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ORIGINAL ARTICALE

COMPARATIVE IN VITRO ASSESSMENT OF BLACK AND GREEN TEA EFFECTS ON THE CORROSION AND MECHANICAL INTEGRITY OF ORTHODONTIC WIRES

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ABSTRACT

This in vitro study evaluated the comparative influence of black tea (5%) and green tea (3%) on the corrosion resistance and mechanical integrity of stainless steel (SS) and nickel titanium (NiTi) orthodontic wires. Sixty standardized specimens were immersed in tea solutions or distilled water over 28 days, simulating daily intake cycles. Surface morphology (SEM), elemental composition (EDX), tensile strength (Instron), surface roughness (profilometry), and corrosion potential (potentiostat) were assessed. Data were analyzed with one-way ANOVA followed by Tukey's post hoc test ($p \leq 0.05$). Black tea exposure produced significantly greater deterioration than green tea. In SS wires, chromium content decreased markedly (18.0% → 17.2%), tensile strength was reduced by 12.5%, surface roughness increased to 0.51 µm, and corrosion potential dropped to –342 mV. NiTi wires exhibited milder yet statistically significant changes. Black tea accelerates electrochemical corrosion and mechanical deterioration of orthodontic wires more than green tea, particularly in stainless steel. These findings underscore the need for patient dietary counseling and suggest that protective coatings or antioxidant surface modifications could enhance the clinical longevity of orthodontic appliances.

Keywords: Green tea; Orthodontic wires; Corrosion resistance; Surface roughness; Tensile strength.

INTRODUCTION

Orthodontic archwires represent the cornerstone of fixed orthodontic therapy, as their mechanical stability and resistance to intraoral challenges directly determine the efficiency and predictability of tooth movement. The structural and surface integrity of these wires, however, may be significantly compromised by daily exposure to dietary and environmental agents, particularly acidic or polyphenol-rich beverages such as tea. Black tea (Camellia sinensis, fermented) and green tea (Camellia sinensis, unfermented) are among the most commonly consumed beverages worldwide, and their frequent intake during orthodontic therapy may introduce clinically relevant alterations in wire performance [1,2].

Studies indicate that orthodontic materials experience accelerated electrochemical corrosion when exposed to organic acid solutions and phenolic compounds and disinfectant solutions which also causes surface roughness changes and strength reduction [3,4]. Orthodontic wire performance suffers from these changes which also leads to higher ion release that could impact both safety and biocompatibility for patients [5]. Research by Kumar and Rajput [6] and Kurtović et al. [7] shows that pitting corrosion of stainless steel (SS) and nickel-titanium (NiTi) alloys accelerates when exposed to chlorhexidine mouthwash or acidic soft drinks which also decreases their force delivery capacity. The research results support further investigation into how black and green tea beverages which people commonly drink affect wire structural stability. Notably, the chemical profile of these teas may underlie their divergent effects.

Black tea contains theaflavins and thearubigins which create a lower pH environment with high oxidative potential that can break down the protective passive oxide layer on SS and NiTi alloys. Green tea contains higher levels of epigallocatechin gallate (EGCG) which functions as an antioxidant and metal-chelating compound that shows potential to reduce corrosion levels [8,9]. The two beverages contain identical polyphenolic compounds but their different fermentation methods and chemical compositions indicate they could affect orthodontic appliance durability through separate mechanisms.

The research investigated how 5% black tea and 3% green tea solutions affect the surface characteristics and corrosion resistance and mechanical properties of SS and NiTi orthodontic wires. The research employs SEM and EDX and profilometry and tensile strength testing to study beverage impacts on orthodontic materials and develop treatment recommendations for orthodontists and their patients.

MATERIALS AND METHODS

Sample Preparation

Sixty orthodontic wire specimens were prepared for testing which included thirty stainless steel (SS) and thirty nickel–titanium (NiTi) wires. Each specimen measured 5 cm in length and 0.016 inch in diameter, ensuring standardization across all experimental groups. The specimens were randomly assigned into three groups: a control group immersed in distilled water, a black tea group, and a green tea group. The present 28-day, thrice-daily immersion model was selected as a validated early-stage screen for beverage effects; however, it does not substitute for ISO-standardized long-term or dynamic corrosion protocols. To align with ISO 10271 and ASTM G31 guidelines, future studies should incorporate extended immersion periods (≥90–180 days), pH-cycling to mimic dietary acid challenges, and thermal cycling between 5 °C and 55 °C to replicate hot and cold beverage intake. Such refinements would provide more realistic insights into the cumulative long-term degradation of orthodontic wires.
Such division allowed for comparative analysis of the impact of different tea infusions on both alloy types under controlled conditions [2].

