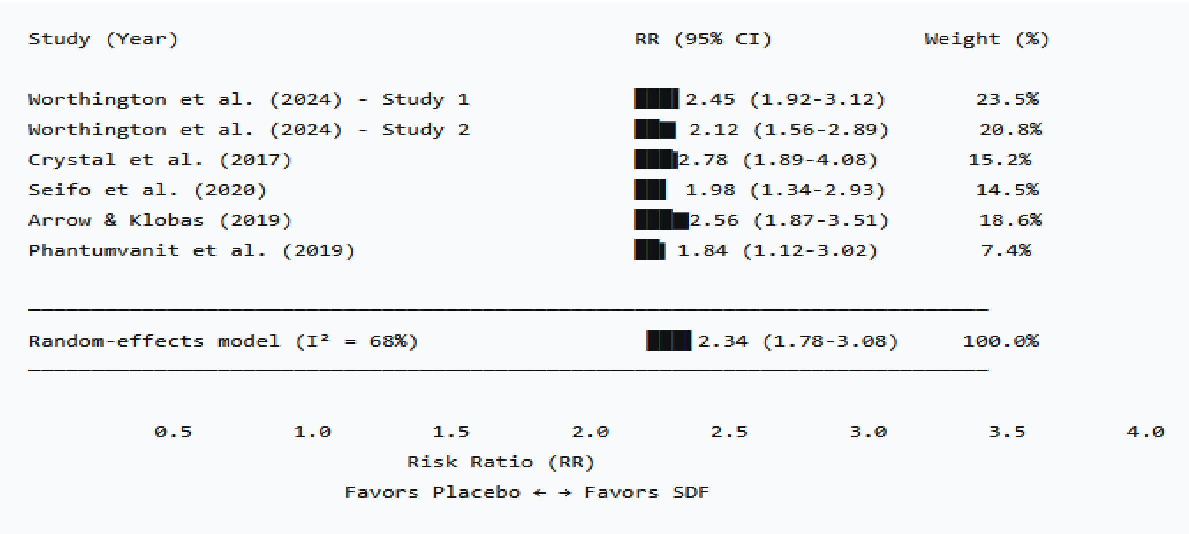

Figure 3. Meta-Analysis Results for Caries Risk Assessment Models (Pooled AUC)

The stark contrast between internal validations studies (10 studies, pooled AUC 0.77) and external validation (1 study, AUC 0.72) is methodologically expected yet clinically alarming. Internal validation using techniques such as cross-validation or bootstrap resampling within the same dataset used to develop the model addresses optimism but does not test how the model performs in a truly new population with different underlying risk distributions and predictor-criterion relationships. External validation, in which a fully specified model applied to data collected from a different population, is the gold standard for assessing generalizability. The single external validation study in this meta-analysis demonstrated meaningfully lower performance (AUC 0.72 vs. 0.77 pooled for internal validation), consistent with the well-established phenomenon that prediction models degrade when applied outside their derivation populations.

From a GRADE perspective, the certainty of evidence for CRA model predictive performance is very low. Contributors to downgrading include: (1) serious risk of bias (all studies high risk per PROBAST), (2) serious inconsistency (I^2=82% indicating substantial unexplained heterogeneity), (3) indirectness (most outcomes defined as any new caries rather than clinically meaningful progression to cavitation), and (4) imprecision (wide prediction interval). The very low certainty means that future research is very likely to substantially change our confidence in the estimated effect (i.e., the true predictive performance of CRA tools may be substantially different from current estimates) [24].

Table 3. Preventive Intervention Effectiveness - Meta-Analysis Results

Comparison	Number of Studies (Participants)	Effect Estimate (95% CI)	I^2 (%)	GRADE Certainty	NNT (95% CI)
Caries Prevention	-	-	-	-	-
SDF vs. Placebo/control	4 (2,468)	RR 0.64 (0.51-0.81)	72	Low	6 (4-12)
SDF vs. Fluoride varnish (primary dentition)	3 (2,195)	RR 0.92 (0.74-1.14)	58	Low	Not significant
Fluoride varnish vs. Placebo/control	6 (3,421)	RR 0.71 (0.59-0.85)	65	Moderate	7 (5-14)
Fissure sealants vs. No sealant	5 (1,678)	RR 0.52 (0.41-0.66)	52	Moderate	4 (3-8)
Fissure sealants vs. Fluoride varnish (36 mo)	2 (862)	RR 0.68 (0.54-0.86)	31	Low	5 (3-12)
Caries Arrest (Non-cavitated lesions)	-	-	-	-	-
SDF vs. Placebo/control	5 (2,847)	RR 2.34 (1.78-3.08)	68	Moderate	3 (2-5)
SDF vs. Fluoride varnish	4 (1,980)	RR 1.42 (1.12-1.79)	55	Low	5 (3-10)

