European Journal of Applied Physiology
https://doi.org/10.1007/s00421-025-05808-z

ORIGINAL ARTICLE

Metabolomic profiles and antioxidant intake in female soccer players: a cross-sectional study

M. M. S. Gouveia[1] · M. B. A. Nascimento[1] · A. C. Crispim[3] · E. R. da Rocha Jr.[3] · M. P. P. Santos[2] · E. S. Bento[3] · T. M. Aquino[3] · P. Balikian Jr.[2] · N. A. Rodrigues[2] · T. Ataide-Silva[1,2] · G. G. de Araujo[1,2] · F. A. B. Sousa[1,2]

Received: 5 February 2025 / Accepted: 14 April 2025

Abstract

Purpose Excessive reactive oxygen species (ROS) production during sports can impair performance and recovery. A diet rich in exogenous antioxidants plays a key role in counteracting oxidative stress, and its complex interactions with various circulating compounds can be explored through metabolomics. With the rising popularity of women's soccer, a deeper understanding of dietary intake and its metabolic interactions in female athletes is needed. The study's aims are to assess the habitual dietary intake of antioxidant micronutrients and their associations with oxidative/antioxidant metabolites in female professional soccer players through NMR-based metabolomics.

Methods This cross-sectional study included 14 professional female soccer players. Urine samples were collected before and immediately after six games (three per championship) and analyzed by NMR-based metabolomics. Habitual food intake was recorded through 11 food diaries during the preseason. The focus was on vitamins A, C, and E, selenium, zinc, and magnesium. Associations were assessed using Pearson correlations and the DIABLO model.

Results Among the antioxidant micronutrients, only vitamin C and selenium met adequate intake levels. The metabolomics analysis identified 41 metabolites, with key markers of oxidative stress—malonic acid, pyruvate, and glycine—showing strong associations with vitamin E, magnesium, selenium, and zinc, particularly before the game.

Conclusion The antioxidant micronutrient intake of most athletes did not meet the recommended levels. Malonic acid showed positive correlations, while glycine had negative correlations with these micronutrients before the game, suggesting a potential link between antioxidant activity at rest and habitual nutrient intake.

Keywords Soccer · Metabolomics · Nuclear magnetic resonance · Oxidative stress · Micronutrients

Introduction

Football is one of the most widely played sports worldwide, characterized by an intensity of approximately 70–80% of VO_2max (Dobrowolski et al. 2020; Ali et al. 2007). It involves intermittent physical and energetic demands, including high-speed running, short sprints, jumps, and turns. The substantial energy requirements of football, often linked to prolonged exertion, lead to muscle contractions, fiber injuries, and muscle damage in athletes (Higgins et al. 2020). This scenario triggers an inflammatory response in the body, resulting in increased production of free radicals or reactive oxygen species (ROS) (Higgins et al. 2020). By definition, a free radical is a molecular species capable of independent existence that contains an unpaired electron in an atomic orbital (Lobo et al. 2010).

Communicated by Giuseppe D'Antona.

F. A. B. Sousa
filipe.sousa@iefe.ufal.br

[1] Faculty of Nutrition, Federal University of Alagoas, Maceió, Brazil

[2] Laboraty of Applied Sports Science, Institute of Physical Education and Sports, Federal University of Alagoas, Macéio, Brazil

[3] Nucleus of Analysis and Research in Nuclear Magnetic Resonance, NAPRMN, Institute of Chemistry and Biotechnology, Federal University of Alagoas, Macéio, Brazil

Published online: 20 May 2025

The production of ROS during physical activities is an expected outcome. When present at moderate concentrations, ROS can enhance muscle contractions by improving calcium release from the sarcoplasmic reticulum, facilitating cellular adaptation and redox balance, and triggering antioxidant responses (Suzuki 2021). Consequently, in response to increased ROS production, the body elevates the endogenous production of antioxidant enzymes, such as glutathione peroxidase, superoxide dismutase, and glutathione reductase, aiming to mitigate damage and decrease ROS reactivity (Suzuki 2021). However, excessive free radical synthesis (oxidant action > antioxidant action) can impair physical performance and recovery, depending on training variables such as intensity, duration, and type of exercise (Hadzovic-Dzuvo et al. 2014; Suzuki 2021). Antioxidants function through two primary mechanisms: (i) a chain-breaking mechanism, in which an electron is donated to neutralize free radicals present in the body, and (ii) the removal of ROS or reactive nitrogen species initiators by eliminating chain-initiating catalysts (Lobo et al. 2010).

