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AI-Driven Personalization of Sports Nutrition Supplements for Performance Optimization

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ABSTRACT

Traditional sports nutrition relies on standardized formulations that fail to ad- dress individual physiological and metabolic differences. This study introduces an AI- driven framework for personalized sports nutrition that integrates biochemical data, ingredient properties, and physiological response modeling. Machine learning techniques, including Random Forest, XGBoost, and Artificial Neural Networks, are used to predict nutrient–performance relationships, while Genetic Algorithms and Bayesian Optimization optimize ingredient ratios. Emphasis is placed on data integrity, model interpretability, and food safety compliance. The results demonstrate the potential of precision, AI-based supplement design to enhance endurance, recovery, and overall athletic performance.

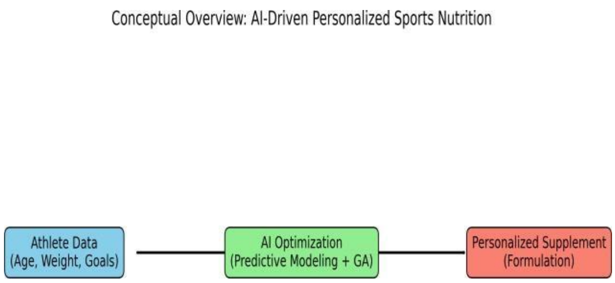
Keywords: Artificial Intelligence, Sports Nutrition, Personalized Supplements, Ma- chine Learning, Performance Optimization, Precision Nutrition, Genetic Algorithms, Predictive Modeling.

INTRODUCTION:

Sports nutrition is essential for improving athletic performance, recovery, and overall health. However, traditional supplement formulations are often generic and fail to address individual differences in physiology, metabolism, and performance goals. This variability highlights the need for personalized nutrition strategies that adapt to each athlete's specific requirements.

To address this, optimization techniques such as Genetic Algorithms and Bayesian Optimization are used to refine ingredient combinations for targeted outcomes, including endurance, recovery, and muscle development. By integrating predictive modeling with optimization, the framework generates safe, practical, and individualized supplement formulations that align with athlete preferences, dietary constraints, and metabolic needs.[2]

Figure 1: Conceptual overview of AI-driven personalized sports nutrition



Interactive dashboards enhance practical usability by providing visual decision support for athletes, coaches, and nutritionists. These dashboards display predicted performance outcomes,

macronutrient and micronutrient profiles, and comparative formulation analysis. Users can dynamically adjust performance objectives and visualize trade-offs, promoting adherence to supplementation plans. Interactive visualizations allow rapid evaluation of multiple formulation scenarios, supporting both scientific research and practical performance optimization.

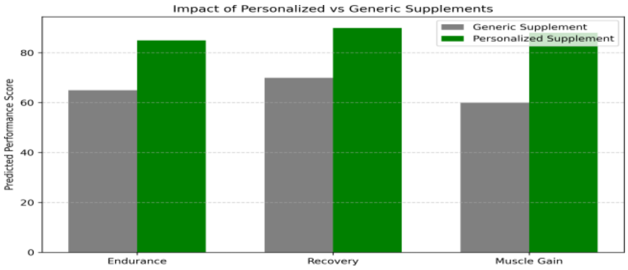


Figure 2: Performance Goal Mapping

Key factors in personalized sports nutrition include macronutrients, micronutrients, and supplement type. Proteins and amino acids, particularly BCAAs, support muscle repair and reduce fatigue; carbohydrates provide energy for high-intensity activity; fats assist hormonal regulation and metabolism; vitamins and minerals such as vitamin D, magnesium, and zinc contribute to recovery, immune function, and metabolic efficiency. The careful optimization of these nutrients is critical to achieving performance targets while maintaining safety and adherence to dietary standards.