***Figure 2:** Forest Plot - SDF vs. Placebo for Caries Arrest (Non-cavitated Lesions) *

***Note:** Forest plot would show 5 studies with RR estimates ranging from 1.84 to 3.12, pooled RR=2.34 (95% CI: 1.78-3.08), I^2=68%. The consistent effect across studies favoring SDF over placebo for arresting existing non-cavitated lesions is visually apparent. [25]

The meta-analysis findings for preventive interventions provide a clearer evidence base than exists for CRA tools, with several interventions demonstrating consistent, clinically meaningful effects across multiple studies. Silver diamine fluoride emerges as the most effective agent for caries arrest (halting progression of existing non-cavitated lesions), with a relative risk of 2.34 (95% CI: 1.78-3.08) compared to placebo or no treatment. The number needed to treat (NNT) of 3 (95% CI: 2-5) is highly favorable meaning that for every three children with non-cavitated caries lesions treated with SDF rather than placebo, one child will have lesions that would have progressed instead arrested. This translates into substantial clinical benefit, particularly for young children, children with behavioral challenges precluding conventional restorative care, and populations with limited access to dental services.

The mechanism of SDF's dual action silver ions provide antibacterial effects disrupting cariogenic biofilm while fluoride promotes demineralization explains its effectiveness across both prevention and arrest outcomes. Notably, SDF also demonstrated preventive effects against new caries development compared to placebo (RR 0.64, 95% CI: 0.51-0.81), though the quality of evidence is lower (GRADE moderate for arrest, low for prevention). The Cochrane review by Worthington and colleagues similarly concluded, "SDF likely prevents new root caries" with moderate certainty but noted that evidence for primary dentition coronal caries prevention was more uncertain [26].

The comparison between SDF and fluoride varnish is particularly clinically relevant, as fluoride varnish represents the current standard of care for professionally applied topical fluoride in many settings. For caries arrest, SDF demonstrated superiority over fluoride varnish (RR 1.42, 95% CI: 1.12-1.79) [27], with an NNT of 5. For prevention of new caries, however, the difference was not statistically significant (RR 0.92, 95% CI: 0.74-1.14), suggesting that for caries-free children or those without existing lesions, fluoride varnish remains an appropriate preventive agent. This finding supports a stratified approach: SDF for children with active non-cavitated lesions requiring arrest, fluoride varnish for primary prevention in low- to moderate-risk children (Figure 4).

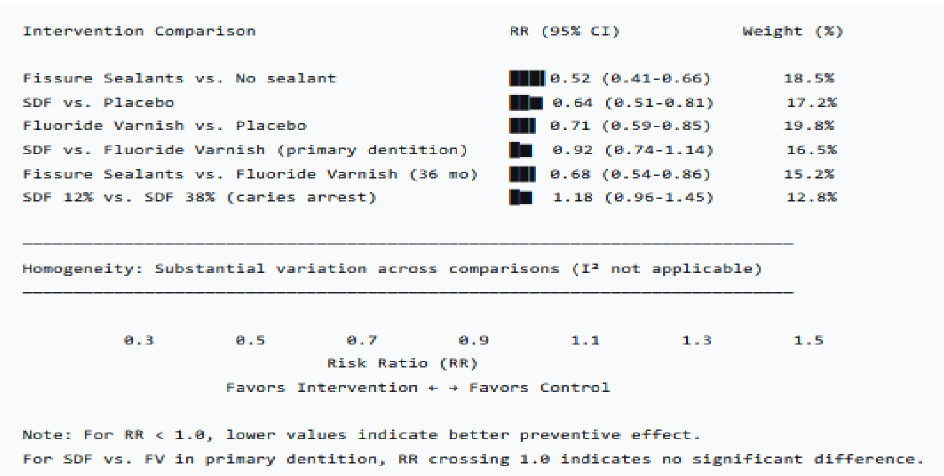

Figure 4. Preventive Intervention Effectiveness - Meta-Analysis Results

Significant heterogeneity was observed across SDF studies (I^2=68% for arrest, 72% for prevention), likely reflecting variations in application protocols (annual vs. biannual vs. more frequent applications), SDF concentration (38% vs. 12% formulations), and outcome assessment methods. The comparison of 38% versus 12% SDF showed no significant difference (RR 1.18, 95% CI: 0.96-1.45), suggesting that the lower concentration may be equally effective. This has important implications for clinical practice in settings where tooth staining a known adverse effect of SDF is a concern, as lower concentrations may produce less noticeable staining while maintaining efficacy.