In this context, a well-balanced diet that provides a substantial intake of exogenous antioxidants may serve as a critical strategy to support the endogenous defenses of athletes (Gravina et al. 2012). However, there is still no well-established guideline for female athletes regarding dietary patterns that best align with their performance goals while accounting for the metabolic stress they endure. Given that men's football was the focus for many years, nutritional requirements for male athletes have often been extrapolated to female athletes (Abreu et al. 2021). Nonetheless, these demands are expected to differ, as female football players typically cover shorter total distances and absolute high-intensity distances during matches compared to their male counterparts (distance > 12 km/h: 3151 ± 87 vs. 3621 ± 117 m; distance > 18 km/h: 777 ± 33 vs. 1184 ± 49 m), despite exhibiting similar relative intensities when measured by heart rate zones (Bradley et al. 2014; McFadden et al. 2020). These game-related differences are accompanied by anatomical and hormonal distinctions (Robles-Palazón et al. 2021), as well as variations in hydration profiles, energy expenditure, bone mineral density, and macro- and micronutrient intake needs (Dobrowolski et al. 2020). Such differences result in distinct concentrations of oxidative stress markers (e.g., protein carbonyls) and antioxidant responses (e.g., catalase, reduced glutathione, and uric acid) after matches in female football players compared to males (Souglis et al. 2018). As a result, inadequate micronutrient intake is not uncommon among female football players.

Thus, it is reasonable to expect that, due to the nature of physical exertion, the quality of nutritional intake, and biological sex, circulating compounds in the body may vary in blood or urine depending on an individual's physiological state (e.g., resting, active, or undergoing hormonal changes), reflecting the organism's condition at a given moment. Metabolomics has been employed to identify alterations in the metabolic profile of athletes across different sports disciplines (Bongiovanni et al. 2019). Metabolomics is an omics science focusing on the end products of various physiological pathways, offering a holistic approach to investigating the interactions between metabolites and contextual factors such as nutritional status, and exercise intensity (Guo et al. 2021; Cao et al. 2020; Kim et al. 2022; Trimigno et al. 2020). For instance, metabolomics has demonstrated sensitivity in detecting changes in urinary metabolite profiles in young male football players induced to fatigue. These changes involved pathways such as tyrosine, the tricarboxylic acid cycle, and glycerophosphate metabolism, as assessed through gas chromatography–mass spectrometry (GC–MS) (Cao et al. 2020). Additionally, it has been utilized to set the recovery times post-training, revealing increased concentrations of ammonia, lactate, and adenine in urine samples via H^{-1}NMR spectroscopy of young male soccer players (Kim et al. 2022). Furthermore, metabolomics has detected diet-induced changes in urinary metabolite profiles related to energy pathways in obese men and women using H^{-1}NMR (Trimigno et al. 2020).

Recently, H^{-1}NMR-based metabolomics in urine has been shown to differentiate pre- and post-match states in female football players, with distinguishing metabolites linked to energy pathways (e.g., glycine, formate, citrate, and glycolic acid) among those with the highest VIP (variable importance in projection) scores (Gouveia et al. 2024). However, there is limited evidence exploring associations between diet and metabolomic profiles, particularly regarding the antioxidant profile of female football athletes. A detailed understanding of the impacts of diet and gameplay on the oxidative/antioxidative metabolomic profile is crucial for developing individualized strategies for micronutrient intake specific to female football players. Therefore, it is essential to investigate potential associations between antioxidant micronutrients and metabolites that serve as indicators of pro-oxidative stress reactions or those involved in the elimination of chain-initiating catalysts.

In this context, using an observational approach, the study aimed to investigate the association between the dietary intake, with a focus on antioxidant micronutrients, and urinary metabolites identified with untargeted H^{-1}NMR-based metabolomics in female soccer players, both pre- and post-soccer matches during a 10-week sports season. Considering the high variability in the habitual, uncontrolled dietary intake of female soccer players (Gravina et al. 2012) and the impact of soccer matches on oxidative stress and antioxidant activity in these athletes (Souglis et al. 2018; Gravina et al. 2011), it will be possible to highlight the dietary intake that best align with performance goals of female soccer athletes.

Methods

Population/sampling

The sample was selected using a non-probabilistic sampling method and consisted of 14 professional female athletes (Table 1) from a high-performance team competing in the national women's championship. The sample size was determined by convenience, as it included all athletes from the same team who actively participated in the six matches (≥ 45 min of play). The included athletes played an average of 74.5 ± 19.5 min per match. Participants comprised forward ($n=3$), attacking midfielders ($n=1$), wingers ($n=3$), midfielders ($n=2$), defensive midfielders ($n=2$), full backs ($n=1$), and defenders ($n=2$). Goalkeepers were excluded due to their unique match demands. Six matches were analyzed, with pre- and post-match sample collections. After excluding samples due to refusal, inability to urinate, or lack of consent, the study included 102 urine samples—51 pre-match and 51 post-match.

Study design

This is a cross-sectional study conducted in accordance with the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) reporting guidelines (von Elm et al. 2008). The athletes were monitored over a ten-week season, which included six matches—three from the national championship and three from a regional tournament—conducted between May 27, 2022, and August 7, 2022, as illustrated in Fig. 1. During this period, the athletes trained daily, with sessions lasting between 60 and 120 min.

For this study, the preseason period was defined as the 23 days preceding the first match of the championship. On the first day of the preseason, anthropometric measurements were taken, followed by the collection of a 24-h dietary recall from each athlete. This initial dietary recall was conducted in person and served as the baseline. Over the following 10 days, daily records of each athlete's dietary intake were collected online using an instant messaging application.

