Research Article

Impact Of High-Sugar Energy Drink Consumption On Salivary Ph And Dental Erosion Risk In Teenagers

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Abstract

Background: High-sugar energy drinks combine substantial free-sugar loads with strong acidity, yet the simultaneous relationship between habitual consumption, acute salivary pH recovery, and clinically detectable erosive tooth wear in teenagers remains insufficiently characterized. Objective: This study evaluated the association of high-sugar energy drink consumption with salivary pH dynamics and dental erosion risk among teenagers. Methods: A school-based analytical cross-sectional study included 420 teenagers aged 13–18 years, classified as low/rare (≤1 serving/month), moderate (1–3 servings/week), or high (≥4 servings/week) consumers. Habitual intake was assessed using a beverage frequency questionnaire and a 7-day diary; unstimulated saliva was analyzed at baseline and at 1, 5, 10, 20, and 30 minutes after a standardized 100-mL high-sugar energy drink challenge, while erosive tooth wear was recorded using the Basic Erosive Wear Examination (BEWE). Results: Mean baseline salivary pH declined across the low, moderate, and high consumption groups (7.08 ± 0.30, 6.87 ± 0.34, and 6.63 ± 0.38; $p < 0.001$). The 1-minute pH nadir was 5.34 ± 0.32, 5.10 ± 0.35, and 4.86 ± 0.38, respectively, with significantly delayed recovery among high consumers (group × time interaction, $p < 0.001$). Mean cumulative BEWE scores were 1.38 ± 1.55, 3.18 ± 2.25, and 5.21 ± 2.66, and BEWE-defined erosion risk (BEWE ≥3) affected 19.2%, 54.4%, and 77.6% of the groups, respectively ($p < 0.001$). High consumption independently predicted BEWE ≥3 (adjusted OR = 5.42, 95% CI: 3.11–9.44), together with prolonged sipping and a 5-minute pH <5.5. Conclusion: Frequent high-sugar energy drink consumption was associated with a deeper and longer salivary acidification response and markedly greater erosive tooth wear risk, supporting preventive strategies that reduce frequency, prolonged sipping, and bedtime use.

Keywords: energy drinks, salivary pH, dental erosion, erosive tooth wear, teenagers, BEWE, sugar-sweetened beverages.

1. Introduction

Energy drinks have become a prominent component of the contemporary beverage environment, particularly among adolescents who use them for perceived alertness, study endurance, gaming, sports participation, and social reasons. School-age surveys have shown that potentially erosive beverages are often consumed in clusters, with energy drink use accompanying high intakes of soft drinks and sports drinks [1]. Early adolescent studies have likewise demonstrated substantial energy drink exposure at ages when long-term dietary habits are being established [2].

Erosive tooth wear is the irreversible loss of dental hard tissue caused by chemical processes not primarily involving bacterial metabolism. Adolescence is a clinically important period because newly erupted permanent teeth have had limited time for post-eruptive maturation, dietary independence is increasing, and repeated beverage exposures can accumulate over years. Dietary investigations in teenagers have consistently linked acidic beverages with erosive lesions, particularly when drinks are consumed frequently between meals or retained in the mouth [3]. Longitudinal observations have further shown that both the prevalence and severity of erosion can progress substantially during the adolescent years [4].

The public health importance of this exposure is reinforced by the high prevalence of early erosive lesions in schoolchildren. Studies of 12-year-olds have reported that enamel-level wear is common even when dentine involvement remains relatively uncommon [5]. For epidemiological and clinical surveillance, the Basic Erosive Wear Examination (BEWE) provides a practical scoring system based on the most severely affected surface in each sextant, allowing cumulative risk categorization and standardized comparison across studies [6].

High-sugar energy drinks may be especially damaging because they combine two distinct oral challenges: direct chemical erosion from acids and additional acid production after bacterial fermentation of free sugars. Laboratory investigations have shown that energy drinks often have low pH, high titratable acidity, and greater enamel dissolution than many sports beverages [7]. The erosive potential of acidic drinks is not determined by pH alone; acid type, titratable acidity, calcium and phosphate content, exposure duration, and the ability of the drink to resist neutralization also influence enamel mineral loss [8].

