UDC: 616.31:663.938

THE EFFECTS OF ENERGY DRINKS ON DENTAL HARD TISSUES: A CHEMICAL, MORPHOLOGICAL AND CLINICAL ANALYSIS

Maxmudjon Madumarov Ma'rufovich
Central Asian Medical University International Medical University Assistant,
Burhoniddin Marg'inoniy Street-64, E-mail: info@camuf.uz, Fergana, Uzbekistan
E-mail: madumarovmahmud@gmail.com
Orcid: https://orcid.org/0009-0005-7472-7741
https://doi.org/10.5281/zenodo.18196859

Abstract: Energy drinks have rapidly gained global popularity, yet their physicochemical properties raise concerns regarding dental health, particularly the integrity of hard dental tissues. These beverages typically contain high concentrations of organic acids (e.g., citric acid), sugars, and other additives that produce a low pH environment in the oral cavity, below the critical threshold (pH 5.5) for enamel demineralization. This review synthesizes the current scientific understanding of how energy drinks interact with enamel and dentin at chemical, morphological, and clinical levels. Chemical acidity promotes dissolution of hydroxyapatite, while titratable acidity and acid composition amplify demineralization beyond the effects of pH alone. Morphological analyses using microscopy techniques show increased surface roughness and loss of structural integrity after exposure. Although clinical evidence varies, in-vitro and epidemiological data consistently demonstrate the erosive potential of energy drinks on dental hard tissues. Comprehensive preventive strategies focusing on reducing exposure and enhancing remineralization are essential to mitigate these adverse effects.

Keywords: energy drinks, dental erosion, enamel demineralization, acidic beverages, hard dental tissues, pH, titratable acidity, hydroxyapatite.

ВЛИЯНИЕ ЭНЕРГЕТИЧЕСКИХ НАПИТКОВ НА ТВЕРДЫЕ ТКАНИ ЗУБОВ: ХИМИЧЕСКИЙ, МОРФОЛОГИЧЕСКИЙ И КЛИНИЧЕСКИЙ АНАЛИЗ

Аннотация: Энергетические напитки быстро завоевали мировую популярность, однако их физико-химические свойства вызывают опасения относительно здоровья зубов, особенно целостности твердых тканей зубов. Эти напитки обычно содержат высокие концентрации органических кислот (например, лимонной кислоты), сахаров и других добавок, которые создают низкую pH-среду в полости рта, ниже критического порога (pH 5,5) для деминерализации эмали. В этом обзоре обобщается современное научное понимание того, как энергетические напитки взаимодействуют с эмалью и дентином на химическом, морфологическом и клиническом уровнях. Химическая кислотность способствует растворению гидроксиапатита, в то время как титруемая кислотность и кислотный состав усиливают деминерализацию сверх воздействия одного только pH. Морфологический анализ с использованием методов микроскопии показывает увеличение шероховатости поверхности и потерю структурной целостности после воздействия. Хотя клинические данные различаются, данные in vitro и эпидемиологические данные последовательно демонстрируют эрозивный потенциал энергетических напитков для твердых тканей зубов. Для смягчения этих неблагоприятных последствий необходимы комплексные профилактические стратегии, направленные на снижение воздействия и усиление реминерализации.

Ключевые слова: энергетические напитки, эрозия зубов, деминерализация эмали, кислые напитки, твердые ткани зубов, pH, титруемая кислотность, гидроксиапатит.