With the start of the season, urine samples were collected pre- and post-match during home games, according to the match schedule. Since the study was descriptive in nature, no dietary interventions or intake recommendations were provided to the athletes, aiming to assess their actual dietary intake without direct interference from the nutrition professionals responsible for the sample collections.

Table 1 Anthropometric characteristics data of the sample

	Age	Body mass (kg)	Height (cm)	BMI (kg/m^2)	Body density (g/cm^3)	% Body fat
Mean	22.6	56.0	162	21.4	1.06	18.8
Standard deviation	3.46	5.99	7.64	1.54	0.04	4.70
Minimum	19.0	45.8	148	19.3	1.00	12.7
Maximum	32.0	69.0	175	23.8	1.10	26.5

BMI body mass index. Values are expressed as mean ± standard deviation

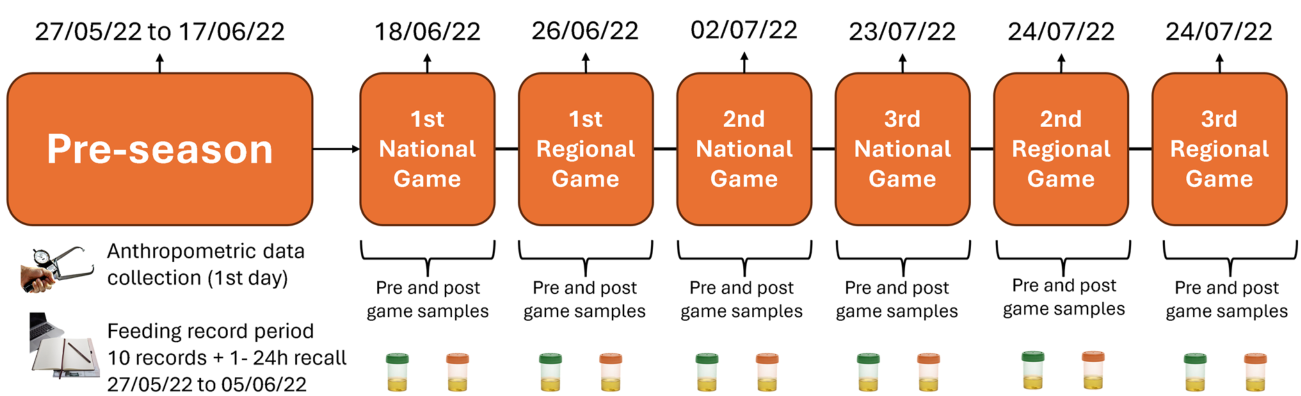

Fig. 1 Experimental design of the study. On game days, urinary collections were carried out pre-game (before the warm-up) and immediately post-game

Habitual dietary intake measurement

For the 24-h dietary recalls, the multiple pass method (MPM) was used to assist the participants in providing more detailed information about their food consumption from the previous day, thereby reducing errors during data collection. The MPM consists of five steps: (1) quick listing (everything consumed on the previous day); (2) listing commonly forgotten foods; (3) defining the time and meal type; (4) detailing and reviewing (flavor, color, type, and preparation method); and (5) final review (Tippett et al. 1999).

Subsequently, during 10 days of the preseason, daily dietary records were collected virtually. These records were sent in real-time by the athletes via an instant messaging app (WhatsApp, Meta Inc., USA), and meal descriptions could be provided through text, audio messages, or photos of the consumed foods. At the start of each day, a message was sent requesting details about the following meals: breakfast, morning snack, lunch, afternoon snack, dinner, and late-night snack, including the respective times and methods of food preparation. The athletes reported their food intake as they consumed each meal. To mitigate reporting bias, after the last meal was reported the nutritionist reviewed all the submitted information and clarified any doubts, such as portion sizes or food preparation methods, when necessary.

Thus, 11 dietary records (1 × 24-h recall and 10 daily dietary records) were obtained from each of the 14 athletes during the preseason. To assess the plausibility of the data, Goldberg's ratio (1991) was applied. Basal Metabolic Rate (BMR) was calculated indirectly using the FAO/WHO (1985) formulas for adult women, based on their age and individual body mass.

Urinary samples

Urine samples were collected using 25 ml containers labeled with the athletes' names, the date, and the time of collection (pre- or post-match). These collections were timed according to the match schedule: before the warm-up (to avoid interference with the metabolome due to physical activity) and immediately after the matches in the locker room, as the athletes returned from the field. The samples were then transported in a thermal container with ice for refrigeration and later analysis via nuclear magnetic resonance (NMR). This approach allowed the characterization of the metabolomic profile both before and after the match efforts, which are key targets of the athletes' training regimen.