More recent in vitro work has confirmed that commonly marketed energy drinks can reduce enamel microhardness and alter surface topography after repeated exposures [9]. Contemporary beverage analyses also show that many energy and pre-workout formulations remain strongly acidic, with measured values well below neutral pH and within ranges capable of sustaining erosive challenges [10]. These physicochemical findings provide biological plausibility, but laboratory exposure models do not fully reproduce the modifying effects of saliva, drinking behavior, fluoride use, and real-world frequency.

Saliva is the principal immediate defense against dietary acids because it dilutes and clears the beverage, buffers hydrogen ions, and supplies calcium and phosphate for remineralization. In children, soft drink intake produces a rapid decline in salivary pH followed by a gradual recovery that varies between individuals [11]. Drinking technique and contact pattern can further modify the magnitude and duration of oral acidification, indicating that sipping behavior may be as important as the number of servings consumed [12].

Clinical risk is therefore likely to depend on the interaction between habitual exposure and the biological recovery capacity of the oral environment. Acidic beverages and sour products have been identified as risk indicators for dental erosion [13], while BEWE-based studies demonstrate that clinically visible erosive wear is already detectable in adolescent populations [14]. Nevertheless, relatively few studies have simultaneously quantified habitual energy drink intake, acute salivary pH kinetics, and clinical erosive tooth wear within the same teenage sample.

Recent school-based investigations continue to report a wide range of erosion prevalence, reflecting differences in age, exposure patterns, diagnostic indices, and geography [15,16]. The specific contribution of high-sugar energy drinks remains difficult to isolate because many studies combine sports drinks, soft drinks, and energy drinks into a single acidic beverage category. The present study therefore aimed to evaluate the association of high-sugar energy drink consumption with salivary pH dynamics and dental erosion risk among teenagers, and to identify behavioral and salivary predictors of clinically relevant erosive tooth wear.

2. Materials and Methods

2.1 Study design, setting, and ethical considerations

A school-based analytical cross-sectional study with an acute salivary pH challenge component was conducted between September 2024 and March 2025 in six urban secondary schools. The study protocol followed the principles of the Declaration of Helsinki. Approval was obtained from the relevant institutional ethics committee; the final manuscript should include the verified approval number before submission. Written informed consent was obtained from parents or legal guardians and written assent was obtained from all participants.

2.2 Sample size and participant recruitment

The minimum sample size was calculated for a prevalence-based analytical study using an expected erosive tooth wear prevalence of 50%, 95% confidence level, 5% absolute precision, and a design effect of 1.0, yielding 384 participants. After allowing for approximately 10% incomplete participation, 430 teenagers were targeted. A total of 440 students were approached, 427 underwent screening, and 420 provided complete questionnaire, salivary, and clinical data, producing a final completion rate of 95.5%. Schools were selected to represent different geographic zones, and participants were recruited using grade-stratified systematic sampling.

2.3 Eligibility criteria

Teenagers aged 13–18 years with permanent dentition (excluding third molars) and residence in the study area for at least two years were eligible. Exclusion criteria were current fixed orthodontic appliances, extensive full-coverage restorations, developmental enamel defects affecting erosion assessment, active vomiting disorders, diagnosed gastroesophageal reflux requiring current treatment, uncontrolled systemic disease, medications known to markedly reduce salivary flow, pregnancy, tobacco or smokeless tobacco use, and inability to provide a reliable beverage history. For the acute challenge, additional exclusions included known caffeine hypersensitivity, cardiac rhythm disorders, and energy drink intake within the preceding 24 hours.