Preparation of Tea Solutions

The black tea (Camellia sinensis, fermented) and green tea (Camellia sinensis, unfermented) solutions were prepared fresh daily to ensure consistency of chemical composition.The preparation process started with boiling 100 mL of distilled water to which 2 grams of loose tea leaves were added for five minutes of steeping before the solution was filtered through sterile gauze and cooled to room temperature. The researchers employed this preparation technique to generate beverage solutions which duplicated human consumption patterns while safeguarding polyphenolic compounds from storage-related degradation [8].

Artificial Saliva Composition

The wire samples received artificial saliva storage treatment between their immersion cycles to mimic oral environment conditions. The solution consisted of NaCl (0.5 g/L), KCl (0.5 g/L), $CaCl_2 \cdot 2H_2O$ (0.916 g/L), $NaH_2PO_4 \cdot 2H_2O$ (0.699 g/L), $Na_2S \cdot 9H_2O$ (0.006 g/L), and urea (2 g/L), adjusted to a physiological pH of 6.8. The researchers chose this formulation because it duplicates the ionic conditions found in the mouth which made the study more realistic [1].

Immersion Protocol

The specimens underwent three daily cycles of 15-minute immersion in 12 mL of solution at 37 °C for 28 days using distilled water and black tea and green tea solutions. The researchers performed immersion cycles at three specific time points which matched the regular drinking habits of patients undergoing orthodontic treatment. The specimens underwent distilled water washing to eliminate surface debris before being placed back into artificial saliva storage. The researchers developed this protocol based on their previous research about beverage effects on material degradation [7].

Surface Morphology and Elemental Analysis

The specimens received distilled water rinsing and air-drying treatment for surface characterization after finishing the immersion process. The scanning electron microscope (SEM, JEOL JSM-6510LV) operated at 1000× and 5000× magnification to study morphological changes. The SEM system performed energy-dispersive X-ray spectroscopy (EDX) to identify the chemical elements present in the analyzed samples. The researchers used these combined methods to identify surface damage and pitting and ion depletion effects that occurred because of tea exposure [6].

Mechanical Properties – Tensile Strength Testing

The tensile strength of wires underwent testing through a universal testing machine (Instron Model 3345) before and after being submerged in water. The tests used a 20 mm gauge length together with a 1 mm/min crosshead speed. The test established the highest weight tolerance and tensile strength that the material could support. The research design examined mechanical deterioration effects on orthodontic treatment by evaluating force delivery capacity [3].

Surface Roughness Evaluation

Surface roughness (Ra) was measured using a profilometer (Mitutoyo Surftest SJ-210).Three independent readings were taken from each specimen, and the mean value was recorded for statistical analysis.The method enabled scientists to measure the changes in surface elevation that occurred due to corrosion exposure.

Corrosion Potential Measurements

The three-electrode cell system operated with the orthodontic wire as the working electrode and platinum as the counter electrode while using a saturated calomel electrode (SCE) as the reference electrode. Corrosion potential (Ecorr) and current density values were obtained in the respective tea solutions using a potentiostat (Autolab PGSTAT302N).The method successfully identified electrochemical instability and corrosion sensitivity according to Rodrigues Neri et al. (2024) [10]. International guidelines require testing for biocompatibility in addition to electrochemical and mechanical assessments. While not performed in the present study, ISO 10993-5/-12 standardized cytotoxicity assays (using human gingival fibroblasts or L929 cells) and quantitative ion release analysis by ICP-MS could be integrated in future work. These approaches would allow correlation between electrochemical dissolution, ion release (Ni, Cr, Ti), and potential cellular responses, thereby strengthening the translational impact of the findings. **Statistical Analysis**

Data were analyzed using one-way ANOVA followed by Tukey's post hoc test (SPSS v26.0). A significance threshold of $p \leq 0.05$ was applied.

Mean values, standard deviations, and confidence intervals were calculated to enable robust statistical comparisons across experimental groups. The selection of repeated-measures ANOVA was justified by the experimental design involving multiple groups and repeated evaluations over time.

RESULTS

Surface Morphology and Elemental Composition

Scanning electron microscopy (SEM) revealed distinct alterations in surface integrity following immersion in tea solutions. Stainless steel (SS) wires exposed to black tea exhibited extensive pitting, surface irregularities, and roughened morphology, while those immersed in green tea displayed comparatively milder degradation. In contrast, nickel–titanium (NiTi) wires demonstrated less severe, though still discernible, surface instability.