Anthropometric measures

Anthropometric data (body mass, height, skinfold thickness, and body fat percentage) was collected only for sample characterization. Body mass (kg) and height (m) were measured using an anthropometric scale with a stadiometer (Balança Mecânica Adulto 180 kg, Welmy®, Santa Bárbara do Oeste, Brazil). Body fat percentage and skinfold thickness were assessed using a caliper (Lange Skinfold Caliper, Cambridge Scientific Industries®, Cambridge, USA), following the Jackson, Pollock, and Ward (1980) protocol, which involves measuring three skinfold sites (suprailiac, thigh, and triceps) to determine the athletes' body fat percentage. The athletes did not train or warm up before the anthropometric measurements were taken. The following formulas were used:

Body density (kg/m^3) = 1.0994921—(0.0009929 × sum of skinfolds) + (0.0000023 × square of the sum of skinfolds)—(0.0001392 × age).

Siri's formula (1956) to estimate body fat percentage (%) = (495/body density)—450.

Data processing and analysis

Sample preparation and H^{-1}NMR experiments

NMR spectra were acquired using a Bruker 600 MHz spectrometer Ascend operating at 600.13 MHz and equipped with a probe PA BBO 600S3 BBF-H-D-05 Z SP. Urine samples (300 µL of the resulting supernatant) were pipetted into an NMR tube (5 mm) with 300 µL phosphate buffer (3-[trimethylsilyl]propionic-2,2,3,3-d4 acid sodium salt 0.1 mM in D_2O). Spectral processing, including phase correction and baseline correction, was executed using TopSpin 3.5 (Bruker BioSpin). The data matrix was prepared using R software and PepsNMR package (version 3.19). Metabolite peaks identification occurred through Chenomx® with the Human Metabolome Database. Additional details are detailed elsewhere (Marinho et al. 2022; Gouveia et al. 2024). A list of the identified metabolites can be found in the supplementary material.

Food intake analysis

Antioxidant nutrients considered for analysis were vitamins A, C, and E, as well as selenium, zinc, and magnesium. The 24-h dietary recalls and daily dietary records were organized using Microsoft Excel 2019 and subsequently analyzed using the Dietbox® software (Dietbox®, Rio Grande do Sul, Brazil). The analysis utilized data from food composition tables (TBCA-USP-FoRC, 2023; Philippi, 2002; IBGE, 2011; NEPA-UNICAMP, 2011; Pacheco 2011; Pinheiro et al., 2020). The percentage of adequacy for energy and macronutrient intake was assessed based on literature recommendations for female soccer players (Dobrowolski et al. 2020) and dietary fiber intake guidelines (Abreu et al. 2021). Antioxidant micronutrient intake was evaluated using the dietary reference intakes (DRIs) framework for nutrient intake assessment in individuals (IOM, 2000). An exception was made for selenium, which lacks a population standard deviation value for detailed analysis; its assessment was based on whether the athletes' average intake exceeded or fell below the estimated average requirement (EAR).

Statistical analysis

The analysis of caloric and macronutrient intake was performed solely for characterization purposes using measures of central tendency and dispersion (mean, median, standard deviation, and range). This analysis was conducted with the Jamovi software (version 2.3, Sydney, Australia) for Windows.

For the metabolomics data analysis, Pearson correlation coefficients were calculated using the R programming language (R Core Team, 2021) to evaluate the degree of association between the average intake of each micronutrient and the 41 metabolites identified in the athletes' samples, as well as metabolite–metabolite correlations (Supplementary Material, Figures S1 and S2) across all six matches. Additionally, statistical significance was tested for all correlation coefficients relative to the sample size (Fig. 2), reinforcing the robustness of the described associations. This analysis was conducted separately for pre- and post-match conditions to explore correlations in readiness for exertion and following a high oxidative stress event.

Furthermore, to holistically compare the athletes' habitual dietary intake (nutrient averages) with the metabolites from samples collected across six matches, a multivariate model for multi-omics data integration was applied. This model utilized partial least squares discriminant analysis (PLS-DA), as described by Singh et al. (2019), and is referred to as Data Integration Analysis for Biomarker discovery using Latent variable approaches (DIABLO). The DIABLO model enabled an integrative analysis to correlate the data in a multivariate context, identifying interactions between variations in micronutrient intake averages and metabolic fluctuations. Additionally, a similarity matrix analogous to a correlation