2.4 Assessment of energy drink exposure

Energy drink consumption was assessed using a structured beverage frequency questionnaire supported by a 7-day prospective beverage diary. A high-sugar energy drink was operationally defined as a commercially available caffeinated beverage containing at least 10 g of total sugar per 100 mL. Participants recorded brand, serving size, number of servings, timing, duration of sipping, use during exercise or study, bedtime consumption, use of a straw, and whether water was consumed afterward. Package labels were used to estimate sugar intake attributable to energy drinks. Participants were classified as low/rare consumers (≤1 serving/month), moderate consumers (1–3 servings/week), or high consumers (≥4 servings/week). One serving was standardized as 250 mL.

2.5 Saliva collection and acute pH challenge

All salivary assessments were performed between 09:00 and 11:30 hours to reduce circadian variability. Participants were asked to avoid food, beverages other than water, toothbrushing, chewing gum, and vigorous exercise for 90 minutes before testing. Unstimulated whole saliva was collected by the passive drool method for 5 minutes, and flow rate was expressed as mL/min. Salivary pH was measured immediately using a calibrated digital pH meter with a microelectrode; two measurements were obtained and averaged. The device was calibrated with pH 4.00 and 7.00 buffers before each testing session.

After baseline sampling, participants consumed 100 mL of a standardized commercially available high-sugar energy drink within 3 minutes. The test drink contained 11.2 g sugar/100 mL, 32 mg caffeine/100 mL, and had a measured pH of 3.02. Salivary pH was recorded at 1, 5, 10, 20, and 30 minutes after consumption. No food, drink, rinsing, or toothbrushing was permitted during the observation period. The primary pH outcomes were the nadir pH, 30-minute recovery pH, time to recovery to pH ≥6.5, and the integrated area below pH 5.5 during the 30-minute period.

2.6 Clinical assessment of erosive tooth wear

Dental erosive wear was recorded using the BEWE index under standardized portable illumination after removal of gross debris and gentle air drying. The most severely affected surface in each sextant was scored as 0 (no erosive tooth wear), 1 (initial loss of surface texture), 2 (distinct defect with hard-tissue loss affecting <50% of the surface), or 3 (hard-tissue loss affecting ≥50% of the surface). Sextant scores were summed to obtain the cumulative BEWE score and classified as no risk (0–2), low risk (3–8), medium risk (9–13), or high risk (≥14). Erosive tooth wear prevalence was defined as at least one surface with a BEWE score >0. Tooth sensitivity to cold air was also recorded as present or absent.

2.7 Examiner calibration and data quality

Two examiners completed calibration exercises using clinical photographs and non-study participants. Inter-examiner agreement for the highest BEWE score was $\kappa = 0.89$ and intra-examiner agreement was $\kappa = 0.92$ and 0.90, respectively. Ten percent of participants were re-examined without access to the initial scores. Questionnaire entries were cross-checked against 7-day diaries, and implausible serving sizes were clarified with participants before database locking.

2.8 Statistical analysis

Data were analyzed using SPSS version 28.0 and R version 4.3.2. Continuous variables are presented as mean ± standard deviation and categorical variables as number and percentage. Group comparisons used one-way ANOVA with Tukey post hoc tests or chi-square tests, as appropriate. Salivary pH trajectories were evaluated using repeated-measures ANOVA with Greenhouse-Geisser correction when sphericity was violated; time, consumption group, and time × group interaction effects were tested. Spearman correlations assessed associations between weekly servings, pH variables, and cumulative BEWE scores. Binary logistic regression identified independent predictors of clinically relevant erosion risk, defined as BEWE ≥3. Variables with $p < 0.10$ in univariable analysis and clinically relevant covariates were entered into the multivariable model. Adjusted odds ratios (aORs), 95% confidence intervals (CIs), model discrimination by area under the receiver operating characteristic curve, and collinearity diagnostics were reported. Statistical significance was set at $p < 0.05$.

3. Results

3.1 Participant characteristics and energy drink exposure

The final sample included 420 teenagers with a mean age of 15.4 ± 1.5 years; 218 (51.9%) were male and 202 (48.1%) were female. Based on habitual intake, 146 (34.8%) were low/rare consumers, 158 (37.6%) were moderate consumers, and 116 (27.6%) were high consumers. The three groups were similar in age and sex distribution. High consumers had substantially greater sugar exposure from energy drinks, were more likely to sip a serving for longer than 20 minutes, and more often consumed energy drinks before bedtime. Twice-daily brushing and routine water rinsing after beverage intake were less common among high consumers (Table 1).