ENERGETIK ICHIMLIKLARNING TISH QATTIQ TO'QIMALARIGA TA'SIRI: KIMYOVIY, MORFOLOGIK VA KLINIK TAHLIL

Annotatsiya: Energetik ichimliklar tezda global miqyosda mashhurlikka erishdi, ammo ularning fizik-kimyoviy xususiyatlari tish salomatligi, xususan, qattiq tish to'qimalarining yaxlitligi bilan bog'liq xavotirlarni keltirib chiqaradi. Ushbu ichimliklar odatda og'iz bo'shlig'ida emal demineralizatsiyasi uchun kritik chegaradan (pH 5.5) past pH muhitini yaratadigan yuqori konsentratsiyali organik kislotalar (masalan, limon kislotasi), shakar va boshqa qo'shimchalarni o'z ichiga oladi. Ushbu sharh energetik ichimliklarning emal va dentin bilan kimyoviy, morfologik va klinik darajalarda qanday o'zaro ta'sir qilishi haqidagi hozirgi ilmiy tushunchani sintez qiladi. Kimyoviy kislotalilik gidroksiapatitning erishini rag'batlantiradi, titrlanadigan kislotalilik va kislota tarkibi esa demineralizatsiyani faqat pH ta'siridan tashqari kuchaytiradi. Mikroskopiya texnikasidan foydalangan holda morfologik tahlillar ta'sirdan keyin sirt pürüzlülüğünün ortishi va strukturaviy yaxlitlikning yo'qolishini ko'rsatadi. Klinik dalillar turlicha bo'lsa-da, in-vitro va epidemiologik ma'lumotlar energetik ichimliklarning tish qattiq to'qimalariga eroziv salohiyatini doimiy ravishda ko'rsatadi. Ta'sirni kamaytirish va remineralizatsiyani kuchaytirishga qaratilgan keng qamrovli profilaktika strategiyalari ushbu salbiy ta'sirlarni yumshatish uchun juda muhimdir.

Kalit so'zlar: energetik ichimliklar, tish eroziyasi, emalning demineralizatsiyasi, kislotali ichimliklar, qattiq tish to'qimalari, pH, titrlanadigan kislotalilik, gidroksiapatit.

INTRODUCTION

Energy drinks represent a significant and growing segment of worldwide beverage consumption, especially among adolescents and young adults. They are marketed primarily for their stimulatory effects, driven by combinations of caffeine, sugars, and other bioactive compounds. Despite widespread use, concerns have emerged within dental science about their deleterious effects on dental hard tissues — namely enamel and dentin. The unique chemical composition of these beverages promotes an oral environment conducive to erosion and demineralization, distinct from classic bacterial caries. Dental erosion refers to irreversible loss of dental hard tissues through direct chemical processes independent of bacterial metabolism; this contrasts with caries, where microbial acids are the primary etiological agents.

The critical plaque pH at which enamel begins to dissolve is approximately 5.5. Below this threshold, the hydroxyapatite crystals — the major mineral component of dental enamel — become undersaturated and begin to demineralize. Many energy drinks exhibit pH levels well below this critical value, often dropping below pH 4.0, which significantly accelerates mineral dissolution kinetics and enamel surface loss. The presence of organic acids, particularly citric acid, exacerbates this process because of both its acidity and chelation properties; it not only lowers pH but also can bind calcium ions, reducing their availability for remineralization. In addition to acidity, the titratable acidity — the total buffering capacity required to neutralize the beverage — correlates strongly with erosive potential. Beverages with higher titratable acidity maintain an acid challenge for longer periods even after initial neutralization starts, prolonging exposure of dental tissues to demineralizing conditions.

Organic acids such as citric and phosphoric acid differ in their mechanisms; citric acid also forms complexes with calcium, increasing enamel solubility.

Moreover, morphological studies using tools like scanning electron microscopy (SEM) and atomic force microscopy (AFM) reveal that energy drink exposure alters the surface microstructure of enamel, increasing surface roughness and creating micro-pits and etching patterns indicative of mineral loss. These morphological changes not only signify chemical dissolution but may also predispose teeth to mechanical wear and bacterial adhesion, further compromising structural integrity. While in-vitro studies provide controlled insights into chemical and morphological changes, clinical evidence on the prevalence of dental erosion associated specifically with energy drink consumption varies due to confounders such as oral hygiene behavior, concurrent dietary habits, and individual salivary characteristics. Nevertheless, the consensus across systematic literature supports a causal link between frequent exposure to highly acidic beverages and increased risk for tooth surface loss.

MATERIALS AND METHODS

Scientific research exploring the effects of energy drinks on dental hard tissues comprises primarily in-vitro experimental studies, complemented by systematic reviews and controlled observational assessments. These methods are designed to isolate chemical variables (e.g., pH, titratable acidity) and morphological endpoints while minimizing biological variability that occurs in the clinical environment.

