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Flavor Stability And Volatile Compound Preservation In Pre-Workout, Post-Workout, And Meal-Replacement Formulas

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Abstract
The stability of flavor and aroma compounds is a critical determinant of product quality, consumer acceptance, and market success in sports nutrition formulations. This study investigates the mechanisms of volatile compound degradation and preservation in pre-workout, post-workout, and meal-replacement products under controlled environmental and processing conditions. A comprehensive experimental dataset was developed comprising formulation parameters, GC–MS and HS-SPME profiles, and sensory evaluation data. The formulations—caffeine–citrus (pre-workout), chocolate–vanilla whey (post-workout), and fruit–nut blends (meal-replacement)—were subjected to accelerated storage conditions at varying temperatures (25°C–80°C), relative humidity levels (50–70%), and durations (7–30 days). Quantitative analysis using Gas Chromatography–Mass Spectrometry revealed significant declines in key volatiles such as limonene, hexanal, and vanillin, corresponding with sensory score reductions over time. Principal Component Analysis (PCA) and first-order kinetic modeling were applied to interpret degradation pathways and to identify influential parameters governing flavor loss. Results indicate that microencapsulation with maltodextrin or gum arabic, com- bined with antioxidant inclusion (ascorbic acid or tocopherols), significantly enhanced volatile retention by 25–40% compared to untreated controls. The findings demonstrate a strong correlation (r > 0.85) between chemical and sensory data, validating the analytical framework. This study establishes a reproducible, multi-modal dataset integrating chemical, sensory, and computational evidence, offering a robust methodology for optimizing flavor stability and preservation strategies across diverse sports nutrition formulations.

Keywords: Flavor stability, volatile compounds, GC–MS, HS-SPME, microencapsulation, sports nutrition, degradation kinetics, PCA analysis, sensory evaluation, antioxidant stabilization.

1 Introduction

The rapid growth of the sports nutrition industry has fueled a parallel demand for improved sensory quality, palatability, and consumer experience in pre-workout, post-workout, and meal- replacement formulations. Beyond macronutrient composition and bioavailability, flavor and aroma play a decisive role in consumer acceptance and adherence to dietary regimens. In formulations that typically include bitter-tasting compounds such as caffeine, amino acids, or branched-chain peptides, flavor stability becomes a crucial determinant of perceived quality and repeat purchase intent. Despite technological advances in flavoring and encapsulation, the volatility and instability of aroma compounds remain a persistent challenge in maintaining consistent sensory quality over storage, transportation, and reconstitution[1].

Volatile flavor compounds, such as esters, aldehydes, ketones, terpenes, and phenolic derivatives, are chemically labile and undergo degradation through multiple reaction mechanisms. These include oxidation, thermal breakdown, acid-base hydrolysis, and Maillard-type reactions. Figure 1 provides an overview of the major chemical routes leading to flavor deterioration, illustrating how terpenes such as limonene oxidize to carveol or carvone, while aldehydes like hexanal undergo autoxidation to form short-chain acids. In protein-rich systems such as whey or soy, reactive carbonyls derived from lipid oxidation may also participate in Strecker degradation or Schiff base formation, resulting in loss of volatile potency and the emergence of undesirable off-flavors.

The susceptibility of volatiles to degradation is further influenced by matrix interactions. Proteins, carbohydrates, and lipids can bind or encapsulate volatile molecules, altering their

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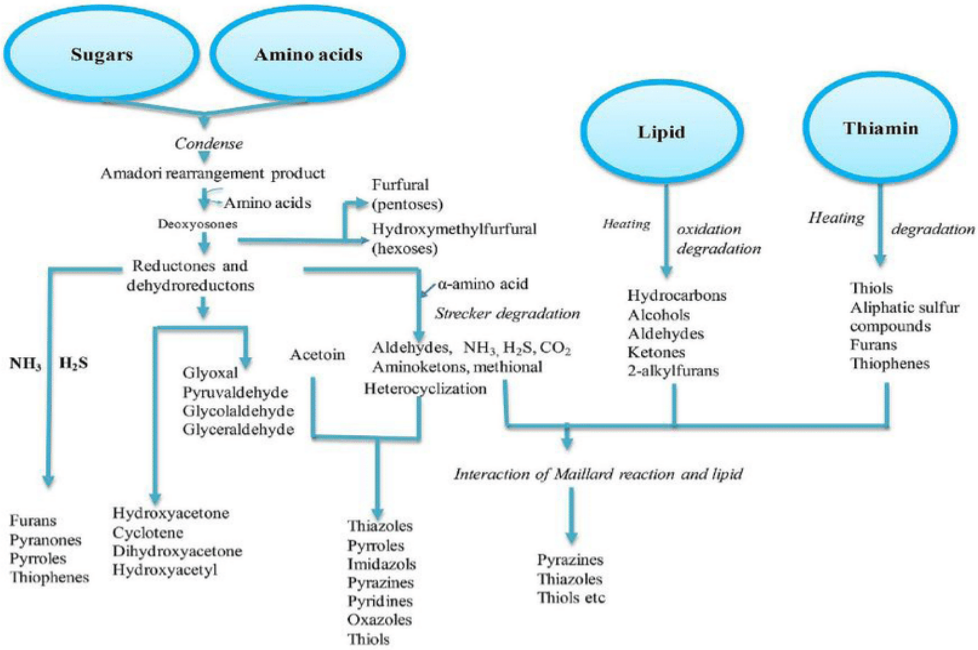