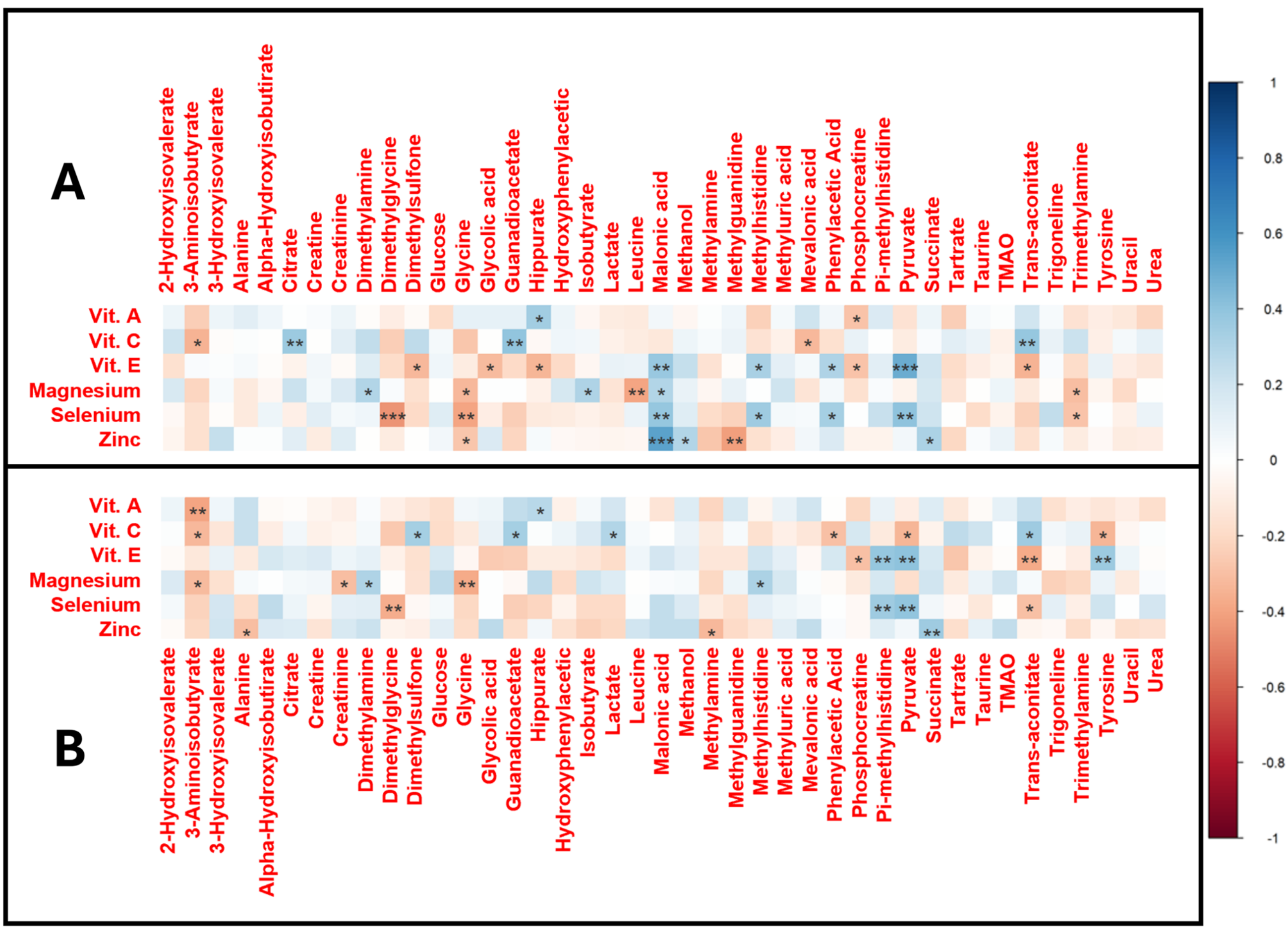

Fig. 2 Heat map with the Pearson's correlation values between 41 metabolites and 6 micronutrients, for the pre-match (**A**) and post-match (**B**) conditions. The color scale represents positive (blue) and negative (red) correlations. Complete heat maps can be found in the supplementary material. Significant correlations are represented by asterisks: $p < 0.05$*; $p < 0.01$**; and $p < 0.001$***

coefficient was derived from the statistical model to estimate the relationship between metabolites and micronutrient intake in an integrated panorama encompassing all conditions (pre- and post-match) and all matches.

Results

Habitual dietary intake

The results for caloric intake, basal metabolic rate (BMR), macronutrient, and fiber consumption are presented in Table 2. On average, the athletes reported a daily caloric intake of 1330 ± 263 kcal, closely matching their BMR (1324 ± 81.6 kcal). Based on the plausibility test, only one athlete had an energy intake below their BMR. The dietary recalls indicated a predominance of carbohydrate consumption (56%) over lipids (27.8%) and proteins (16.2%), with an average fiber intake of 13.4 ± 4.55 g.

Table 3 summarizes the intake of antioxidant micronutrients and their corresponding EAR (estimated average requirement). The probabilities of correctly assessing the adequacy of habitual dietary intake for each nutrient are detailed in the Supplementary Material, except for selenium. Regarding vitamin intake, the analysis revealed that 12 athletes had a 70–98% probability of inadequacy in their habitual vitamin A intake (Supplementary Table S1). This issue was more pronounced for vitamin E, with 13 athletes demonstrating an 85–98% probability of habitual intake inadequacy (Supplementary Table S2). In contrast, vitamin C intake was adequate for most athletes ($n = 11$) with a 98% probability of adequacy (Supplementary Table S3). In terms of mineral intake, all 14 athletes showed a high probability of inadequacy in their habitual magnesium intake (Supplementary Table S5). For zinc, 10 athletes exhibited a 70–98% probability of inadequate intake (Supplementary Table S4). In the case of selenium, only 4 athletes had habitual intake levels below the EAR. These findings indicate significant deficiencies in the habitual dietary intake of antioxidant micronutrients among the athletes, emphasizing the importance of individualized nutritional strategies to address their specific physiological needs.