In in-vitro experiments, extracted human or bovine teeth — especially enamel specimens — are commonly used due to their similarity in mineral composition and microstructure to in-vivo human enamel. Teeth are thoroughly cleaned and stored in physiologically relevant solutions prior to experimentation to simulate baseline oral conditions. These specimens are then immersed in various commercial energy drinks under controlled temperature and exposure times that mimic frequent human consumption patterns.

Chemical analyses begin with measuring the pH and titratable acidity of tested beverages using calibrated pH meters and standardized titration protocols. These physicochemical parameters provide quantitative data on the acid challenge that each beverage represents. Additionally, concentrations of calcium, phosphate, and other ions are often measured to assess potential contributions to demineralization kinetics.

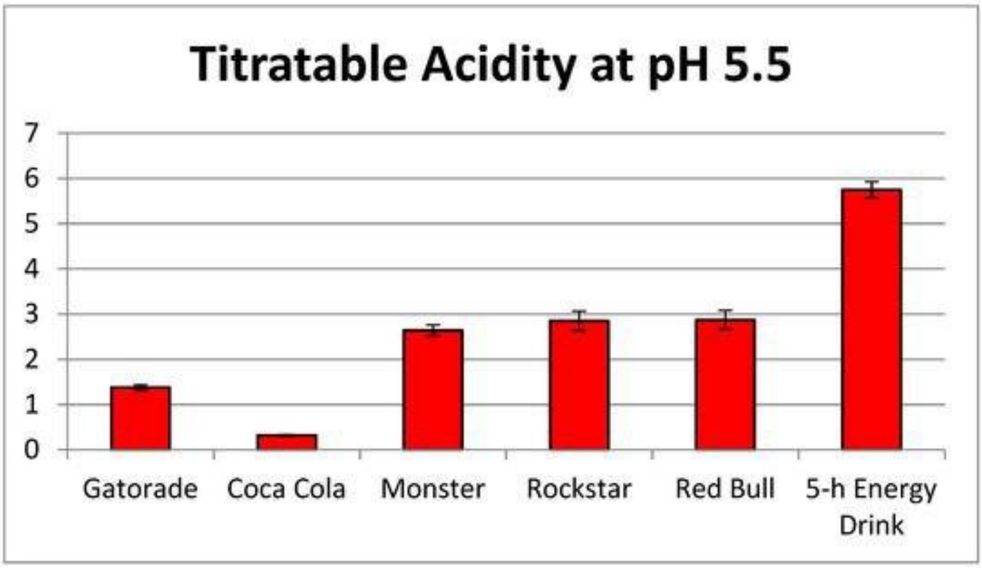
Surface microhardness — a proxy for mineral integrity — is evaluated using Vickers or Knoop hardness tests. Hardness reductions after exposure indicate loss of mineral content and structural weakening. Morphological characterization follows using SEM, which reveals topographical changes such as surface roughening, micro-pitting, and etching indicative of acid dissolution. Atomic force microscopy may complement SEM by quantifying changes in surface roughness at nanometer scales.

Figure-1: Despite many reports stating energy drinks are bad for your health (and teeth), they continue to gain popularity. What most people don't know is that the high

acidity level in these beverages can strip teeth enamel and leave permanent damage. It's time to consider whether the extra boost is worth the permanent risk to your smile.

In certain studies, energy drink formulations are chemically modified — for example, by adding calcium or phosphate complexes — to evaluate how alterations in composition influence erosive potential. Such experimental variations help isolate the roles of individual ingredients and improve understanding of mechanisms underlying enamel loss. Systematic reviews of existing literature employ rigorous inclusion criteria to synthesize results from observational and in-vitro studies. These reviews typically screen large datasets across multiple databases, applying standardized indices of dental erosion and demineralization, and perform statistical assessments to evaluate prevalence and severity outcomes.

Together, these methodologies form a comprehensive scientific basis that integrates chemical, morphological, and statistical analyses to elucidate the effects of energy drinks on dental hard tissues without reliance on individual clinical case reports.



RESULTS

Chemical Effects Chemical analyses consistently show that energy drinks are highly acidic, with measured pH values often substantially below the enamel dissolution threshold of pH 5.5. The presence of organic acids, especially citric acid, contributes not only to low pH but also to high titratable acidity — meaning the drinks resist neutralization and sustain an acid challenge.