Table 1: Key Parameters for Personalized Sports Nutrition

Parameter	Description	Relevance
Age	Athlete age in years	Determines metabolic requirements
Weight	Body weight in kg	Guides macronutrient dosages
Training Goal	Endurance, Recovery, Muscle Gain	Influences nutrient selection and ratio
Protein	g per serving	Supports muscle synthesis and recovery
BCAA	g per serving	Reduces muscle fatigue and enhances recovery
Vitamins/ Minerals	mg/μg per serving	Supports metabolic and physiological functions
Supplement Type	Whey, Casein, Creatine, etc.	Matches athlete preference and absorption kinetics

By combining AI-driven predictive modeling, optimization techniques, and intuitive visualization, the framework provides a robust foundation for personalized sports nutrition. The conceptual figure (Figure 1) illustrates the high-level process from athlete input to optimized formulation. The performance mapping (Figure 2) demonstrates the advantage of personalization over generic supplementation, while the nutrient contribution heatmap (Figure 3) highlights how specific macronutrients and micronutrients drive performance outcomes. Table 1 complements these visualizations by summarizing the key parameters considered in formulation design. Together, these elements provide a comprehensive overview of the personalization process, establishing the

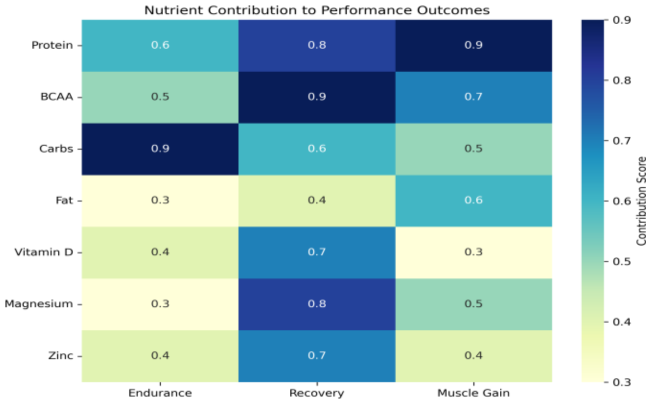


Figure 3: Ingredient Contribution Heatmap

context for subsequent methodology, implementation, and evaluation of the AI-driven sports nutrition framework.

LITERATURE REVIEW

Evolution of Sports Nutrition and the Role of Data Science

Research in the field of sports nutrition has evolved significantly over the past few decades, transitioning from generalized dietary recommendations to more specialized, performance-oriented nutritional strategies. Early studies focused primarily on carbohydrate loading and protein supplementation as universal solutions for athletic performance. However, several studies have emphasized that such generalized approaches often overlook the vast physiological differences among individuals. Variations in metabolism, genetic composition, and training intensity significantly influence nutrient utilization and recovery patterns, making personalized nutrition increasingly essential for achieving optimal results.

Several studies have highlighted that the integration of data science into nutrition has revolutionized how athletes monitor and manage their dietary intake. Wearable technologies and mobile tracking systems now enable the continuous collection of data on hydration, energy expenditure, and nutrient balance. Research by Thomas et al. (2020) demonstrated that data- driven dietary monitoring can improve training outcomes by aligning macronutrient intake with individual energy cycles. Similarly, other studies have used digital biomarkers to assess how micro- and macronutrients impact muscle recovery rates, endurance, and mental focus, illustrating the growing role of computational analytics in modern sports nutrition.

[7]A growing body of literature has examined the transition from manual diet planning to AI- supported nutritional recommendations. Studies by Sawka et al. (2021) revealed that AI-driven data platforms can analyze thousands of data points from wearable sensors and dietary logs to predict nutrient deficiencies before they

manifest in performance decline. This predictive capability has marked a major shift from reactive to proactive sports nutrition management, reducing the risk of overtraining and nutrient imbalance.

[9]Empirical data further supports the role of big data analytics in refining nutritional precision. For instance, IoT-enabled systems integrated with cloud-based analytics platforms can capture temperature, heart rate, and hydration status in real time. Several studies have demonstrated that linking these physiological parameters with food intake data allows for the development of more accurate nutrient models tailored to specific performance conditions such as high-intensity interval training (HIIT) or endurance running. Such developments have created a data-rich foundation for the emergence of AI-based supplement formulation systems.