Habitual micronutrients intake versus metabolomics profile

Using H^{-1}NMR spectroscopy, 41 metabolites were identified in the urine samples collected pre- and post-game. Figure 2 illustrates the correlation matrices depicting relationships between these metabolites and the habitual intake of antioxidant micronutrients under both conditions (panels A and B, respectively). The full correlation matrix, covering all variables (metabolites and micronutrients), is available in the Supplementary Material (Figs. S1 and S2).

For vitamin A, positive correlations were observed with hippurate in both pre- and post-match conditions. Negative correlations included phosphocreatine (pre-match) and 3-amino isobutyrate (post-match). Vitamin C showed a broad spectrum of correlations: positive associations with guanidoacetate (pre- and post-match), trans-aconitate (pre- and post-match), citrate (pre-match), lactate (post-match), and dimethylsulfone (post-match). Negative associations were observed with 3-amino isobutyrate (pre- and post-match), mevalonic acid (pre-match), pyruvate (post-match),

Table 2 Food consumption of energy and macronutrients

	Energy	BMR	PTN/Kg	% PTN	CH/Kg	% CH	LIP/Kg	% LIP	Fibers (g)
Mean	1330	1324	0.99	16.2	3.28	56	0.75	27.8	13.4
Standard deviation	263	81.6	0.35	3.72	0.51	8.55	0.24	5.35	4.55
Minimum	843	1216	0.46	11.4	2.49	41.9	0.36	18.2	8.61
Maximum	1981	1510	1.49	23.2	4.26	66.7	1.08	35.1	25.2

Energy kilocalories, *BMR* basal metabolic rate in kcal, *PTN/Kg* protein per kilogram of body weight, *PTN* % proteins in percentage, *CH/Kg* carbohydrates per kilogram of body weight, *CH* % carbohydrates in percentage, *LIP/Kg* lipids per kilogram of body weight, *LIP* % lipids in percentage

Table 3 Dietary intake of antioxidant micronutrients

	Vitamin A	Vitamin E	Vitamin C	Zinc	Magnesium	Selenium
Mean	513	6.7	312	6.01	140	58.4
Standard deviation	1066	3.05	342	2.12	27	18.8
Minimum	25.7	2.72	23.3	2.94	90.9	30.2
Maximum	4187	13.6	1134	11.4	194	88
EAR	500	12	60	6.8	255	45

EAR estimated average requirement

tyrosine (post-match), and phenylacetic acid (post-match). Vitamin E positively correlated with pyruvate (pre- and post-match), malonic acid (pre-match), methylhistidine (pre-match), phenylacetic acid (pre-match), pi-methylhistidine (post-match), and tyrosine (post-match). In contrast, negative correlations were identified with phosphocreatine (pre- and post-match), trans-aconitate (pre- and post-match), dimethylsulfone (pre-match), glycolic acid (pre-match), and hippurate (pre-match).

For the mineral magnesium, positive correlations were found with dimethylamine (pre- and post-match), isobutyrate (pre-match), malonic acid (pre-match), and methylhistidine (post-match). Negative correlations included glycine (pre- and post-match), leucine (pre-match), trimethylamine (pre-match), 3-amino isobutyrate (post-match), and creatinine (post-match). Selenium positively correlated with pyruvate (pre- and post-match), malonic acid (pre-match), methylhistidine (pre-match), phenylacetic acid (pre-match), and pi-methylhistidine (post-match). Negative correlations included dimethylglycine (pre- and post-match), trimethylamine (pre-match), glycine (pre-match), and trans-aconitate (post-match). zinc exhibited positive correlations with succinate (pre- and post-match), malonic acid (pre-match), and methanol (pre-match), while negative correlations were observed with methylguanidine (pre-match), glycine (pre-match), alanine (post-match), and methylamine (post-match).

These results underscore the complex interactions between habitual antioxidant micronutrient intake and urinary metabolite profiles under varying physiological states. This intricate network reflects the metabolic response to both habitual diet and the oxidative stress induced by soccer matches.

To provide a holistic perspective of these relationships across the season, including pre- and post-game moments, Fig. 3 displays a similarity matrix derived from the correlation between metabolites and antioxidant micronutrient intake, as estimated using the DIABLO model. To enhance interpretability and exclude biologically insignificant correlations or noise from the multivariate model, a correlation threshold of 50% ($r = 0.5$) was applied.