Comparative studies between different energy drink brands indicate variability in pH and acidic strength, yet nearly all tested products exhibit erosive potential. Dissolution studies reveal significant reductions in enamel surface microhardness after exposure, suggesting demineralization and weakening of the crystalline structure. This mineral loss is directly correlated with both pH and titratable acidity, confirming that acidity magnitude and buffering capacity are critical determinants of chemical impact. Energy drinks modified with added calcium, phosphorus, or citrate complexes demonstrate reduced erosive potential — increased solution pH and decreased net demineralization — supporting the hypothesis that elevated mineral availability can partially counteract acid-driven dissolution. This finding aligns with the fundamental chemistry of hydroxyapatite dissolution, where increased external calcium and phosphate ions reduce the thermodynamic driving force for mineral loss.

MORPHOLOGICAL CHANGES: SEM and AFM imaging consistently demonstrate morphological alterations on enamel surfaces subjected to energy drink exposure. Unexposed enamel typically exhibits a smooth, prism-organized structure with tightly packed hydroxyapatite crystallites. After acid exposure, enamel surfaces show micro-pitting, loss of prism integrity, and increased nanoscale roughness — all hallmarks of acid etching and structural dissolution.

Quantitative roughness measurements from AFM indicate statistically significant increases in surface roughness parameters (Ra values) after energy drink treatment compared to control conditions. Such increases in roughness can enhance bacterial adhesion and contribute to progression of surface loss in vivo when coupled with mechanical and microbial factors. Morphological effects also extend to restorative dental materials when immersed in energy drinks. In vitro data find that acid exposure alters the surface roughness and microstructural properties of composite resins and fissure sealants, potentially compromising their longevity. While these materials are not part of natural dental hard tissues, this finding highlights the broad erosive influence of acidic beverages on both biological and synthetic substrates.

Statistical and Systematic Findings: Systematic reviews of studies on athletes and other high consumers of sports and energy drinks reveal a wide range of dental erosion prevalence, with some cohorts showing up to 100% affected enamel surfaces. However, these epidemiological data are confounded by variables such as mechanical stress, oral hygiene practices, and individual salivary buffering capacity. Nonetheless, most studies indicate that regular consumption of acidic drinks correlates with elevated risk for enamel and dentin erosion. Controlled in-vitro experiments support these epidemiological trends by demonstrating dose-dependent effects: longer exposure times and higher frequency of acidic contact result in greater mineral loss and more pronounced morphological changes. These patterns hold across multiple beverage types and experimental setups.

Experimental comparison of modified drinks further underlines the statistical significance of composition changes: adding calcium and other remineralizing agents statistically reduces enamel surface loss compared to unmodified energy drinks in controlled settings. Overall, results from chemical, morphological, and statistical analyses provide a coherent picture: frequent or prolonged exposure to acidic energy drinks leads to measurable chemical dissolution and morphological degradation of dental hard tissues under experimental conditions.