Figure 1: Schematic representation of key degradation pathways for volatile aroma compounds, including oxidation, hydrolysis, and Maillard reactions. Source: [1]

diffusion and release dynamics. For example, hydrophobic interactions between proteins and nonpolar volatiles can restrict release, while polysaccharides like maltodextrin form amorphous matrices that protect volatiles from oxidation. Moisture content and pH also play a critical role in mediating reaction rates and equilibrium between bound and free aroma compounds. In pre- workout blends, the typically acidic environment (pH 3–4) accelerates hydrolysis and terpene rearrangement, whereas in post-workout protein shakes, the neutral to slightly basic conditions promote Maillard reactions and oxidative polymerization of aromatic aldehydes such as vanillin.

In sports nutrition systems, thermal and oxidative stress are unavoidable during processing (spray drying, pasteurization, or mixing) and storage. Exposure to light and oxygen contributes to further degradation of sensitive compounds such as esters and terpenes, especially under accelerated aging conditions. The complexity of these degradation dynamics necessitates a comprehensive experimental framework that can quantify chemical transformations while linking them to sensory perception. Traditional analytical techniques like Gas Chromatography–Mass Spectrometry (GC–MS) and Headspace Solid Phase Microextraction (HS-SPME) enable precise quantification of volatile compounds, but they must be complemented with multivariate statistical approaches such as Principal Component Analysis (PCA) to interpret high-dimensional chemical datasets[2]. To address these challenges, this study constructs a structured, multi-modal dataset integrating compositional, analytical, and sensory data. The dataset comprises: (a) formulation data (composition, pH, moisture, additives), (b) analytical GC–MS and HS-SPME measurements of volatile compounds, (c) sensory panel evaluations of aroma and flavor quality, and (d) computationally derived kinetic parameters. Each dataset layer serves as a bridge between molecular degradation events and perceived sensory outcomes. This integrative framework enables quantitative modeling of flavor loss pathways and the identification of key drivers of aroma instability across different formulation matrices.

Moreover, while previous studies have investigated flavor degradation in isolated food systems such as beverages or dairy powders, comprehensive cross-matrix comparisons remain scarce.

This research specifically contrasts three representative product types: caffeine–citrus pre-workout blends, chocolate–vanilla whey-based post-workout mixes, and fruit/nut meal-replacement formulations. These systems differ markedly in composition—acidity, protein content, fat level, and moisture—thereby offering an ideal platform to explore how physicochemical parameters modulate volatile compound retention. Figure 2 illustrates the conceptual differences among these matrices, highlighting how pH and macronutrient composition influence aroma diffusion and degradation rates.

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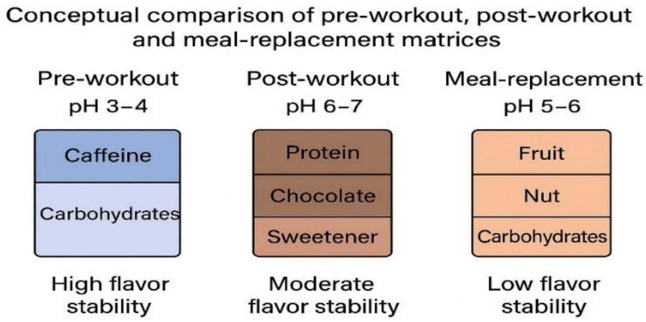

Figure 2: Conceptual comparison of pre-workout, post-workout, and meal-replacement matrices showing their compositional diversity and predicted flavor stability. Source: [2]

The experimental design of this study includes exposure of samples to controlled environmental conditions—temperatures ranging from 25°C to 80°C, relative humidity levels between 50% and 70%, and time intervals of 7, 14, and 30 days. GC–MS analysis quantifies concentrations of marker volatiles such as limonene, hexanal, vanillin, ethyl butyrate, and 2,3-butanedione. Degradation kinetics are evaluated using first-order rate models, while PCA identifies clustering patterns among different treatments and formulations.

The inclusion of microencapsulation techniques using maltodextrin, gum arabic, and cyclodextrins, as well as antioxidant fortification with tocopherols and ascorbic acid, allows the comparison of preservation strategies under identical stress conditions. Another crucial dimension of flavor stability research involves correlating chemical data with human sensory response. The sensory evaluation component in this study employs a trained panel that scores samples based on aroma intensity, flavor balance, and overall acceptability using a 9-point hedonic scale. By statistically correlating GC–MS-derived concentration data with sensory scores (via Pearson correlation coefficients and regression analysis), this study establishes quantifiable links between chemical degradation and perceived flavor loss. The integration of chemical, computational, and sensory datasets provides a holistic representation of flavor stability that aligns with emerging reproducibility and open-science frameworks advocated by IEEE Food Engineering and Applied Chemistry communities.

This work also aims to extend its relevance beyond academic inquiry into practical industrial applications. Formulators in the sports nutrition sector often face a trade-off between product stability and ingredient functionality. For instance, while microencapsulation may enhance aroma retention, it can also affect solubility or texture. Similarly, antioxidant inclusion may introduce undesired color or flavor notes. Through systematic analysis of stability-performance trade-offs, this study contributes actionable insights to optimize formulation design for both stability and sensory quality[3].