Among the positive interactions, strong associations were identified between vitamin E and phenylacetic acid, methylhistidine, and tyrosine, with a less pronounced correlation observed with pi-methylhistidine. Additionally, vitamin C

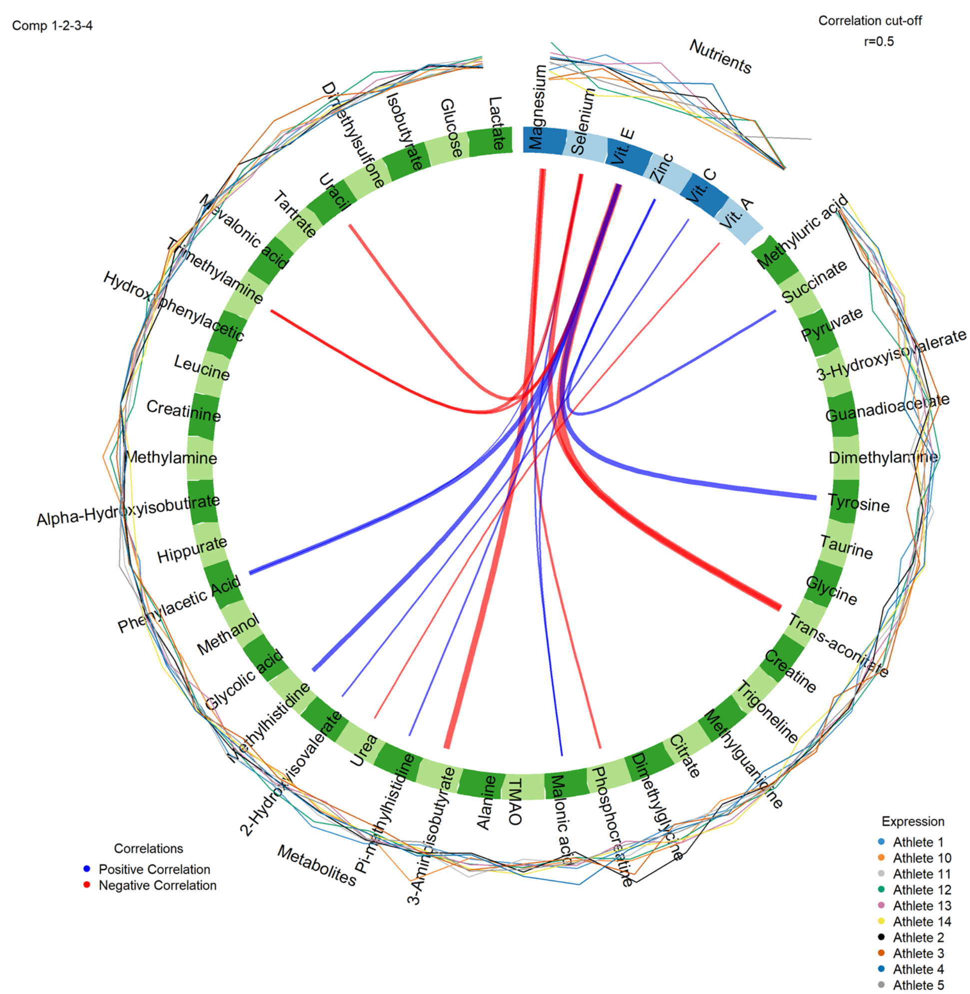

Fig. 3 Circus plot illustrates the correlations between metabolomes (green blocks) and antioxidant antioxidants micronutrients (blue blocks). A correlation cutoff of 0.5 was applied. Positive correlations are represented by blue lines, while negative correlations are indicated by red lines. The line thickness corresponds to the correlation strength, with thicker lines representing stronger correlations closer to 1. The colored lines outside the circle depict the average metabolite expression for each athlete. Larger peaks in the external lines indicate higher metabolite expression in a given athlete, whereas more rectilinear lines represent lower expressions

exhibited a positive relationship with 2-hydroxyisovalerate, zinc was correlated with succinate and malonic acid, and selenium showed strong associations with phenylacetic acid and malonic acid.

For the negative interactions, notable relationships were found between magnesium and 3-aminoisobutyrate, as well as between both selenium and vitamin E with trans-aconitate. Weaker negative correlations were observed between magnesium and phosphocreatine, selenium and vitamin E with trimethylamine, vitamin E with uracil, and vitamin A with urea.

These associations, analyzed using a multivariate approach, provide a more robust and integrated perspective than those from the heat map alone. This model accounts for both physiological conditions (pre- and post-match), the six games across the season, and all participating athletes, offering deeper insights into the relationships between habitual micronutrient intake and urinary metabolite profiles.

Discussion

In this study, we characterized the dietary intake of female soccer players, with a particular focus on antioxidant micronutrients, and identified associations with urinary metabolites observed over the course of a competitive season. The decision to use an untargeted approach was driven by its capacity to explore metabolites potentially linked to oxidative and antioxidant processes that might not be typical targets in other analytical methods. Consequently, the discussion centers on the relationships between key micronutrients and metabolites involved in redox reactions, oxidative stress, and antioxidant defense mechanisms. In this context, vitamins A, C, and E, along with zinc, magnesium, and selenium, are expected to function as exogenous antioxidants derived from the habitual dietary intake of the athletes. These nutrients, in addition to the body's endogenous defenses against reactive oxygen species, are hypothesized to provide a secondary layer of protection by mitigating the free radicals generated during physical exertion. The findings from this study reveal that vitamin C intake had a high probability of adequacy, and selenium intake exceeded the EAR. Conversely, vitamin A, vitamin E, zinc, and magnesium intake demonstrated a higher likelihood of inadequacy for most participants. This variability in micronutrient intake creates a favorable scenario for investigating potential correlations between these nutrients and metabolites identified by H^{-1}NMR spectroscopy in urine that may play roles in antioxidant activity.