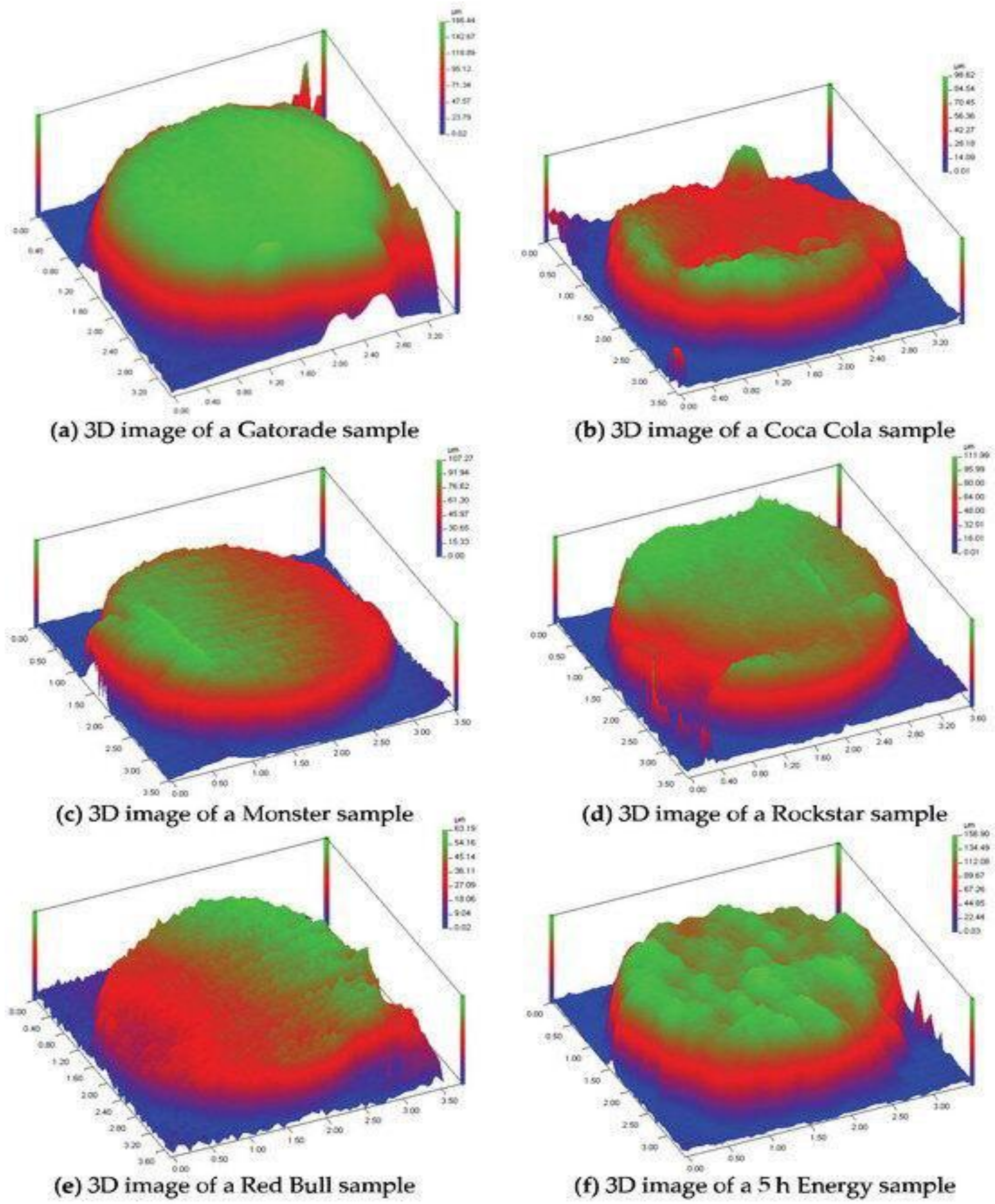
DISCUSSION

Interpreting Chemical Mechanisms: The erosion of dental hard tissues can be described thermodynamically and kinetically. Hydroxyapatite, the principal mineral in enamel and dentin, dissolves when the surrounding solution becomes undersaturated with respect to calcium and phosphate. The critical plaque pH of ~5.5 marks the onset of this undersaturation. Energy drinks, due to their composition, frequently produce oral environments below this threshold.

Citric acid plays a dual role: it contributes to low pH and acts as a chelating agent. Chelation binds free calcium ions, which further reduces mineral saturation and accelerates dissolution rates. This mechanism is supported by experiments showing that beverages with higher citric acid concentrations produce greater enamel microhardness loss than drinks with similar pH but lower chelating capacity.

Titratable acidity extends this concept by factoring in the total amount of base required to neutralize the solution. A beverage with moderate pH but high titratable acidity poses a sustained acid challenge, prolonging the time that enamel remains undersaturated and susceptible to dissolution. In a physiological context, saliva plays a buffering role; however, high titratable acidity can overwhelm this buffer, keeping acid conditions longer than would pH alone suggest.

Enhanced mineral concentrations — as in drinks supplemented with calcium and phosphate — shift the dissolution equilibrium toward saturation, reducing net mineral loss. This supports a preventive approach where beverage formulation could mitigate erosive potential. While modifying energy drinks in this way does not eliminate risk entirely, it demonstrates a viable chemical strategy for reducing enamel dissolution in research settings.