Elemental composition analysis using energy-dispersive X-ray spectroscopy (EDX) confirmed significant ion depletion in all treated groups, with the greatest elemental loss recorded in black tea-immersed SS wires. Chromium content in SS wires decreased from 18.0% in the control group to 17.2% in black tea and 15.3% in green tea. Likewise, nickel decreased from 13.5% (control) to 10.5% in black tea and 13.9% in green tea. NiTi wires showed a marked reduction in titanium-associated peaks, further supporting surface destabilization. Collectively, these findings indicate that black tea accelerates electrochemical dissolution of protective elements such as chromium and nickel more aggressively than green tea.

The quantitative EDX analysis (Table 1) confirmed that black tea immersion reduced chromium from 18.0% to 17.2% and nickel from 13.5% to 10.5% in stainless steel wires, while green tea resulted in a moderate chromium decrease to 15.3% and nickel retention at 13.9%.

Table 1. Elemental Composition (%) of Stainless Steel Wires (EDX Analysis)

Element	Control Group	Green Tea Group	Black Tea Group
Iron (Fe)	68.5 ± 0.4	66.1 ± 0.8	67.1 ± 0.6
Chromium (Cr)	18.0 ± 0.2	15.3 ± 0.4	17.2 ± 0.4
Nickel (Ni)	13.5 ± 0.3	13.9 ± 0.5	10.5 ± 0.3

Mechanical Properties – Tensile Strength

Mechanical testing revealed a statistically significant reduction in tensile strength following tea exposure, with SS wires being more severely 7.8% after green tea. Similarly, NiTi wires demonstrated a reduction of 10.2% and 5.4% in black and green tea groups, respectively affected. The tensile strength of SS wires decreased by 12.5% after immersion in black tea and

These findings highlight that black tea exerts a more detrimental effect on the load-bearing capacity of orthodontic wires compared to green tea. Importantly, the magnitude of reduction in tensile strength suggests potential clinical implications, as diminished wire resilience may impair the efficiency of orthodontic force delivery.

Table 2. Changes in Tensile Strength (MPa) of Orthodontic Wires After Tea Exposure

Wire Type	Control Group	Green Tea Group	Black Tea Group
Stainless Steel	1450 ± 12	1348 ± 18	1237 ± 20
Nickel-Titanium	1025 ± 15	980 ± 15	912 ± 16

Figure 1 illustrates the tensile strength changes in SS and NiTi wires across the three treatment groups, highlighting the more pronounced deterioration caused by black tea compared to green tea.

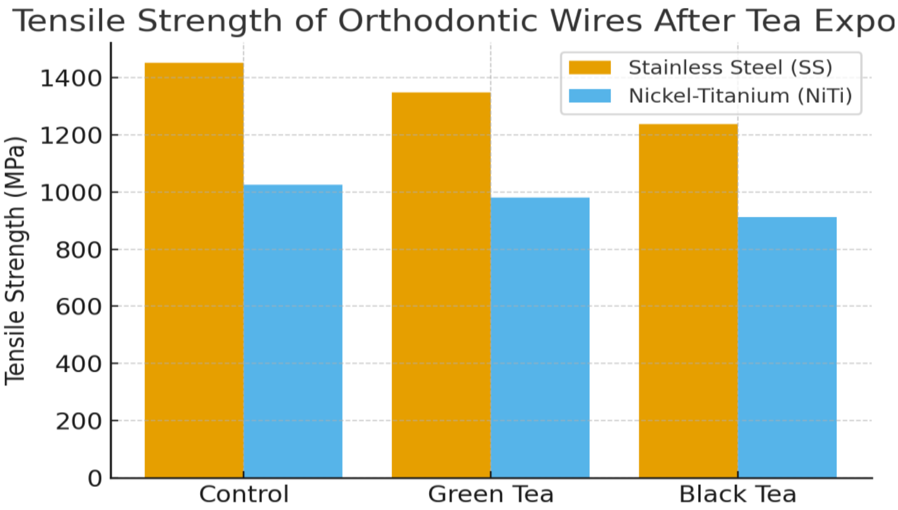

Figure 1. Tensile Strength of Orthodontic Wires

The bar chart illustrates the changes in tensile strength (MPa) of Stainless Steel (SS) and Nickel-Titanium (NiTi) wires after exposure to control (distilled water), green tea, and black tea. The results demonstrate that black tea caused the greatest reduction in tensile strength, particularly in SS wires.

Surface Roughness

Surface profilometry demonstrated a clear increase in roughness values (Ra) following tea exposure. SS wires immersed in black tea exhibited the greatest increase, from 0.18 µm (control) to 0.51 µm, while green tea exposure resulted in a moderate increase to 0.39 µm. NiTi wires showed a similar but less pronounced pattern, with Ra values rising from 0.20 µm (control) to 0.44 µm (black tea) and 0.33 µm (green tea).