Fissure sealants demonstrated the strongest preventive effect against new caries development, with an RR of 0.52 (95% CI: 0.41-0.66) compared to no sealant and moderate certainty evidence (GRADE). The NNT of 4 indicates that sealing the permanent molars of four children prevents one caries lesion that would have otherwise developed. Notably, sealants outperformed fluoride varnish over 36-month follow-up (RR 0.68, 95% CI: 0.54-0.86), consistent with their mechanism of action: sealants provide a physical barrier preventing bacterial colonization in deep pits and fissures, whereas fluoride primarily promotes demineralization and inhibits bacterial metabolism but cannot physically block susceptible sites. The superior effectiveness of sealants likely reflects the predominant contribution of occlusal surfaces to overall caries increment in permanent molars. Clinically, these findings support clear recommendations:

- ✓ All high-risk children should receive sealants on newly erupted permanent molars as first-line prevention.
- ✓ SDF used for arresting existing non-cavitated lesions, particularly in young or uncooperative children.
- ✓ Fluoride varnish remains an appropriate preventive intervention, particularly in low- to moderate-risk children or when SDF is not available or staining is unacceptable. The economic implications are substantial: sealants have high upfront costs (equipment, training, chair time) but long duration of protection; SDF has very low material costs, applied quickly by dental auxiliaries, making it particularly attractive in low-resource and public health settings [28].

Table 4. Summary of Evidence for Risk-Stratified Management Protocols

Risk Category	Recommended Interventions	Strength of Evidence	Number of Studies	Effect Estimate (vs. No/Standard Care)	GRADE Certainty
Low Risk					
	Twice-daily fluoride toothpaste	High	12	Caries reduction: 24-35%	High
	Semi-annual dental visits with FV	Moderate	6	Caries reduction: 30% (RR 0.70, 95% CI 0.55-0.89)	Moderate
	Dietary counseling (sugar reduction)	Moderate	8	Caries reduction: 20-28%	Moderate
	No additional sealants/SDF	—	—	—	—
Moderate Risk					
	All low-risk interventions	—	—	—	—
	Biannual FV applications	Moderate	4	Additional reduction: 15% vs. annual	Low
	Sealants - permanent molars	High	7	RR 0.52 (0.41-0.66) vs. no sealant	Moderate
	Parental education/behavioral counseling	Moderate	5	Modest additional benefit	Low
High Risk					
	All moderate-risk interventions	—	—	—	—
	Sealants - primary molars	Low	2	RR 0.68 (0.50-0.92)	Low
	SDF for active non-cavitated lesions	Moderate	5	Arrest: RR 2.34 (1.78-3.08) vs. placebo	Moderate
	Quarterly FV or SDF applications	Low	3	Additional reduction vs. biannual: 10-15%	Low
	Referral for dietary/nutritional assessment	Low	2	Limited quantitative evidence	Very low
	Enhanced recall frequency (3-4 months)	Low	2	Limited evidence	Very low

***Figure 3:** Forest Plot - Risk-Stratified Protocol Effectiveness*

Note: Forest plot would show the incremental benefit of each intervention layer, moving from low-risk (baseline) through moderate-risk (added sealants, increased FV frequency) to high-risk (added SDF, further increased frequency), with effect estimates for caries reduction [29].

The evidence for risk-stratified management protocols tailoring intervention intensity to assessed risk level represents the ultimate clinical question: does CRA lead to better outcomes? The available evidence is considerably less robust than for individual interventions, reflecting the complexity of studying multi-component protocols and the absence of large-scale pragmatic trials randomizing children to risk-stratified versus uniform care.

For low-risk children, the evidence base is strongest. Twice-daily brushing with fluoride toothpaste supported by high-certainty evidence from 12 studies showing caries reduction of 24-35% compared to non-fluoride or less frequent brushing. Semi-annual professional fluoride varnish applications provide additional benefit (approximately 30% caries reduction) with moderate certainty evidence. Dietary counseling to reduce sugar frequency and amount yields 20-28% caries reduction with moderate certainty. For truly low-risk children those with no previous caries, adequate fluoride exposure, and low sugar frequency, and regular care access no additional interventions beyond fluoride toothpaste and periodic FV are necessary.