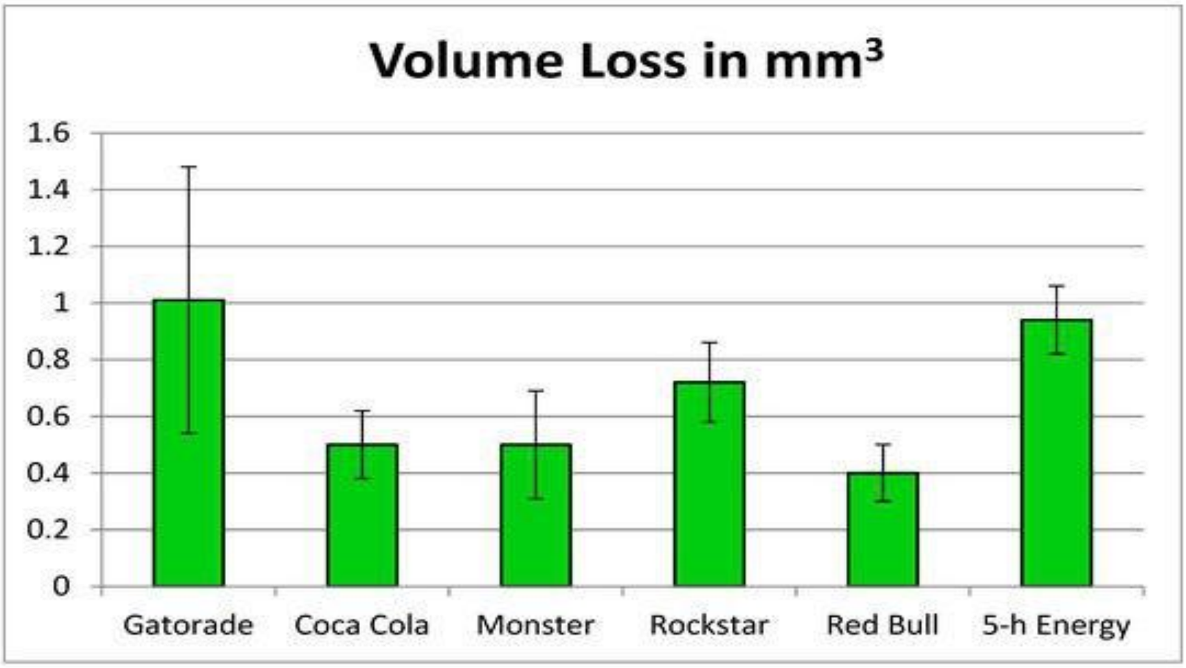
(a) 3D image of a Gatorade sample
(b) 3D image of a Coca Cola sample
(c) 3D image of a Monster sample
(d) 3D image of a Rockstar sample
(e) 3D image of a Red Bull sample
(f) 3D image of a 5 h Energy sample

2-Figure: Despite many reports stating energy drinks are bad for your health (and teeth), they continue to gain popularity. What most people don't know is that the high acidity level in these beverages can strip teeth enamel and leave permanent damage. It's time to consider whether the extra boost is worth the permanent risk to your smile.