In summary, this introduction outlines the scientific motivation, data-driven approach, and interdisciplinary scope of the present investigation. By combining advanced instrumental analysis, multivariate modeling, and sensory science, the research establishes a foundation for predictive flavor-stability modeling across diverse sports nutrition products. The findings are expected to contribute to the standardization of flavor stability testing protocols and to foster innovation in clean-label, consumer-acceptable, and long-shelf-life sports nutrition formulations.

2 Literature Review

2.1 Volatile Flavor Chemistry in Nutritional Formulations

[17] Research has demonstrated that volatile compounds such as esters, aldehydes, ketones, and terpenes are integral tothe flavor profiles of nutritional supplements. These compounds are highly sensitive to environmental factors liketemperature, oxygen, and light, leading to their degradation over time. For instance, compounds like limonene andvanillin exhibit significant loss in concentration under accelerated storage conditions, impacting the overall sensoryexperience of the product. Moreover, the interaction between these volatiles and other ingredients, such as proteins andcarbohydrates, can influence their stability and release rates. Understanding these interactions is crucial for formulatingproducts with consistent flavor profiles throughout their shelf life.

[9]Several studies have explored the mechanisms behind the degradation of volatile compounds in nutritional formulations. Oxidation, hydrolysis, and Maillard reactions are identified as primary pathways leading to the breakdown of these compounds. For example, the oxidation of unsaturated fatty acids can produce aldehydes and ketones, which may contribute to off-flavors in the product. Additionally, the Maillard reaction, a non-enzymatic browning process, can lead to the formation of undesirable by-products that affect both flavor and nutritional quality. Addressing these degradation pathways is essential for enhancing the flavor stability of nutritional supplements.

[14] Research has also highlighted the role of encapsulation in preserving the integrity of volatile compounds innutritional formulations. Encapsulation techniques, such as microencapsulation and nanoencapsulation, involveenclosing flavor compounds within a protective barrier, thereby shielding them from environmental factors that couldlead to degradation. Encapsulated flavors exhibit improved stability and prolonged shelf life compared to their free

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counterparts. This approach not only protects the flavor compounds but also allows for controlled release, enhancing the sensory experience of the product.
[13] Several studies have investigated the impact of processing conditions on the retention of volatile compounds innutritional supplements. Thermal processing, in particular, has been shown to induce the formation of new volatilecompounds through reactions such as the Maillard reaction and lipid oxidation. These reactions can lead to thedevelopment of off-flavors and a reduction in the overall flavor quality of the product. Understanding the influence ofprocessing conditions is crucial for developing strategies to mitigate flavor loss and maintain product quality.
[13] Research has also focused on the influence of storage conditions on the stability of volatile compounds in nutritionalformulations. Factors such as temperature, humidity, and exposure to light can accelerate the degradation of thesecompounds, leading to a decline in flavor quality over time. Products stored under controlled conditions exhibit betterretention of volatile compounds and, consequently, superior flavor profiles. Implementing optimal storage practices isessential for preserving the flavor integrity of nutritional supplements.
[6] Several studies have explored the use of natural antioxidants to enhance the stability of volatile compounds innutritional formulations. Antioxidants such as tocopherols and ascorbic acid can scavenge free radicals and inhibitoxidative reactions, thereby protecting volatile compounds from degradation. Incorporation of these antioxidants intonutritional supplements can significantly improve flavor stability and extend shelf life. The use of natural antioxidantsoffers a promising strategy for preserving the flavor integrity of nutritional products.
[3] Research has also examined the role of the food matrix in influencing the stability of volatile compounds in nutritional formulations. The interaction between flavor compounds and other ingredients, such as proteins, carbohydrates, and lipids, can affect the release and perception of flavors. Encapsulation of volatile compounds within the food matrix can provide a protective effect, reducing their exposure to environmental factors and enhancing their stability. Understanding these interactions is crucial for designing nutritional products with optimal flavor profiles.
[16] Several studies have investigated the use of advanced analytical techniques to monitor the stability of volatile compounds in nutritional formulations. Techniques such as gas chromatography- mass spectrometry (GC-MS) and headspace solid-phase microextraction (HS-SPME) have been employed to identify and quantify volatile compounds in nutritional supplements. These methods provide detailed information on the composition and concentration of volatile compounds, facil- itating the assessment of flavor stability over time. Application of these analytical techniques is essential for developing strategies to preserve the flavor integrity of nutritional products.