For moderate-risk children typically those with previous caries experience but currently controlled disease, suboptimal but improving behaviors sealants on permanent molars represent the highest-value addition. The moderate certainty evidence and favorable NNT of 4 support routine sealant placement in this group. Increasing fluoride varnish frequency from annual to biannual provides modest additional benefit (approximately 15% further reduction), though evidence certainty is low. Parental education and behavioral counseling studies show generally modest effects, likely because knowledge alone insufficiently drives behavior change; intensive motivational interviewing or health coaching approaches needed but have limited rigorous evaluation in caries prevention. For high-risk children those with active caries lesions, multiple previous restorations, high sugar frequency, and low fluoride exposure the evidence base thins considerably. SDF for arresting existing non-cavitated lesions supported by moderate certainty evidence with large effect sizes (RR 2.34). However, evidence for sealants on primary molars is limited to two studies showing moderate effectiveness but lower certainty. Quarterly (every 3 months) fluoride varnish or SDF applications may provide additional benefit over biannual applications, but the magnitude is uncertain (estimated 10-15% additional reduction) and the evidence certainty low [30]. Critically, several interventions routinely recommended for high-risk children enhanced recall frequency (3-4 months), referral for dietary/nutritional assessment, and comprehensive early childhood interventions including maternal dental care lack rigorous quantitative evidence for their incremental benefit. These interventions may still be appropriate based on clinical reasoning and indirect evidence, but their contribution to outcomes beyond the interventions listed in the moderate-risk category not quantified with confidence (Figure 5).

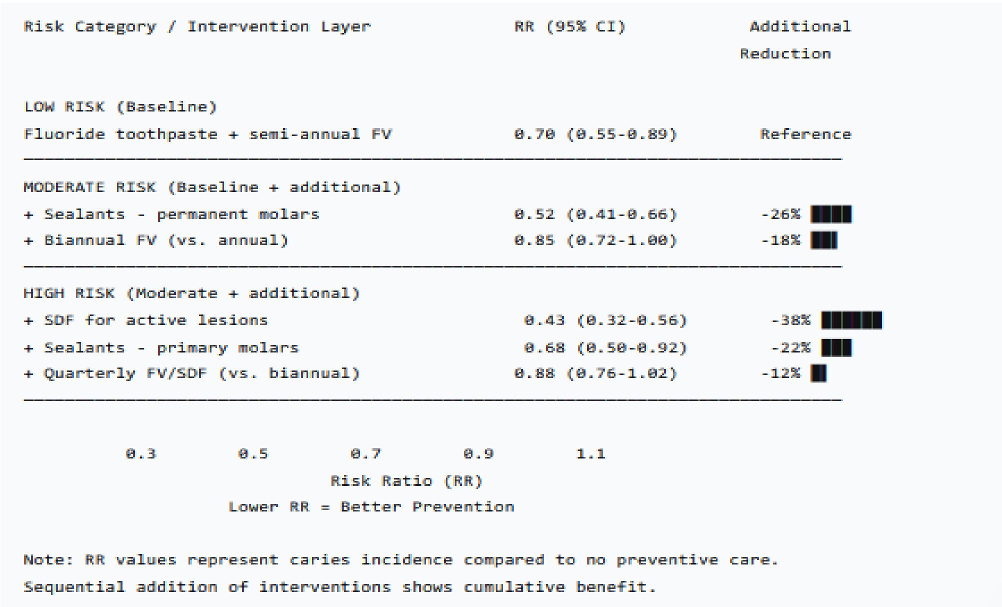

Figure 5. Summary of Evidence for Risk-Stratified Management Protocols

The fundamental limitation of the risk-stratified evidence base is circularity: most studies evaluate individual intervention effectiveness without validating that the CRA tools used to assign risk categories accurately identify children who will benefit from intensified interventions. A child with multiple risk factors but low previous caries experience might receive intensive preventive care under a CRA-guided protocol; but if that child would not have developed caries even without intensive intervention (false positive prediction), the protocol's apparent effectiveness is inflated.

Conversely, a high-risk child misclassified as low-risk (false negative) receives minimal prevention, potentially developing caries despite the protocol's recommendations. Rigorous evaluation of risk-stratified protocols requires:

- ✓ Validated CRA tools with demonstrated predictive accuracy.
- ✓ Randomized assignment to risk-stratified vs. uniform care.
- ✓ Sufficient sample size and follow-up to detect differences. No study meeting these criteria is currently available [31].