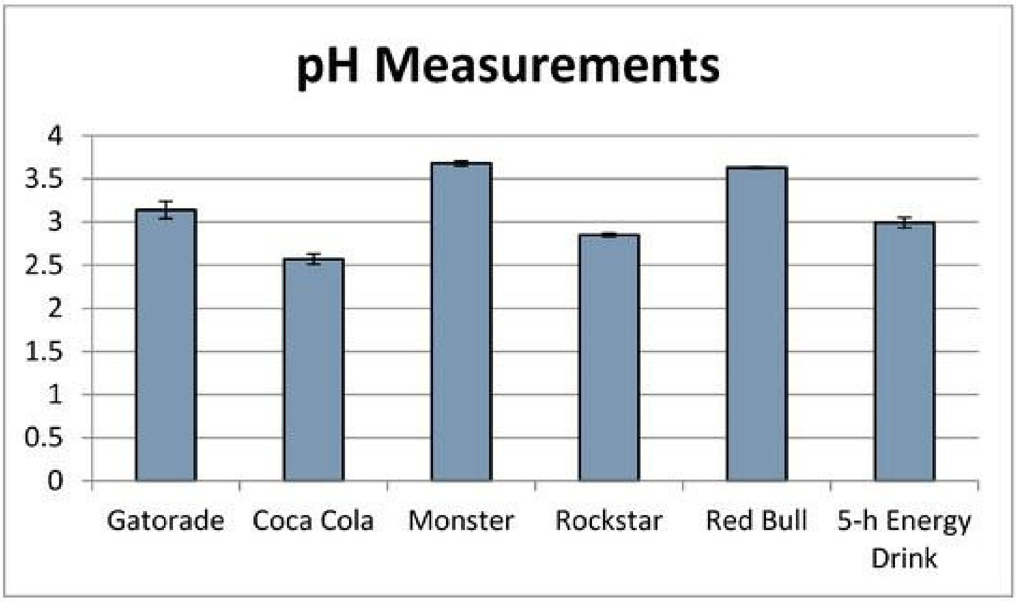
Morphological Implications for Teeth: Surface morphology directly reflects underlying chemical dissolution. SEM and AFM imaging reveal changes that cannot be detected by bulk mineral measurements alone. Increased surface roughness (Ra) is significant because rougher surfaces facilitate plaque retention and bacterial colonization. These conditions can indirectly accelerate caries and mechanical wear. Moreover, micro-pits and disrupted enamel prisms represent structural vulnerabilities that may not fully remineralize if demineralization is persistent.

The morphological degradation observed in vitro suggests that teeth exposed repeatedly to acidic conditions will have compromised mechanical properties. Loss of enamel thickness reduces its ability to protect the underlying dentin and pulp, potentially increasing sensitivity and susceptibility to fracture. Although in vitro systems cannot fully replicate in-vivo complex dynamics (e.g., salivary flow, oral clearance), they provide compelling evidence of direct acid effects at the tissue level.

Clinical and Public Health Perspectives: Epidemiological data from athletes and frequent consumers highlight the real-world relevance of in-vitro findings. High prevalence of erosion in these groups suggests that repeated acid exposure, combined with mechanical stresses (e.g., bruxism or training conditions), accelerates dental hard tissue loss. However, clinical studies often vary due to confounders like oral hygiene practices, fluoride exposure, and genetics. Therefore, while a direct causal link is supported mechanistically, more standardized clinical research is needed for quantifying population risk precisely.



Clinical prevention strategies should focus on reducing the frequency and duration of acid exposure. This may include limiting energy drink intake, encouraging water rinsing post-consumption, and increasing salivary stimulation through sugar-free gum. Fluoride and other remineralizing agents may help re-establish enamel saturation post-challenge, but cannot fully reverse morphological changes once they occur. Thus, preventive emphasis remains paramount. Limitations and Future Directions Most evidence stems from in-vitro studies, which, by design, isolate specific variables but cannot fully mimic the oral environment's complexity. Factors such as salivary flow, pellicle formation, and dynamic pH fluctuations are difficult to replicate. More longitudinal clinical studies with standardized erosion indices and controlled dietary recording are needed to quantify real-world risk and threshold levels of consumption.



Future research could explore beverage reformulation with higher buffering capacity or added minerals, as initial in-vitro Evidence indicates potential mitigation of erosive effects. Additionally, investigating individual susceptibility factors — such as saliva composition and genetic determinants of enamel composition — may refine risk stratification.

CONCLUSION

Scientific evidence consistently demonstrates that energy drinks pose a significant risk to dental hard tissues due to their low pH, high titratable acidity, and chelating organic acids. These chemical properties create an environment that promotes enamel demineralization beyond the critical saturation point, resulting in measurable mineral loss and reduced surface microhardness. Morphological analyses reveal surface roughening, pitting, and structural deterioration consistent with acid erosion. While in-vitro conditions cannot fully recapitulate the oral environment, they provide fundamental mechanistic insights that align with epidemiological observations in populations with high beverage consumption. Preventive strategies should emphasize reducing frequency of exposure, supporting salivary buffering, and enhancing remineralization, but the irreversible nature of enamel loss underscores the importance of public health education on limiting energy drink intake. Continued research, particularly longitudinal clinical studies, is necessary to establish standardized risk models and effective mitigation approaches.