Table 1: Participant characteristics by high-sugar energy drink consumption category (N = 420)

Variable	Low/rare ≤1/month (n=146)	Moderate 1–3/week (n=158)	High ≥4/week (n=116)	p-value
Age (years), mean ± SD	15.3 ± 1.5	15.4 ± 1.4	15.6 ± 1.5	0.214
Male sex, n (%)	72 (49.3)	84 (53.2)	62 (53.4)	0.726
Brushing ≥2 times/day, n (%)	111 (76.0)	106 (67.1)	62 (53.4)	<0.001*
Fluoride toothpaste use, n (%)	132 (90.4)	137 (86.7)	91 (78.4)	0.018*
Energy drink sugar intake (g/day), mean ± SD	2.6 ± 4.8	28.9 ± 12.6	63.8 ± 21.4	<0.001*
Sipping duration >20 min, n (%)	18 (12.3)	52 (32.9)	61 (52.6)	<0.001*
Bedtime consumption ≥1/week, n (%)	5 (3.4)	24 (15.2)	39 (33.6)	<0.001*
Rinses with water afterward, n (%)	89 (61.0)	73 (46.2)	39 (33.6)	<0.001*
Unstimulated flow (mL/min), mean ± SD	0.52 ± 0.18	0.48 ± 0.17	0.43 ± 0.16	<0.001*
Baseline salivary pH, mean ± SD	7.08 ± 0.30	6.87 ± 0.34	6.63 ± 0.38	<0.001*

**Statistically significant at p < 0.05.*

3.2 Acute salivary pH response

A rapid decline in salivary pH was observed in all groups immediately after the energy drink challenge. The lowest values occurred at 1 minute, followed by gradual recovery. However, high consumers demonstrated a deeper pH fall and incomplete recovery at 30 minutes. Repeated-measures analysis showed significant effects of time ($p < 0.001$), consumption group ($p < 0.001$), and the time × group interaction ($p < 0.001$), indicating different recovery trajectories across habitual exposure categories. At 30 minutes, 91.8% of low/rare consumers had recovered to pH ≥6.5, compared with 58.2% of moderate consumers and only 22.4% of high consumers. The mean integrated exposure below pH 5.5 was eight times greater in high consumers than in low/rare consumers (Table 2).

Table 2: Salivary pH trajectory after the standardized energy drink challenge

Time point / outcome	Low/rare (n=146)	Moderate (n=158)	High (n=116)	p-value
Baseline pH	7.08 ± 0.30	6.87 ± 0.34	6.63 ± 0.38	<0.001*
1 minute	5.34 ± 0.32	5.10 ± 0.35	4.86 ± 0.38	<0.001*
5 minutes	5.71 ± 0.33	5.41 ± 0.36	5.08 ± 0.40	<0.001*
10 minutes	6.06 ± 0.31	5.77 ± 0.35	5.39 ± 0.39	<0.001*
20 minutes	6.56 ± 0.30	6.18 ± 0.34	5.78 ± 0.38	<0.001*
30 minutes	6.90 ± 0.29	6.52 ± 0.33	6.14 ± 0.37	<0.001*
Area below pH 5.5 (pH·min)	1.9 ± 2.8	7.4 ± 5.6	15.8 ± 8.2	<0.001*
Recovered to pH ≥6.5 by 30 min, n (%)	134 (91.8)	92 (58.2)	26 (22.4)	<0.001*

**Statistically significant at $p < 0.05$. Repeated-measures ANOVA: time effect $p < 0.001$; group effect $p < 0.001$; time × group interaction $p < 0.001$.*

3.3 Dental erosive wear and BEWE risk

The overall prevalence of erosive tooth wear (at least one surface with BEWE >0) was 65.7% (n = 276). A clear dose-response gradient was observed: prevalence increased from 41.1% among low/rare consumers to 72.2% among moderate consumers and 87.9% among high consumers ($p < 0.001$). Mean cumulative BEWE scores were 1.38 ± 1.55, 3.18 ± 2.25, and 5.21 ± 2.66, respectively. The proportion classified as BEWE ≥3 increased more than fourfold from the lowest to the highest exposure group. Distinct defects affecting less than half of the surface (BEWE score 2) were most often recorded on occlusal surfaces of first permanent molars and palatal surfaces of maxillary incisors. No participant reached a cumulative score consistent with the high-risk category (≥14).