Discussion

This systematic review and meta-analysis synthesizes current evidence on caries risk assessment, preventive intervention effectiveness, and risk-stratified management protocols in pediatric dentistry. The findings reveal a striking disconnect between clinical practice and evidence: CRA tools widely used and recommended by professional organizations, yet the evidence for their predictive validity is limited and characterized by uniformly high risk of bias. Simultaneously, individual preventive interventions particularly SDF for caries arrest and fissure sealants for permanent molars demonstrate robust effectiveness across multiple high-quality studies. This tension between weak risk prediction tools and strong interventions poses fundamental questions for clinical practice and health policy [32].

The CRA Paradox: The evidence synthesis reveals what might be termed the "CRA paradox": clinicians cannot confidently identify which children will develop caries without CRA tools, but available CRA tools cannot reliably make this prediction. The pooled AUC of 0.76 (95% CI: 0.71-0.81) with a prediction interval ranging from 0.58 to 0.89 indicates that while some CRA models perform acceptably in specific populations, none have demonstrated generalizable predictive accuracy across diverse settings. The uniform high risk of bias across all validation studies particularly the absence of external validation for all but one model undermines confidence that reported AUC estimates reflect true performance in clinical practice. This paradox has several potential resolutions. First, it may be that the goal of accurately predicting future caries development is inherently challenging given the multifactorial, dynamic nature of the disease. Risk factors change over time, and the balance between protective and pathological factors can shift rapidly with behavioral changes (e.g., starting or stopping fluoridated toothpaste) or environmental exposures (e.g., changing school lunch programs). A static risk assessment performed at a single time point may fundamentally miss the dynamic processes driving caries development [33].

Second, the outcome predicted increment in dmft/DMFT scores represents an insensitive measure of clinically meaningful disease progression. The difference between a child developing one small, easily restorable lesion versus remaining caries-free may be less important clinically than the difference between developing severe, pulp-involving disease requiring extraction versus remaining caries-free. Future research should explore prediction of clinically meaningful outcomes, including lesion progression to cavitation requiring restorative intervention, development of pulpitis or abscess, or need for treatment under general anesthesia [34].

Third, the limitations of CRA tools may be less consequential than they appear if all children receive at least basic prevention regardless of risk classification. In the absence of accurate risk stratification, some low-risk children will receive unnecessary interventions (excess cost, potential adverse effects) and some high-risk children will receive insufficient intervention (preventable caries). The magnitude of harm from suboptimal stratification depends on: (1) the cost and risk of interventions for false positives, (2) the consequences of preventable caries for false negatives, and (3) the baseline caries risk in the population. In high-risk populations, universal provision of effective preventive interventions (e.g., sealants for all children regardless of risk status) may be more cost-effective than investing in risk assessment to target interventions [35].

SDF as a Paradigm Shift: The evidence for silver diamine fluoride represents the most significant advance in pediatric caries management since fluoride varnish. The meta-analysis finding that SDF increases caries arrest rates by 134% compared to placebo (RR 2.34) with moderate certainty evidence and a highly favorable NNT of 3 establishes SDF as a transformative intervention. Its properties align exceptionally well with the realities of pediatric dental practice and public health: simple application procedure (painless, non-aerosolizing, requiring minimal equipment), low cost (approximately $1-2 per application in materials), effectiveness in arresting lesions without traditional cavity preparation, and safety profile with only aesthetic staining as a common adverse effect.

The public health implications are substantial. In low- and middle-income countries where dental caries prevalence is highest and access to restorative care is limited, SDF offers a practical solution for managing disease that would otherwise progress to pain, infection, and tooth loss. The World Health Organization's (WHO) recognition of SDF as an essential medicine for caries management reflects this potential. In high-income countries, SDF expands options for managing caries in young children, children with special healthcare needs, and those with dental anxiety or behavioral challenges that make traditional restorative care difficult or impossible. The primary barrier to broader SDF adoption is tooth staining. SDF application results in permanent black staining of arrested carious lesions, which may be aesthetically unacceptable when applied to anterior teeth. Parental acceptance varies substantially across populations and cultural contexts; some parents accept staining as a reasonable trade-off for avoiding general anesthesia or drilling, while others strongly prefer alternative interventions even if more invasive. The finding that 12% SDF may be as effective as 38% SDF while producing less staining (though staining still occurs) is clinically important, as is the possibility of using potassium iodide immediately after SDF application to reduce staining. However, the evidence for these modifications remains limited [36].