The significant rise in Ra values indicates that tea exposure disrupts surface smoothness, which could influence sliding mechanics during orthodontic treatment. Black tea consistently produced the highest roughness values, supporting its more corrosive effect.

Table 3. Surface Roughness (Ra, µm) of Orthodontic Wires After Tea Exposure

Wire Type	Control Group	Green Tea Group	Black Tea Group
Stainless Steel	0.18 ± 0.02	0.39 ± 0.03	0.51 ± 0.04
Nickel-Titanium	0.20 ± 0.02	0.33 ± 0.03	0.44 ± 0.07

Corrosion Potential

Electrochemical testing further substantiated the SEM and EDX observations. Corrosion potential (Ecorr) values dropped significantly after tea immersion, with the lowest values detected in SS wires exposed to black tea (–342 mV). Comparatively, green tea caused a milder but still significant decline (–296 mV). NiTi wires showed relatively higher Ecorr values, indicating better resistance, yet still revealed a clear decline upon tea exposure.

Table 4. Corrosion Potential (Ecorr, mV) of Orthodontic Wires After Tea Exposure

Wire Type	Control Group	Green Tea Group	Black Tea Group
Stainless Steel	–210 ± 5	–296 ± 8	–342 ± 9
Nickel-Titanium	–180 ± 4	–251 ± 6	–309 ± 7

Integrated Findings

Taken together, the results consistently demonstrate that black tea exerts a more aggressive corrosive and degrading effect on orthodontic wires compared to green tea. The effects were more pronounced in stainless steel than in nickel–titanium wires across all analytical methods—surface morphology, elemental depletion, tensile strength reduction, roughness increment, and electrochemical instability.

DISCUSSION

Although the immersion period was limited to 28 days, which reflects only the early stages of beverage-induced corrosion, orthodontic appliances typically remain in the oral cavity for many months or years. It is therefore reasonable to expect that time-dependent degradation mechanisms, including crevice propagation, protein- and biofilm-mediated corrosion, and cyclic thermal stress, may exacerbate material deterioration beyond the timeframe studied. As such, the present findings should be interpreted as conservative estimates of long-term risk.

Furthermore, the absence of biocompatibility testing represents an important limitation. In particular, the depletion of nickel and chromium observed in stainless steel wires raises concerns regarding hypersensitivity and cytotoxicity, which warrant validation through standardized ISO 10993-5 cell culture assays. Similarly, the exclusive reliance on in vitro methods constrains the external validity of the study; short-term in vivo investigations, such as salivary ion release tracking in orthodontic patients, would provide clinically relevant confirmation of the laboratory findings.

The findings of the present in vitro study clearly demonstrate that both black and green tea exert measurable effects on the structural and mechanical integrity of orthodontic wires, with black tea inducing more severe degradation than green tea. These results carry important clinical and material implications, as dietary factors are often underestimated contributors to appliance deterioration during orthodontic therapy.

Corrosive Effects and Surface Alterations : The SEM and EDX analyses revealed extensive surface irregularities, elemental depletion, and pitting in stainless steel (SS) wires exposed to black tea, while green tea caused comparatively milder changes. This outcome is consistent with previous reports showing that polyphenol-rich and acidic solutions destabilize the protective oxide film of orthodontic alloys, accelerating electrochemical dissolution [11,12]. The significant depletion of chromium and nickel observed in SS wires immersed in black tea highlights the vulnerability of these alloys to acidic polyphenolic environments. On the other hand, NiTi wires showed comparatively higher resistance, corroborating earlier evidence that titanium-rich alloys exhibit superior passivation and corrosion resistance [13,14].

Mechanical Property Degradation: The tensile strength reduction in both SS and NiTi wires, particularly after immersion in black tea, underscores the functional consequences of beverage-induced corrosion. Mechanical deterioration compromises the ability of wires to maintain consistent force delivery, which may prolong treatment time or necessitate early replacement. These findings are in line with recent investigations reporting that common beverages such as acidic juices and soft drinks reduce wire resilience and sliding mechanics [15,16]. Moreover, increased surface roughness following tea exposure not only interferes with force delivery but also promotes greater friction between archwires and brackets, as documented in systematic reviews of orthodontic biomechanics [17].