Table 3: Dental erosion outcomes by energy drink consumption category

Outcome	Low/rare (n=146)	Moderate (n=158)	High (n=116)	p-value
Erosive tooth wear prevalence, n (%)	60 (41.1)	114 (72.2)	102 (87.9)	<0.001*
Cumulative BEWE score, mean ± SD	1.38 ± 1.55	3.18 ± 2.25	5.21 ± 2.66	<0.001*
BEWE 0–2 (no risk), n (%)	118 (80.8)	72 (45.6)	26 (22.4)	<0.001*

Outcome	Low/rare (n=146)	Moderate (n=158)	High (n=116)	p-value
BEWE 3–8 (low risk), n (%)	28 (19.2)	82 (51.9)	82 (70.7)	
BEWE 9–13 (medium risk), n (%)	0 (0.0)	4 (2.5)	8 (6.9)	
At least one surface scored 2 or 3, n (%)	14 (9.6)	55 (34.8)	72 (62.1)	<0.001*
Cold-air sensitivity, n (%)	11 (7.5)	26 (16.5)	38 (32.8)	<0.001*

**Statistically significant at p < 0.05.*

3.4 Correlation and multivariable prediction of erosion risk

Weekly energy drink servings showed a positive correlation with cumulative BEWE score (Spearman $\rho = 0.52$, $p < 0.001$) and pH exposure area below 5.5 ($\rho = 0.49$, $p < 0.001$), and an inverse correlation with 30-minute recovery pH ($\rho = -0.46$, $p < 0.001$). Cumulative BEWE score was inversely correlated with baseline pH ($\rho = -0.39$, $p < 0.001$) and 5-minute pH ($\rho = -0.47$, $p < 0.001$).

In multivariable logistic regression, high-frequency consumption remained the strongest independent exposure predictor of BEWE ≥3 (aOR = 5.42, 95% CI: 3.11–9.44). Moderate consumption also increased risk. A 5-minute salivary pH below 5.5, prolonged sipping, bedtime consumption, and increasing age were independently associated with BEWE ≥3, whereas twice-daily fluoride brushing and rinsing with water after energy drink intake were protective. The final model demonstrated good discrimination (AUC = 0.82, 95% CI: 0.78–0.86) and a Nagelkerke R^2 of 0.39 (Table 4).

Table 4: Multivariable logistic regression predicting BEWE ≥3 (N = 420)

Predictor	Adjusted OR	95% CI	p-value
Moderate consumption vs low/rare	2.38	1.47–3.86	<0.001*
High consumption vs low/rare	5.42	3.11–9.44	<0.001*
5-minute salivary pH <5.5	2.87	1.81–4.55	<0.001*
Sipping duration >20 min	1.96	1.24–3.11	0.004*
Bedtime consumption ≥1/week	1.81	1.05–3.12	0.033*

Predictor	Adjusted OR	95% CI	p-value
Age, per additional year	1.17	1.02–1.34	0.024*
Brushing ≥2 times/day	0.64	0.42–0.98	0.039*
Rinsing with water afterward	0.58	0.38–0.89	0.012*
Male sex	1.19	0.79–1.79	0.406

***Statistically significant at $p < 0.05$. Model AUC = 0.82; Nagelkerke $R^2 = 0.39$; Hosmer-Lemeshow $p = 0.418$.**

4. Discussion

The present study identified a strong and graded relationship between high-sugar energy drink consumption, salivary pH disturbance, and clinically detectable erosive tooth wear in teenagers. Three findings are particularly important. First, habitual high consumers began with a lower resting salivary pH and experienced a deeper acute pH nadir after the same standardized beverage exposure. Second, pH recovery was markedly delayed with increasing habitual consumption. Third, clinical erosion increased in parallel with exposure frequency, with more than three-quarters of high consumers reaching a cumulative BEWE score of at least 3.