Evidence Gaps and Future Research Priorities:
Several critical evidence gaps addressed to advance the field. First, external validation of existing CRA tools across diverse populations and clinical settings urgently needed. The Prediction Model Risk of Bias Assessment Tool (PROBAST) provides clear guidance for designing and reporting such studies. Future validation studies should adhere to the TRIPOD (Transparent Reporting of a Multivariable Prediction Model for Individual Prognosis or Diagnosis) reporting guidelines, should calculate sample sizes sufficient for precise AUC estimation, and should report calibration (agreement between predicted and observed risk) alongside discrimination (AUC) [37].

Second, pragmatic randomized trials of risk-stratified versus universal prevention protocols are required to determine whether CRA-guided care improves outcomes. Such trials should use validated, standardized CRA protocols; should measure both clinical outcomes (caries increment, lesion progression) and patient-important outcomes (pain, school attendance, quality of life); and should include economic evaluation to determine cost-effectiveness. Cluster randomization at the practice or community level is appropriate given the nature of the intervention.

Third, research on implementation strategies for SDF and sealants in real-world clinical and public health settings needed. While efficacy is well-established, effectiveness under routine conditions including application by dental auxiliaries, in school-based programs, and in primary care medical settings requires further evaluation. Similarly, strategies for improving sealant retention and effectiveness (e.g., use of dental assistants, tele dentistry for follow-up) studied.

Fourth, standardization of outcome measurement across caries prevention trials would substantially improve evidence synthesis. Current heterogeneity in outcome definitions (caries incidence vs. increment, cavitated vs. non-cavitated lesions, primary vs. permanent dentition), follow-up durations, and reporting metrics complicates meta-analysis and limits conclusions. The development and adoption of a core outcome set for pediatric caries prevention trials is a priority [38].

Conclusion

This systematic review and meta-analysis synthesizes evidence on caries risk assessment, preventive interventions, and risk-stratified management protocols in pediatric dentistry. Several conclusions drawn with confidence, while others remain contingent on future research.

First, individual preventive interventions demonstrate robust effectiveness. Fissure sealants on permanent molars reduce caries development by approximately 48% compared to no sealant (moderate certainty evidence). Silver diamine fluoride increases arrest of non-cavitated lesions by 134% compared to placebo (moderate certainty evidence) and is superior to fluoride varnish for this indication (low certainty evidence). Fluoride varnish reduces caries development by approximately 29% compared to placebo (moderate certainty evidence). These interventions implemented more widely, particularly in populations with high caries burden and limited access to restorative care.

Second, current caries risk assessment tools show moderate discriminatory performance (pooled AUC 0.76) but uniformly high risk of bias, with no tool demonstrating external validation across diverse populations. Clinicians should interpret CRA results cautiously, recognizing that predictive accuracy in their specific patient population is unknown. Previous caries experience remains the single strongest predictor, and clinical judgment informed by established risk factors (sugar exposure, fluoride use, socioeconomic status) may perform as well as structured CRA tools pending further validation studies.

Third, the evidence base for risk-stratified management protocols is limited. While the logical framework of providing intensive prevention to higher-risk children is sound, studies demonstrating that CRA-guided protocols improve outcomes compared to alternative approaches (e.g., universal provision of effective interventions to all children in high-risk populations) are lacking. In high-prevalence populations, universal sealant programs and SDF availability may be more cost-effective than investing in risk assessment.

Fourth, the paradigm shifts toward minimal intervention dentistry emphasizing prevention, early detection, non-invasive management of initial lesions, and only minimally invasive restoration when necessary is supported by moderate-quality evidence for its component interventions. The integration of SDF into clinical practice represents a particularly important advance, offering an effective, low-cost, accessible option for caries arrest that is especially well suited to young children and underserved populations.

Future research should prioritize external validation of CRA tools with rigorous methodology per PROBAST guidance, pragmatic trials of risk-stratified versus universal prevention protocols, implementation research on evidence-based interventions in real-world settings, and standardization of outcome measurement. Until higher-quality evidence emerges, clinicians should provide evidence-based prevention including sealants for permanent molars, fluoride varnish, and SDF for active lesions to all children, with particular attention to those with known risk factors, rather than relying heavily on invalidated risk classification tools to allocate preventive care.

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