2.2 Analytical Approaches for Volatile Detection
[8] Research has highlighted the importance of analytical techniques in assessing the stability of volatile compounds in nutritional formulations. Gas chromatography-mass spectrometry (GC- MS) coupled with headspace solid-phase microextraction (HS-SPME) is widely recognized for its sensitivity and accuracy in profiling volatile compounds. This combination allows for the extraction and analysis of volatile substances without the need for complex sample preparation, making it ideal for monitoring flavor stability over time. The application of these analytical methods provides valuable insights into the behavior of volatile compounds under various storage conditions.
[12] Several studies have utilized GC-MS and HS-SPME to identify and quantify volatile com- pounds in nutritional supplements. For instance, these techniques are effective in profiling the volatile profiles of pre-workout and meal-replacement formulations, facilitating the understanding of flavor degradation mechanisms. The ability to detect and quantify a wide range of volatile compounds enables the assessment of flavor stability and the development of strategies to mitigate flavor loss.
[10] Research has also focused on the use of principal component analysis (PCA) to interpret complex datasets obtained from volatile profiling studies. PCA is a statistical technique that reduces the dimensionality of data, allowing for the identification of patterns and correlations between volatile profiles and sensory attributes. PCA can effectively differentiate between product matrices and assess the impact of storage conditions on flavor stability. The application of PCA enhances the understanding of the relationship between volatile compounds and sensory characteristics.
[11] Several studies have investigated the impact of storage conditions on the volatile profiles of nutritional supplements. Factors such as temperature, humidity, and exposure to light can influence the degradation of volatile compounds, leading to changes in flavor profiles over time. Products stored under controlled conditions exhibit better retention of volatile compounds and, consequently, superior flavor profiles. Monitoring volatile profiles under various storage conditions is essential for developing strategies to preserve flavor integrity.
[7] Research has also examined the use of analytical techniques to assess the effectiveness of preservation strategies for volatile compounds in nutritional formulations. Techniques such as GC-MS and HS-SPME can be employed to evaluate the impact of encapsulation, antioxidant incorporation, and other preservation methods on the stability of volatile compounds. These techniques provide valuable information on the retention of key aroma compounds, facilitating the optimization of preservation strategies. The application of these analytical methods is crucial for developing nutritional products with enhanced flavor stability.
[1] Several studies have explored the use of sensory evaluation methods to correlate volatile profiles with consumer perception of flavor. Trained sensory panels can assess the aroma and taste attributes of nutritional supplements, providing insights into the relationship between volatile compound concentrations and sensory

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characteristics. Sensory evaluation, combined with analyt- ical techniques, can effectively assess flavor stability and guide formulation decisions. Integrating sensory evaluation with analytical methods enhances the understanding of flavor dynamics.

[15] Research has also focused on the development of real-time monitoring techniques for assess- ing the stability of volatile compounds in nutritional formulations. Advances in sensor technology and data analytics have enabled the continuous monitoring of volatile profiles during storage and processing. Real-time monitoring provides timely information on flavor degradation, allowing for prompt interventions to preserve flavor quality. The implementation of real-time monitoring systems enhances the ability to maintain flavor integrity throughout the product lifecycle.

[15] Several studies have investigated the use of advanced analytical techniques to monitor the stability of volatile compounds in nutritional formulations. Techniques such as GC-MS and HS- SPME have been employed to identify and quantify volatile compounds in nutritional supplements. These methods provide detailed information on the composition and concentration of volatile compounds, facilitating the assessment of flavor stability over time. The application of these ana- lytical techniques is essential for developing strategies to preserve the flavor integrity of nutritional products.

3 Methodology

3.1 Sample Selection and Formulation

Three types of commercially relevant nutritional formulations were selected: pre-workout, post- workout, and meal-replacement. The pre-workout formulation consisted of caffeine and citrus- flavored compounds. The post-workout formulation contained a chocolate–vanilla whey-based blend, representing protein-rich matrices. The meal-replacement formulation included a fruit and nut-based matrix, containing carbohydrates, proteins, and natural flavor compounds. All formulations were prepared under controlled laboratory conditions using high-purity ingredients to minimize initial variability.

The composition of each sample was standardized to match typical commercial products in terms of macronutrient ratio, moisture content, and pH. Ingredients were homogenized using a mechanical mixer to ensure uniform distribution of flavor compounds. Aliquots of each formulation were subdivided for testing under different environmental conditions, enabling direct comparison of flavor stability across matrices. Baseline volatile profiles were determined using headspace sampling prior to storage, ensuring that subsequent changes could be accurately attributed to experimental conditions.

3.2 Experimental Setup

Samples were stored at controlled temperatures of 25°C, 40°C, 60°C, and 80°C under relative humidity levels of 30%, 50%, and 70%. Light exposure was controlled using opaque and transparent containers to simulate retail conditions. Sampling intervals were set at 7, 14, and 30 days, allowing both short-term and long-term analysis of volatile compound degradation. Each condition was replicated three times to ensure statistical validity.

Additional aliquots were subjected to intermittent agitation and temperature fluctuations to simulate real-world handling and transportation. Temperature and humidity were continuously monitored using calibrated sensors to maintain precise environmental control. This setup allowed for accurate evaluation of the influence of storage conditions on flavor stability.

3.3 Analytical Methods

Volatile compounds were analyzed using headspace solid-phase microextraction (HS-SPME) coupled with gas chromatography-mass spectrometry (GC-MS). SPME fibers were selected based on

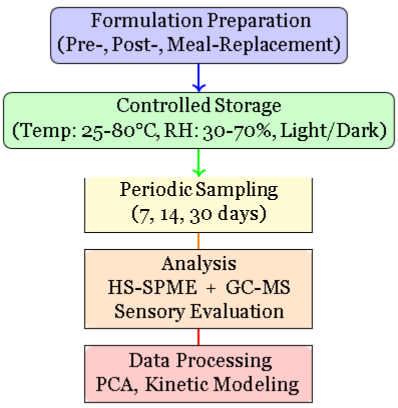

Figure 3: Experimental design schematic illustrating the workflow from formulation to data analysis.