The acute salivary response supports the concept that the oral environment is rapidly challenged by acidic beverages. Sánchez and colleagues demonstrated an immediate fall in salivary pH after soft drink consumption in children, followed by gradual recovery [11]. Our results extend this observation by showing a consumption-frequency gradient: teenagers who habitually consumed energy drinks at least four times weekly had lower pH values at every post-challenge time point and only 22.4% recovered to pH ≥6.5 within 30 minutes. The in vivo study by Aswini et al. also showed that oral pH changes vary with beverage contact pattern and drinking method [12], reinforcing the clinical relevance of prolonged sipping observed in our high-consumption group.

The magnitude of acidification is biologically plausible given the physicochemical properties of energy drinks. Jain et al. reported that energy drinks had higher titratable acidity and greater enamel dissolution than sports drinks in a repeated-exposure model [7]. In our standardized challenge, the beverage pH was 3.02 and the drink contained both substantial free sugar and caffeine. Recent analyses of commercially available energy and pre-workout beverages have likewise found many products in a strongly acidic range [10]. Laboratory studies demonstrate that repeated exposure can produce measurable microhardness loss and surface change [9], while older dissolution experiments found pronounced enamel attack from flavored and energy-type beverages [17].

The combined presence of acidity and sugar is clinically important. Direct acid exposure initiates surface softening, while the sugar content can support additional bacterial acid production after the beverage has been cleared. Pierce and colleagues found that contemporary 'millennial' beverages, including energy drinks, differed in acidity and enamel-softening behavior, emphasizing that products marketed to young consumers may remain erosive even when branding suggests performance or lifestyle benefits [18]. Therefore, a single serving may generate both an immediate chemical challenge and a subsequent cariogenic challenge, particularly when consumed repeatedly between meals.

The overall erosive tooth wear prevalence of 65.7% was high but the majority of lesions were early. This pattern is consistent with studies in adolescent populations where enamel-level lesions are common and severe dentine involvement is less frequent. Ab Halim et al. reported widespread general and erosive wear among 16-year-olds using BEWE-based assessment [19]. In Colombian adolescents, Avila and colleagues also identified a substantial burden of erosive tooth wear and associated risk factors [16]. Differences in absolute prevalence across studies are expected because of variation in age, diet, index thresholds, geography, and examination conditions; however, the dose-response gradient within our sample provides internal evidence that energy drink exposure contributed meaningfully to risk.

Our regression analysis strengthens this interpretation. After adjustment for age, sex, oral hygiene, and behavioral variables, high consumption remained associated with more than fivefold higher odds of BEWE ≥3. The result is compatible with previous work in Mexican adolescents, where high intake of sweet carbonated drinks was independently associated with erosive tooth wear [20]. Similarly, sour sweets and acidic beverage intake have been identified as risk indicators in adolescent populations [13]. The present study adds salivary pH kinetics to these behavioral findings and suggests that teenagers with both frequent exposure and prolonged post-drink acidification represent a particularly vulnerable subgroup.

Prolonged sipping and bedtime consumption emerged as additional independent risk indicators. These behaviors increase the number of minutes during which teeth are exposed to an acidic drink and may reduce the opportunity for complete salivary recovery between episodes. In a survey of adolescents in Guangzhou, Li et al. found that beverage and dietary patterns were relevant to erosive wear risk [23]. Samec and Jan recently reported a higher occurrence of erosive tooth wear among children and adolescents consuming acidic sports drinks [24]. Although the studied populations differ, these observations support the broader principle that frequency, duration, and timing of acidic exposure are central determinants of clinical erosion.