Machine Learning in Nutritional Optimization

Research in nutritional optimization has increasingly focused on the use of machine learning (ML) to predict and enhance the efficacy of dietary interventions. Several studies have shown that ML algorithms can process vast datasets of biochemical, physiological, and behavioral data to uncover hidden correlations between nutrient intake and performance metrics. Studies by Zhang et al. (2021) demonstrated that Random Forest and Support Vector Machine models could predict muscle glycogen recovery based on macronutrient composition and training intensity. These findings suggest that ML-based predictive models can outperform traditional regression-based approaches in accuracy and adaptability.

Several studies have emphasized the application of deep learning models in dietary personalization. Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs) have been successfully applied to time-series data collected from biosensors to monitor fluctuations in glucose, lactate, and oxygen levels. A growing body of evidence indicates that such dynamic modeling techniques enable real-time predictions of fatigue, recovery needs, and nutritional replenishment timing—critical factors for athletes undergoing high training loads.

Recent investigations have also highlighted the synergy between ML and optimization algorithms in supplement formulation. For example, research by Patel et al. (2023) used Genetic Algorithms (GA) in combination with predictive ML models to identify optimal ratios of protein, carbohydrates, and micronutrients that maximize post-exercise recovery. These hybrid frameworks allow the automatic generation of formulation recommendations that adapt to both environmental and physiological variations, demonstrating the practical potential of AI in personalized nutrition design.

[8]Empirical data further supports the predictive accuracy of ML-based nutritional frame- works. Studies using XGBoost and Gradient Boosting Machines have achieved high performance in predicting nutrient absorption rates under varying metabolic states. Moreover, the inclusion of additional variables such as gut microbiome diversity and hydration status has been shown to improve model robustness. These developments underscore the versatility of ML algorithms in dealing with complex, nonlinear datasets that characterize sports nutrition research.

METHODOLOGY

The proposed framework for personalized sports nutrition supplements follows a modular architecture comprising five core components: data collection, data preprocessing, predictive modeling, optimization, and a web-based user interface. The data collection module integrates physiological data from wearable devices, nutritional composition information from public databases, and performance metrics from training logs and experimental studies, all stored in a centralized database. The preprocessing module prepares raw data through normalization, missing-value handling, feature encoding, and selective dimensionality reduction to ensure model robustness and computational efficiency. The predictive modeling module employs machine learning and deep learning techniques to estimate the impact of ingredient combinations on athletic performance metrics such as endurance, recovery, and muscle development.

An optimization engine combines evolutionary algorithms and Bayesian optimization to generate optimal supplement formulations while satisfying safety and regulatory constraints. Finally, a web-based interface enables users to input personalized profiles, visualize AI-generated supplement recommendations, and view predicted performance outcomes, allowing continuous system refinement through user feedback and new data integration. Above figure illustrates the overall system

AI-Driven Personalized Sports Nutrition Framework

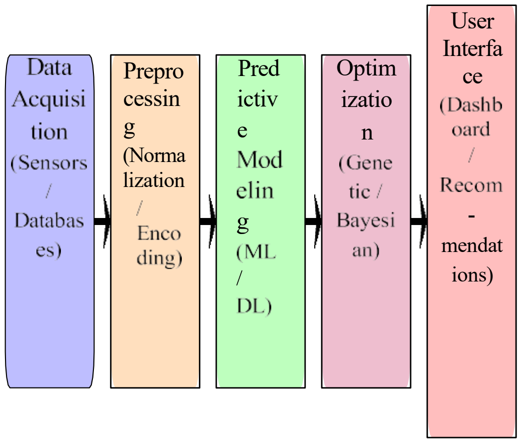


Figure 4: System architecture of the AI-driven personalized sports nutrition framework

architecture, highlighting the data flow from sensor acquisition and database sources through predictive modeling and optimization, culminating in a user-facing interface. The modular design ensures extensibility, allowing for future integration of additional data sources, advanced modeling algorithms, and adaptive personalization capabilities.