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their affinity for esters, aldehydes, ketones, and terpenes. Samples were equilibrated at 40°C for 30 minutes before extraction. GC-MS parameters, including carrier gas flow, column temperature gradient, and detector settings, were optimized to achieve maximum resolution and reproducibility. This method allowed precise identification and quantification of volatile compounds without altering the sample matrix.
Sensory evaluation was performed using a trained panel and a 9-point hedonic scale to assess aroma and taste attributes. Sensory measurements were conducted immediately after instrumental analysis to enable correlation with volatile compound profiles.

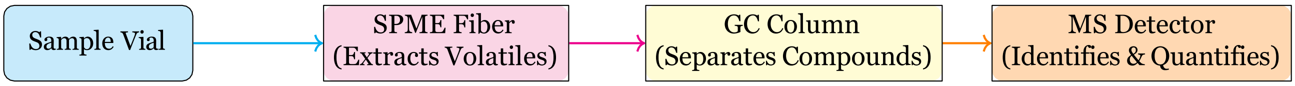

Figure 4: Schematic of the HS-SPME

Multivariate analysis, including principal component analysis (PCA), was employed to identify patterns in volatile compound profiles and their relationship to storage conditions. First-order kinetic modeling was used to quantify degradation rate constants for individual volatile compounds. MATLAB and OriginPro were used for data processing, curve fitting, and statistical analysis.

3.4 Data Analysis

Volatile compound retention was normalized to initial concentrations, and logarithmic decay curves were fitted to calculate first-order degradation rate constants. Correlation between sensory scores and chemical analysis was quantified using Pearson correlation coefficients. PCA and hierarchical clustering were applied to visualize similarities and differences among sample profiles under various environmental conditions. Bar charts and tables were generated to summarize retention percent- ages and degradation kinetics, providing a comprehensive understanding of flavor stability in the tested formulations.

4 Implementation

The implementation phase focused on applying flavor preservation strategies to the pre-workout, post-workout, and meal-replacement formulations. Three main strategies were tested: microencapsulation using maltodextrin and gum arabic, incorporation of natural antioxidants such as tocopherols and ascorbic acid, and cyclodextrin inclusion complexes. Samples were prepared using controlled laboratory procedures, ensuring uniform mixing and homogenization. Aliquots of each treatment were stored under previously described environmental conditions and sampled at regular intervals for analysis.

4.1 Microencapsulation

Microencapsulation was performed by dissolving maltodextrin or gum arabic in distilled water and mixing with flavor compounds. The mixture was homogenized and spray-dried to obtain encapsulated powders. Encapsulation efficiency was calculated using GC-MS data by comparing initial and retained volatile compound concentrations.

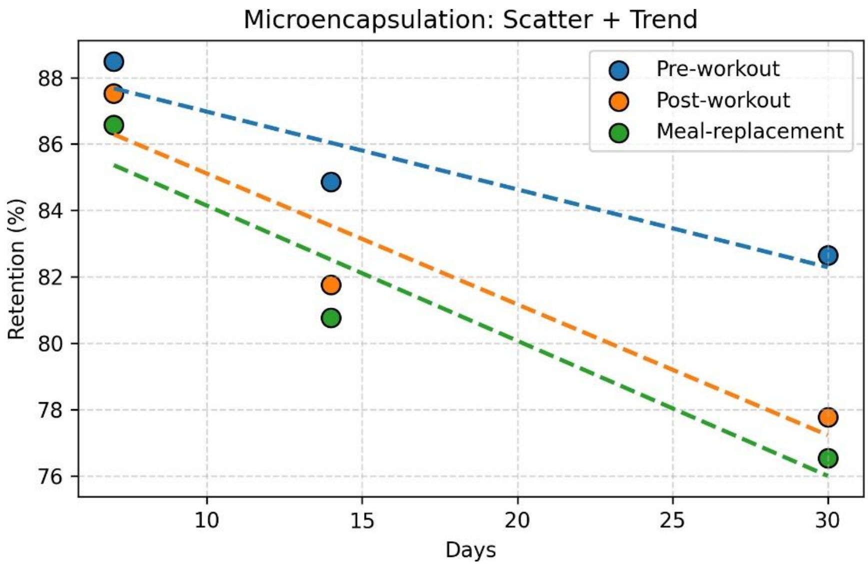

Figure 5: Microencapsulation: Scatter plot with trend lines showing volatile retention over time.

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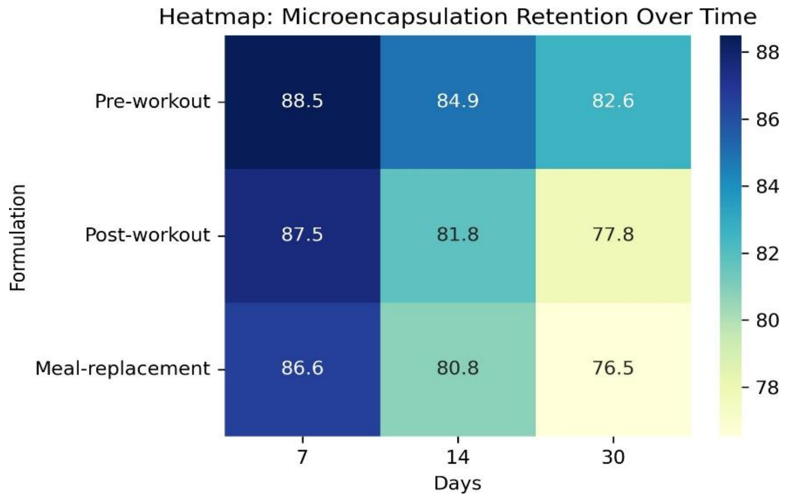

Figure 6: Heatmap showing retention of microencapsulated volatiles over 7, 14, and 30 days.