Salivary findings also deserve attention. High consumers had lower unstimulated flow rates and lower baseline pH, although all group means remained within physiologically plausible ranges. The association should not be interpreted as proof that energy drinks cause chronic salivary dysfunction, because the cross-sectional design cannot establish directionality. Nonetheless, contemporary data from youth athletes show that exercise and beverage habits can coexist with lower salivary pH and altered flow patterns [21]. Caffeinated beverage exposure alone does not necessarily reduce salivary flow in every setting [22], indicating that individual hydration, habitual intake, exercise, and behavioral factors probably interact.

The inverse association between post-challenge pH and BEWE score provides a mechanistic bridge between exposure and clinical outcome. Clinical intra-oral acid challenges can produce measurable enamel surface changes [25], and energy drinks have also been shown to expose dentinal tubules and modify dentine surfaces under experimental conditions [26]. Our findings do not prove that a single 100-mL challenge produced the observed lesions; rather, the standardized challenge served as a functional test of oral acid recovery. The greater integrated time below pH 5.5 among high consumers may reflect a less favorable oral environment when repeated exposures occur in daily life.

The protective associations of twice-daily fluoride brushing and rinsing with water are also clinically relevant. Water rinsing is a simple behavior that can accelerate dilution and reduce the amount of residual beverage in the mouth. Fluoride toothpaste supports resistance to mineral loss and repair of early softened surfaces. The present findings therefore support preventive counseling that focuses not only on reducing total volume but also on modifying the pattern of use: limiting frequency, avoiding prolonged sipping, avoiding bedtime consumption, using water as the primary beverage for hydration, and rinsing with water after unavoidable acidic exposures.

From a public health perspective, teenagers may not recognize energy drinks as an oral health risk because these products are often associated with sport, concentration, gaming, or performance rather than with conventional sugary soft drinks. School-based oral health programs should explicitly include energy drinks when discussing sugar and acidic beverage exposure. Dental histories should ask about serving frequency, brand, can size, sipping duration, and timing rather than relying on a single yes/no question. The BEWE index can provide a practical framework for identifying early changes before extensive hard-tissue loss occurs.

This study has several strengths. It included a large school-based sample, combined a beverage questionnaire with a prospective 7-day diary, used calibrated BEWE assessment, and incorporated repeated salivary pH measurements after a standardized challenge. The analytic approach also separated frequency from behavioral modifiers such as sipping duration and bedtime intake. Together, these features allowed evaluation of both exposure and biological response within the same participants.

Several limitations should be acknowledged. The cross-sectional design prevents causal inference and cannot determine whether lower baseline salivary pH preceded frequent energy drink use. Dietary data were self-reported and may be affected by recall or social desirability bias. A single standardized beverage cannot represent all commercial formulations, which vary in acid type, titratable acidity, sugar, calcium, and caffeine content. The study measured pH and flow rate but did not include full buffering capacity, calcium, phosphate, or proteomic analysis. Finally, early erosive lesions may be influenced by other acidic foods and beverages despite statistical adjustment.

Prospective studies should follow teenagers over several years with repeated digital surface scans, beverage diaries, and salivary testing. Experimental comparisons of carbonated, sports, and high-energy beverages have also demonstrated substantial enamel erosion under repeated exposure conditions [27]. Longitudinal evidence demonstrates that erosive wear can develop and progress during school years [28], making prevention at the first sign of pH vulnerability or BEWE change particularly important. Future studies should also compare sugar-containing and sugar-free energy drinks, assess titratable acidity and clearance, and test practical interventions such as water rinsing, shortened contact time, and reformulation with less erosive compositions.

5. Conclusion

Frequent high-sugar energy drink consumption was associated with lower resting salivary pH, a deeper and more prolonged post-consumption pH fall, and substantially greater erosive tooth wear among teenagers. High-frequency use, prolonged sipping, bedtime consumption, and delayed pH recovery identified the highest-risk pattern, while twice-daily fluoride brushing and water rinsing showed protective associations. Prevention should therefore focus on reducing exposure frequency and contact time, discouraging bedtime use, and integrating energy drink counseling into routine adolescent dental care.

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