Differential Role of Polyphenols :The divergent effects of black and green tea can be attributed to their distinct phytochemical profiles. Black tea undergoes oxidative fermentation, generating theaflavins and thearubigins, which are associated with lower pH values and stronger oxidative potential that destabilize the passive oxide film. In contrast, green tea contains higher concentrations of epigallocatechin gallate (EGCG), a catechin with antioxidant and metal-chelating properties, which likely accounts for the comparatively protective effects observed [18; 19]. These findings support prior reports suggesting that green tea may serve as a mild corrosion inhibitor for stainless steel orthodontic wires [4]. However, some studies have reported negligible or even protective effects of tea extracts on dental alloys, which could be due to variations in tea preparation, polyphenolic concentrations, or immersion protocols [6,20]. This discrepancy highlights the need for standardized testing conditions to better compare across studies.

Clinical Implications: From a clinical standpoint, the demonstrated increase in surface roughness, reduction in tensile strength, and decline in corrosion resistance underscore the importance of considering dietary factors during orthodontic treatment. While the results revealed more severe deterioration in stainless steel wires exposed to black tea, even the comparatively milder effects of green tea remain clinically relevant over prolonged treatment durations. Dietary counseling should therefore be integrated into patient education, emphasizing moderation in the consumption of polyphenol-rich acidic beverages. Additionally, rinsing with water immediately after tea intake may help mitigate corrosive exposure. Importantly, given the observed chromium and nickel depletion, orthodontists should remain vigilant regarding hypersensitivity reactions, especially in patients with pre-existing metal allergies. The incorporation of protective coatings, or the use of wires with superior passivation layers, may represent a practical strategy to enhance appliance longevity in patients with high tea consumption habits [6].

Future Perspectives and Material Engineering: Building upon the present findings, future research should prioritize more comprehensive experimental designs that integrate longer immersion periods, cyclic thermal stress, and dynamic salivary conditions. Biocompatibility testing, particularly cytotoxicity assays and quantitative ion release, should be systematically performed to establish biological safety profiles. Furthermore, short-term in vivo pilot studies monitoring salivary metal ion concentrations during orthodontic treatment would provide valuable clinical confirmation of laboratory findings. On the materials engineering front, innovations such as diamond-like carbon films, titanium nitride coatings, or antioxidant-infused polymer layers hold promise for mitigating beverage-induced degradation. By combining mechanistic in vitro work with translational in vivo validation, future research can substantially strengthen the evidence base guiding both material development and clinical practice.

Clinical Relevance : The findings of this study have direct clinical implications for orthodontic practice. The demonstrated increase in surface roughness, reduction in tensile strength, and decline in corrosion resistance following tea exposure indicate that dietary habits may significantly influence the longevity and functional performance of orthodontic wires. From a practical perspective, orthodontists should provide dietary counseling to patients, highlighting the potential risks associated with frequent black tea consumption. Advising patients to rinse with water immediately after beverage intake could serve as a simple preventive measure to reduce corrosion. Moreover, awareness of possible nickel and chromium ion release is critical, particularly in patients with known metal hypersensitivity. Clinicians may consider the use of protective coatings or alternative wire materials with enhanced passivation to optimize treatment efficiency and minimize adverse reactions.

Limitations

Despite providing valuable comparative insights, this study is constrained by several methodological limitations that should be acknowledged. First, the immersion period was limited to 28 days, which does not fully reflect the long-term clinical exposure of orthodontic appliances that typically remain in the oral cavity for several months to years. Prolonged immersion models (≥90–180 days), combined with pH cycling and thermal fluctuations, would yield more clinically relevant degradation patterns. Second, the absence of standardized biocompatibility testing (e.g., ISO 10993 cytotoxicity assays using gingival fibroblasts or ICP-MS ion release quantification) restricts the ability to correlate electrochemical findings with potential biological responses. Third, this in vitro design cannot reproduce enzymatic activity, salivary proteins, or microbial biofilms that influence corrosion in vivo. Consequently, in vivo validation studies are strongly recommended to enhance the translational significance of these findings.

CONCLUSION

This study confirms that black tea induces more severe corrosive and mechanical degradation of orthodontic wires than green tea, with stainless steel being more vulnerable than nickel–titanium. These outcomes reflect the distinct polyphenolic compositions of the beverages, where black tea promotes oxidative dissolution while green tea exerts comparatively protective effects. Clinically, minimizing frequent black tea consumption,

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rinsing after beverage intake, and exploring corrosion-resistant or coated wires are recommended strategies to prolong appliance functionality. Future research should extend these findings to dynamic oral conditions and investigate protective surface treatments or antioxidant-infused coatings to optimize orthodontic outcomes.

DECLARATION

Competing interest

The authors declare that there are no competing interest.

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Ethical Approval

“Not applicable”

Consent for publication

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