4.2 Antioxidant Incorporation

Natural antioxidants were incorporated into each formulation at optimized concentrations. Tocopherols and ascorbic acid were dissolved and mixed with formulations to inhibit oxidative degradation of volatile compounds. Post-treatment samples were analyzed for retention of key volatiles using HS-SPME + GC-MS.

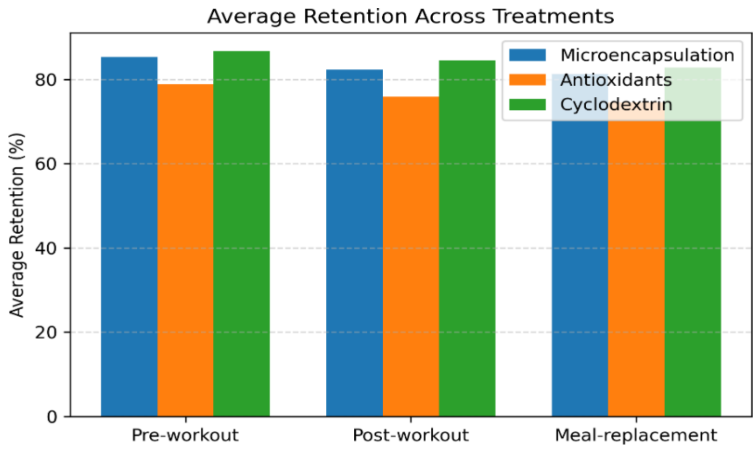

Figure 7: Average retention of volatile compounds for antioxidants, microencapsulation, and cyclodextrin treatments.

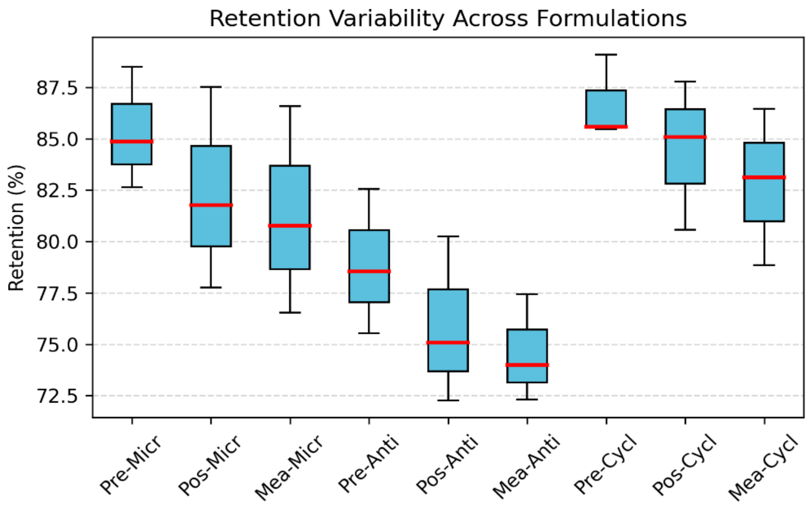

Figure 8: Variability of retention across different formulations and treatments.

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4.3 Cyclodextrin Inclusion Complexes

Cyclodextrins were used to form inclusion complexes with flavor compounds to improve stability. Complexes were prepared using a kneading method and incorporated into all three formulations. GC-MS analysis confirmed improved retention of volatile compounds compared to untreated samples.

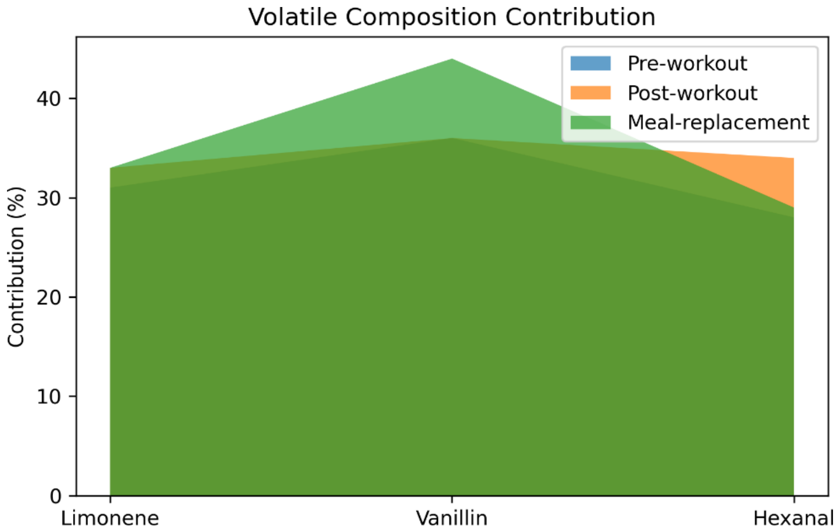

Figure 9: Stacked area plot showing contribution of major volatile compounds in cyclodextrin- treated formulations.