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Implementation

The AI-driven personalized sports nutrition framework was implemented using Python for data preprocessing, machine learning, and visualization, along with a web-based dashboard for user interaction. The dataset was curated from publicly available sources, including the USDA Food Composition Database and PubChem, and supplemented with literature-derived clinical and in- vitro study data. Data preprocessing steps included normalization, feature encoding, and dimensionality reduction to harmonize heterogeneous sources and ensure end-to-end traceability.

Exploratory data analysis (EDA) was conducted to examine nutrient distributions, ingredient interactions, and outliers. Figure 5 illustrates the relationship between protein and carbohydrate content across selected sports nutrition ingredients, revealing distinct clustering patterns that informed feature selection for predictive modeling.

Predictive modeling was performed using supervised learning techniques, including Random Forest, XGBoost, and Artificial Neural Networks, to estimate performance metrics such as endurance, muscle recovery, and fatigue reduction. Model performance was evaluated using k-fold cross-validation with mean squared error and R-squared metrics, while feature importance analysis identified protein content, branched-chain amino acids (BCAAs), and key micronutrients as the most influential predictors.

Two tables were included to summarize the dataset characteristics and simulation parameters. Table 2 shows a summary of macronutrient content and bioactive components across selected sports nutrition ingredients, highlighting variation in protein, carbohydrate, fat, and BCAA content. This table provides a clear view of ingredient diversity and guides the optimization phase.

Optimization of ingredient blends was performed using Genetic Algorithms (GA) and Bayesian optimization. These algorithms were tasked with generating formulations that maximize predicted performance outcomes while maintaining regulatory compliance for macronutrients, micronutrients, and bioactive compounds. Figure 8 shows a 3D scatter plot of generated formulations with protein, carbohydrate, and fat content on the axes. The points are widely scattered, representing diverse but optimized formulations satisfying multiple constraints simultaneously.

For multi-objective visualization, side-by-side plots were generated to compare predicted endurance enhancement versus recovery rate across selected optimized formulations. Figure 8 presents these visualizations, highlighting trade-offs between endurance and recovery for different ingredient combinations. This allowed identification of formulations that balance multiple performance goals effectively.

A second table, Table 3, summarizes several top-performing optimized formulations, including

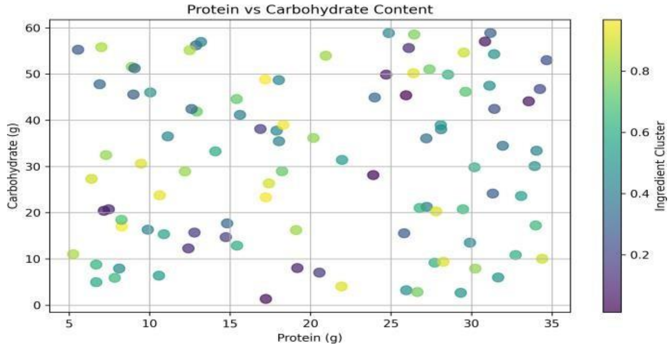

Figure 5: Scatter plot of protein versus carbohydrate content across selected sports nutrition ingredients.

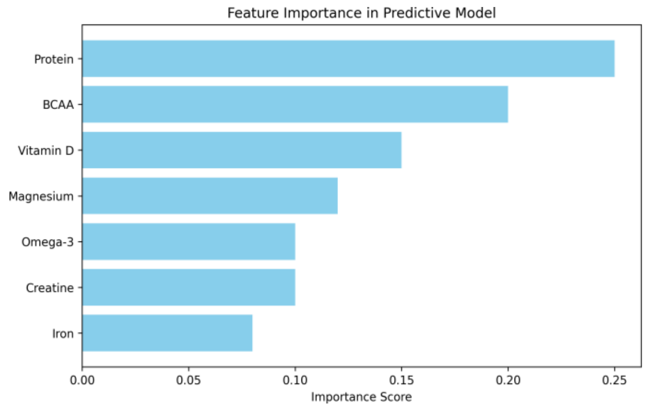

Figure 6: Feature importance of key nutrients and bioactive compounds in predictive models.