References:

1. Boyd RL, Baumrind S. The effects of orthodontic treatment on periodontal status. Am J Orthod Dentofacial Orthop.
2. van der Weijden F, Slot DE. Oral hygiene in orthodontic patients: a systematic review. Am J Orthod Dentofacial Orthop.
3. Ergashev, B. (2025). Sirkon dioksid qoplamalari va materialining klinik laborator ahamiyati. Journal of Uzbekistan’s Development and Research (JUDR), 1(1), 627–632.
4. Ergashev, B. (2025). Gingivitning bakteriologik etiologiyasi va profilaktikasi. In International Scientific Conference: Innovative Trends in Science, Practise and Education, 1(1), 122–128.
5. Ergashev, B. (2025). Bemorlar psixologiyasi va muloqot ko‘nikmalari. Modern Science and Research, 4(2), 151–156.
6. Ergashev, B. (2025). Pulpitning etiologiyasi, patogenezi, morfologiyasi va klinik simptomlari. Modern Science and Research, 4(3), 829–838.

7. Ergashev, B. (2025). Stomatologiyada tish kariesi: Etiologiyasi, diagnostika va davolash usullari. Modern Science and Research, 4(3), 821–828.
8. Ergashev, B. (2025). Tish emal prizmalariga yopishib olgan tish blyashka matrixning mikrobiologiyasi va tarkibi. Modern Science and Research, 4(3), 815–820.
9. Ergashev, B. (2025). Advances in oral health: Prevention, treatment, and systemic implications. American Journal of Education and Learning, 3(3), 1108–1114.
10. Tursunaliyev, Z., & Ergashev, B. (2025). Bolalarda tish kariesini oldini olish usullari. Modern Science and Research, 4(4), 686–691.
11. Ergashev, B. (2025). Karies va paradont kasalliklari profilaktikasi. Modern Science and Research, 4(4), 732–741.
12. Ergashev, B. (2025). Psychological support for cancer patients. ИКРО журнал, 15(1), 164–167.
13. Ergashev, B., & Raxmonov, Sh. (2025). Oral trichomoniasis: Epidemiology, pathogenesis, and clinical significance. Kazakh Journal of Ecosystem Restoration and Biodiversity, 1(1), 19–27.
14. Ergashev, B., & Raxmonov, Sh. (2025). Transmission dynamics of tuberculosis. Kazakh Journal of Ecosystem Restoration and Biodiversity, 1(1), 28–35.
15. Ergashev, B. J. (2025). Uch shoxli nervning yallig‘lanishi. Research Focus, 4(3), 162–169.
16. Ergashev, B. J. (2025). Tish kariesi tarqalishining ijtimoiy va biologik omillari. Журнал научных исследований и их решений, 4(2), 427–430.
17. Raxmanov, Sh., Baxadirov, M., & Ergashev, B. (2025). Skin diseases laboratory diagnosis. Международный мультидисциплинарный журнал исследований и разработок, 1(3), 130–132.
18. Ergashev, B. J. (2025). Tish olish operatsiyasidan keyingi asoratlar. Журнал научных исследований и их решений, 4(2), 421–426.
19. Ergashev, B. J. (2025). Tish og‘rig‘ining etiologiyasi va zamonaviy davolash usullari. Ta’lim Taraqqiyoti, 1(1), 57–63.
20. Ergashev, B. J. (2025). To‘liq va qisman adentiya etiologiyasi. Is’hoqxon Ibrat Followers Journal, 1(1), 9–17.
21. Ergashev, B. J. (2025). Yuz nervining yallig‘lanishi. Research Focus, 4(3), 155–161.
22. Ergashev, B. J. (2025). Energetik ichimliklarning tish emaliga ta’siri. Журнал научных исследований и их решений, 4(2), 416–420.
23. Ergashev, B. J. (2025). Kennedy classification: Its significance. Tabib, 1(1), 1–7.
24. Ergashev, B. (2023). Tish toshlari. Models and Methods for Increasing the Efficiency of Innovative Research, 1(2), 67–75.Chang HS, Walsh LJ, Freer TJ. Enamel demineralization during orthodontic treatment. Orthod Craniofac Res.
25. Benson PE, Parkin N, et al. Preventing white spot lesions in orthodontics. Cochrane Database Syst Rev.