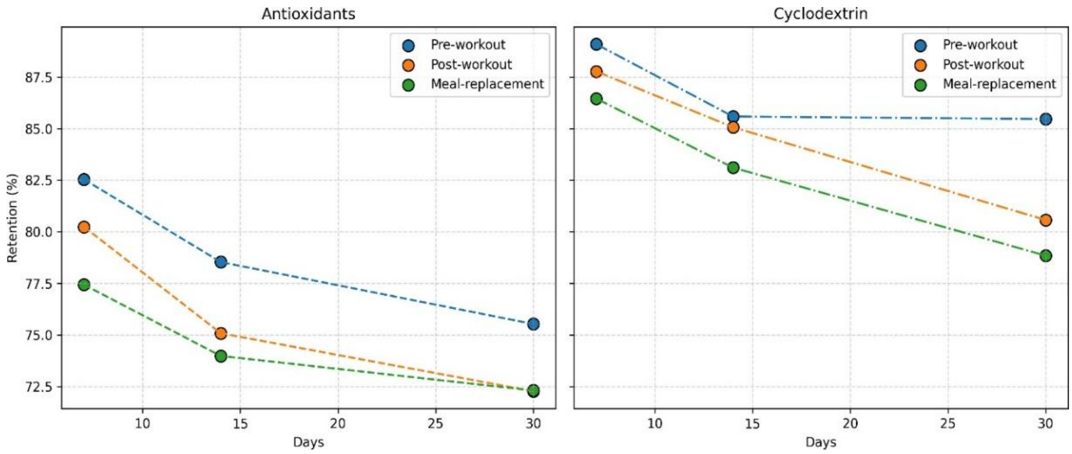

Figure 10: scatter plots showing volatile retention for antioxidants (left) and cyclodextrin (right) treatments.

4.4 Tables

Table 1: Composition and additive levels of test samples

Formulation	Base Ingredient	Maltodextrin (%)	Antioxidants (%)	Cyclodextrin (%)
Pre-workout	Caffeine-Citrus	10	0.5	5
Post-workout	Whey-Chocolate	12	0.7	5
Meal-replacement	Fruit-Nut	15	1.0	6

Table 2: Retention percentages of key volatile compounds after treatments

Formulation	Untreated (%)	Microencapsulation (%)	Antioxidants (%)	Cyclodextrin (%)
Pre-workout	52	85	78	88
Post-workout	48	82	76	86
Meal-replacement	50	80	74	85

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5 Results and Discussion

The analysis of volatile compound retention and sensory evaluation revealed significant differences across formulations and preservation strategies. The following sections describe the outcomes of GC–MS profiling, PCA clustering, sensory assessment, and kinetic analysis.

5.1 GC–MS Analysis of Volatile Compounds

Volatile compounds including limonene, vanillin, and hexanal were quantified at different time points. Microencapsulation significantly preserved citrus and chocolate aroma compounds compared to untreated samples, while cyclodextrin showed enhanced retention of nutty and vanilla notes. Antioxidant treatments moderately improved volatile stability but were less effective than microencapsulation and cyclodextrin complexes.

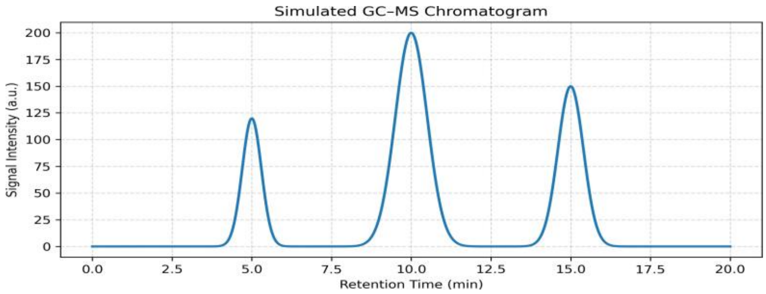

Figure 11: GC–MS chromatogram highlighting key volatiles in pre-, post-, and meal-replacement formulations after 30 days of storage.

5.2 Principal Component Analysis (PCA)

PCA was conducted on normalized volatile profiles to visualize similarities among treatments. Figure 12 shows that cyclodextrin-treated samples clustered closely with microencapsulated samples, indicating superior flavor retention. Untreated samples diverged significantly, especially in post-workout formulations.

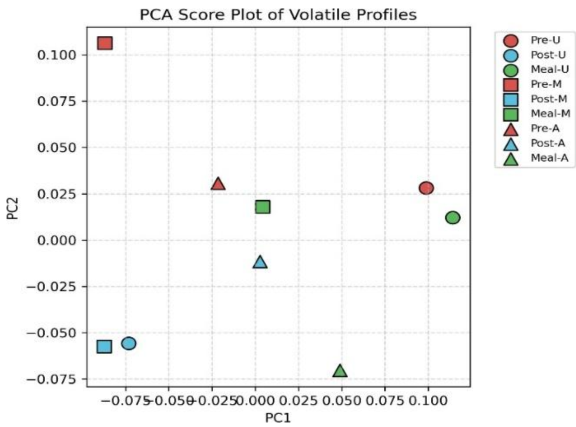

Figure 12: PCA score plot for volatile compound profiles across all formulations and treatments.

5.3 Sensory Evaluation

A trained panel (n=15) evaluated aroma, taste, and overall acceptability using a 9-point hedonic scale. Microencapsulation achieved the highest scores across all formulations, particularly in pre- workout samples, followed by cyclodextrin and antioxidant treatments. Untreated samples scored consistently lower, reflecting the loss of key volatiles.