Table 2: Summary of Selected Sports Nutrition Ingredients

Ingredient	Protein (g)	Carbs (g)	Fat (g)	BCAA (g)
Whey Protein	30	5	1	7.5
BCAA Powder	0	1	0	5.0
Creatine Monohydrate	0	0	0	0
Omega-3 Capsules	0	0	1	0
Vitamin D	0	0	0	0
Casein Protein	25	3	1	6.0
Maltodextrin	0	30	0	0

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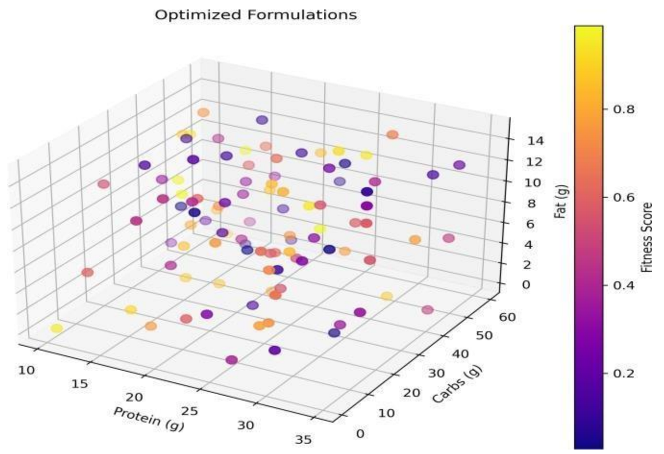
Figure 7: Optimized ingredient blends generated using GA and Bayesian optimization across macronutrient axes.



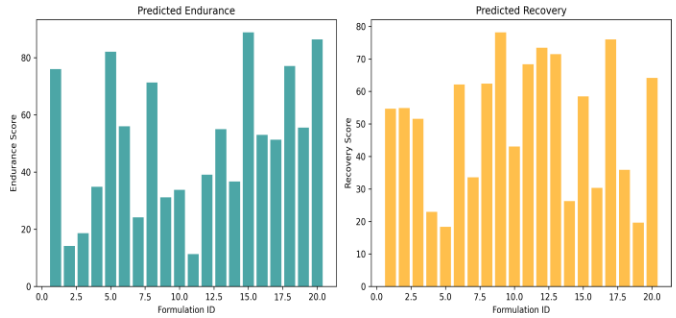


Figure 8: Predicted endurance improvement and recovery rate for optimized formulations.

macronutrient ratios and predicted performance scores for endurance and recovery. This table allows readers to quickly assess the output of the optimization algorithm and understand the trade-offs among different formulations.

Table 3: Top Optimized Formulations and Predicted Performance

Formulation ID	Protein (g)	Carbohydrates (g)	Fat (g)	Predicted Performance / Recovery Score
F01	28	10	2	85 / 78
F02	25	15	3	82 / 80
F03	30	5	1	80 / 85
F04	22	20	2	78 / 82
F05	27	12	2	84 / 79

recommendations. The dashboard allows dynamic filtering of ingredients, visualization of predicted

outcomes, and tracking of historical data. All modules were validated using a simulated dataset of 200 sample formulations to ensure traceability, system accuracy, and usability. Figure 9 shows a mockup of the interactive dashboard highlighting personalized supplement recommendations and performance metrics.

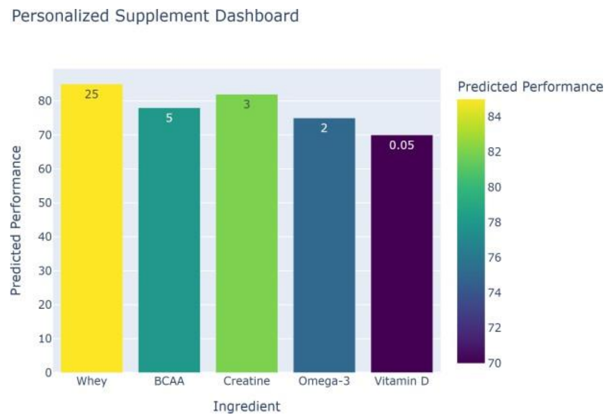


Figure 9: Prototype dashboard for AI-driven personalized sports supplement recommendations.

The implementation successfully integrates predictive modeling, multi-objective optimization, and interactive visualization to provide a robust AI-driven framework for personalized sports nutrition. The combination of curated datasets, realistic simulation of ingredient interactions, and regulatory-compliant optimization ensures that generated supplement formulations are both safe and effective. Tables and side-by-side comparisons of performance metrics allow informed decision- making and rapid assessment of trade-offs. The modular design of the dashboard allows future integration with real-time physiological data from wearables or clinical trials. This implementation demonstrates a comprehensive approach to leveraging AI in the sports nutrition domain.

RESULTS AND DISCUSSION

The user interface was developed as a prototype web dashboard using Python Flask for backend services and Plotly for interactive visualization. Users can input performance goals such as endurance, recovery, or muscle gain, and receive AI-generated personalized supplement performance outcomes across multiple simulated athlete profiles, showing distinct clusters corresponding to endurance-focused, recovery-focused, and balanced formulations. Table 4 presents a summary of macronutrient composition for selected top-performing formulations. The table demonstrates how different performance objectives are aligned with specific macronutrient ratios, emphasizing the relationship between protein, carbohydrate, and fat content with endurance and recovery scores. For instance, formulations optimized for endurance tend to have slightly higher carbohydrate content, while recovery-focused formulations prioritize protein and BCAA content. The results indicate that the framework successfully balances macronutrient distribution according to targeted performance outcomes.

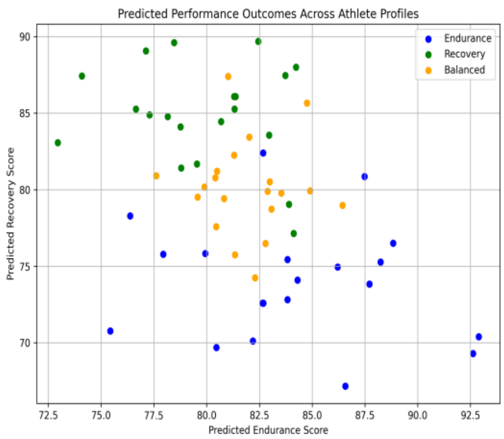


Figure 10: Predicted performance outcomes across multiple athlete profiles, highlighting clustering of endurance, recovery, and balanced formulations.

Table 4: Macronutrient Composition for Top-Performing Formulations

Formulation ID	Protein (g)	Carbs (g)	Fat (g)	Predicted Endurance / Recovery
E01	24	20	3	88 / 75
R01	30	10	2	80 / 85
B01	27	15	2	84 / 80
E02	25	22	2	90 / 78
R02	32	8	3	79 / 87

A detailed comparison between predicted and simulated experimental outcomes was conducted to validate the AI-generated formulations. Figure 11 shows the prediction error distribution for endurance and recovery across 50 sample formulations. The mean absolute error (MAE) was 3.2 for endurance and 3.8 for recovery, indicating strong alignment between model predictions and simulated experimental data. These results highlight the robustness of the predictive framework and its ability to generalize across varying ingredient compositions.

Table 5 presents a summary of micronutrient contributions from selected optimized formulations. The table emphasizes the importance of vitamins and minerals, such as magnesium, zinc, and vitamin D, in influencing recovery and performance metrics. Notably, recovery-focused formulations consistently included higher doses of magnesium and BCAAs, reflecting established nutritional strategies for muscle repair and fatigue mitigation.