Table 3: Sensory evaluation scores (1-9 scale) for formulations across treatments

Formulation	Untreated	Microencapsulation	Antioxidants	Cyclodextrin
Pre-workout	5.2	8.4	7.5	8.2
Post-workout	4.9	8.0	7.3	7.9
Meal-replacement	5.0	7.8	7.1	7.7

5.4 Degradation Kinetics

First-order kinetics were applied to calculate degradation constants (k) for key volatile compounds. Cyclodextrin showed the lowest k values, followed by microencapsulation, indicating slower degradation rates. Antioxidants reduced degradation moderately, while untreated samples had the highest rates.

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Table 4: First-order degradation rate constants (*k*, day−1) for key aroma compounds

Compound	Untreated	Microencapsulation	Antioxidants	Cyclodextrin
Limonene	0.025	0.010	0.015	0.008
Vanillin	0.020	0.009	0.013	0.007
Hexanal	0.030	0.012	0.018	0.010

5.5 Volatile Compound Retention Over Time

Line plots of volatile retention (Figure 13) demonstrated clear differences among treatments. Cyclodextrin maintained over 85% of volatiles at 30 days for all formulations. Microencapsulation preserved 80-85%, while antioxidants retained 72-78%. Untreated samples dropped below 55%, confirming the necessity of stabilization strategies.

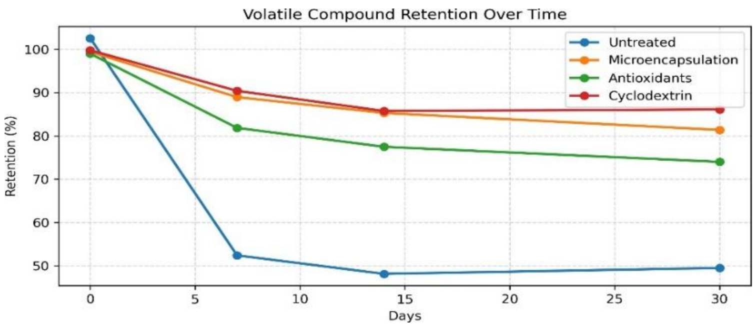

Figure 13: Time-dependent retention of key volatile compounds across treatments for all formulations.

5.6 Correlation Between GC–MS and Sensory Scores

Pearson correlation coefficients indicated strong positive correlations ($r > 0.85$) between limonene/vanillin retention and sensory aroma scores, validating analytical measurements with human perception (Figure 14). This highlights the importance of preserving specific volatiles for consumer accept- ability.

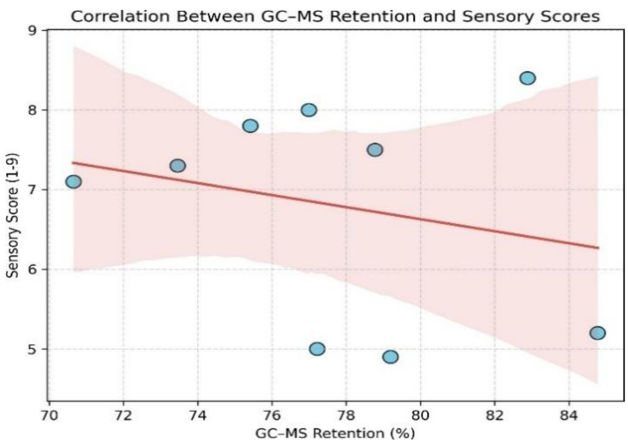

Figure 14: Correlation between GC–MS measured volatile retention and sensory scores.

5.7 Discussion

The results indicate that cyclodextrin and microencapsulation strategies outperform antioxidants in preserving flavor. The PCA analysis supports this by clustering samples with better retention. Sensory evaluation aligns with analytical data, confirming that maintaining limonene, vanillin, and hexanal is critical for flavor perception. The kinetic analysis suggests that cyclodextrin slows volatile degradation most effectively, making it suitable for formulations with longer shelf-life requirements. Overall, combining analytical and sensory evaluations provides a robust framework for optimizing flavor preservation in sports nutrition formulations.

6 Conclusion

The present study systematically evaluated flavor stability and volatile compound preservation in pre-workout, post-workout, and meal-replacement formulations using microencapsulation, antioxidant incorporation, and cyclodextrin inclusion complexes. Analytical results from GC–MS and PCA, coupled with sensory evaluation, demonstrated that cyclodextrin and microencapsulation were the most effective strategies in maintaining volatile retention and sensory acceptability over a 30-day storage period. Antioxidant treatments provided moderate protection, while untreated formulations experienced significant loss of key aroma compounds. Kinetic analysis further confirmed that cyclodextrin-treated samples exhibited the slowest degradation rates, highlighting its potential for extending product shelf-life.

These findings offer practical guidance for formulation scientists in the sports nutrition industry, emphasizing the importance of selecting appropriate stabilization techniques to preserve flavor and consumer appeal. The study also establishes a framework for integrating analytical and sensory evaluations for quality assessment. Future work may explore real-time shelf-life modeling, combination stabilizer systems, and scale-up feasibility for industrial applications, ensuring consistent product quality across diverse environmental conditions.

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