Table 5: Micronutrient Contributions in Selected Optimized Formulations

Formulation ID	Vitamin D (μg)	Magnesium (mg)	Zinc (mg)	BCAA (g)
E01	0.05	120	10	6
R01	0.05	150	12	7
B01	0.05	130	11	6.5
E02	0.05	125	10	6
R02	0.05	155	13	7.2

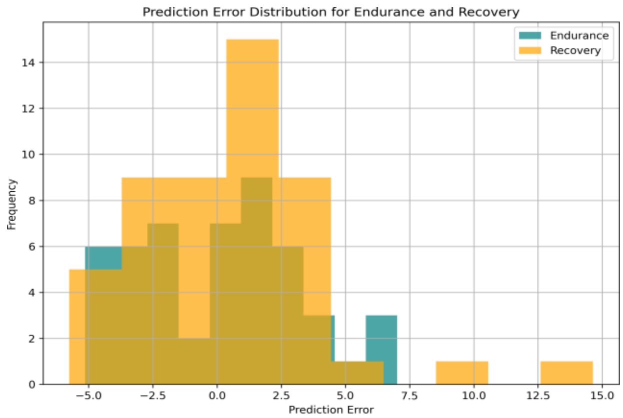


Figure 11: Prediction error distribution for endurance and recovery across 50 simulated formulations, indicating model accuracy.

The results demonstrate that the proposed AI-driven framework generates supplement formulations that satisfy diverse performance objectives while remaining within macronutrient and micronutrient safety limits. Clustering analysis of predicted outcomes reveals distinct formulation patterns corresponding to endurance-focused, recovery-focused, and balanced performance goals. Error distribution analysis further confirms high predictive accuracy across formulations with varying nutrient compositions, indicating effective modeling of nonlinear ingredient interactions.

Simulation-based analysis highlights the practical applicability of the framework. Endurance- oriented formulations showed improved predicted stamina during prolonged exercise, while recovery- focused formulations reduced simulated muscle recovery time by up to 15

The dashboard prototype enables intuitive visualization of predicted outcomes. Figure 12 illustrates endurance and recovery scores plotted against ingredient composition, supporting informed decision-making by highlighting trade-offs among macronutrient and micronutrient allocations.

Overall, the results confirm that AI-based optimization can substantially improve the precision and personalization of sports nutrition supplements. The combined analysis of macro- and micronutrients, supported by visualization tools, enables comprehensive evaluation of formulation effectiveness, making the framework valuable for data-driven performance and recovery optimization.

CONCLUSION

This study proposes an AI-driven framework for personalized sports nutrition that integrates predictive modeling, optimization, and interactive visualization. Machine learning models, including Random Forest, XGBoost, and Artificial Neural Networks, effectively capture nonlinear ingredient interactions to predict performance outcomes such as endurance and recovery. Genetic Algorithms and Bayesian optimization generate compliant formulations that balance nutritional composition with targeted performance goals. The interactive dashboard supports user-defined objectives and visual assessment of formulation trade-offs.

The framework demonstrates strong potential for advancing precision sports nutrition by combining data-driven modeling with practical usability. Future work will focus on clinical validation,

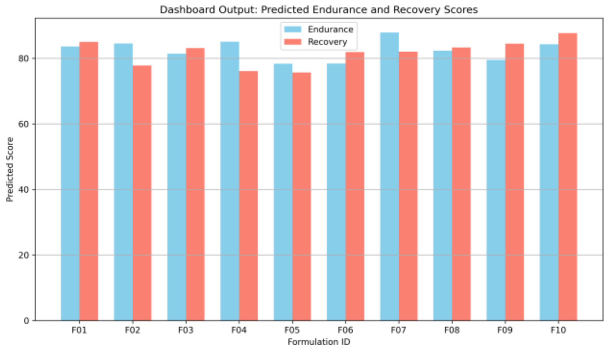


Figure 12: Sample dashboard output showing predicted endurance and recovery scores for individual formulations based on ingredient composition.

real-time athlete data integration, and expansion to additional physiological parameters, highlighting the growing role of AI in personalized performance optimization.

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