In line with our findings, the study by Dobrowolski and Wlodarek (2019) on Polish female soccer players also examined micronutrient intake, though it used only EAR values as a reference. Their results showed that the intake of vitamins A, C, and zinc exceeded the recommended levels, whereas the intake of vitamin E and magnesium fell below the EAR. Selenium was not evaluated in their study. Another study, which assessed the dietary intake of 33 adolescent female soccer players, found that vitamins A and C, along with the minerals magnesium and zinc, were consumed at levels above the EAR. However, the mean intake of vitamin E was below the reference value, and selenium was not assessed (Gibson et al. 2011). These findings suggest that inadequate intake of antioxidant micronutrients is not uncommon among female soccer players, highlighting the need for further investigation into their dietary patterns and potential impacts on performance and oxidative stress management.

The vitamins included in this study—vitamins A, C, and E—were chosen due to their well-established roles in supporting antioxidant defenses (Urso and Clarkson 2003; Lobo et al. 2010). These vitamins are considered capable of mitigating oxidative stress induced by acute exercise without negatively affecting performance, with particular emphasis on vitamins C and E (de Oliveira et al. 2019). Vitamin A, for instance, exhibited a negative correlation with only one of the metabolites of interest, 3-aminoisobutyrate (also known as BAIBA or β-aminoisobutyric acid), in the post-match samples. BAIBA, a metabolite involved in β-alanine metabolism, has been implicated in oxidative metabolism, particularly in regulating lipid metabolism by promoting the oxidation of free fatty acids (Yi et al. 2023). In our findings, higher habitual intake of vitamin A—and other micronutrients with similar associations, such as vitamin C and magnesium—was linked to lower levels of BAIBA in the urine. While these observations are intriguing, it is important to note that they do not imply a causal relationship. Further studies are required to clarify the physiological significance of these associations and to explore the potential impact of dietary intake on metabolites involved in oxidative stress and metabolic regulation.

Vitamin C's role in antioxidant defenses is attributed to its ability to act as a reducing agent, neutralizing reactive oxygen species (ROS) like hydrogen peroxide (Lobo et al. 2010). In this study, vitamin C was negatively correlated with 3-aminoisobutyrate and showed a positive post-match association with lactate while being negatively correlated with pyruvate. These relationships could be influenced by the high levels of glycolytic activity often observed in soccer players, particularly females (Krustrup et al. 2022). The elevated lactate and decreased pyruvate levels might reflect the intense metabolic demands during matches, especially in the context of muscle glycolysis. Given that games acutely increase oxidative stress, it is expected the body to rely on both endogenous and exogenous antioxidant mechanisms to manage this stress.

Vitamin E, recognized as the most potent lipophilic radical-scavenging antioxidant (Lobo et al. 2010), exhibited the highest number of associations with metabolites of interest in this study. Positive pre- and post-match correlations were observed with pyruvate and methylhistidine (including pi-methylhistidine), as well as a pre-match association with malonic acid. These interactions suggest potential links between vitamin E and metabolites involved in redox balance and antioxidant activity. Regarding pyruvate, its antioxidant role has been previously suggested. Enea et al. (2009) observed an increase in acetate levels in urine samples of female athletes (NMR-based analysis) following intense, short-duration exercise (cycle ergometer). This was attributed to pyruvate reacting with H_2O_2 (a pro-oxidant molecule), producing acetate and CO_2 via oxidative decarboxylation. Similarly, methylhistidine and pi-methylhistidine are well-known markers of skeletal muscle protein breakdown (NCBI, 2024), which can be triggered by intense physical activity. Muscle damage, in turn, is associated with heightened oxidative stress, given its contribution to muscle dysfunction and tissue injury (Powers and Jackson 2008). Vitamin E has been shown to protect skeletal muscle against exercise-induced damage, preserving cell membrane integrity (Mancio et al. 2017; Jackson et al. 1983). However, in this study, the observed positive correlations of vitamin E with methylhistidine and pi-methylhistidine both pre- and post-match may reflect the generally inadequate vitamin E intake reported for most athletes, which may not be sufficient to mitigate muscle damage.

Specifically, regarding zinc's role in exercise, a study by Toro-Román et al. (2022) suggests a direct relationship between this mineral and sports performance, given that approximately 60% of zinc's total concentration is found in skeletal muscle. Zinc also functions as a cofactor for various metalloenzymes, such as lactate dehydrogenase and superoxide dismutase, playing critical roles in immune system function, cellular division, and development. In this study, zinc showed positive associations with succinate (pre- and post-game) and malonic acid (pre-game). Succinate is a key marker of activity in the TCA cycle, associated with both inflammation and the production of reactive oxygen species (ROS) (Osuna-Prieto et al. 2021). Malonic acid, formed through the oxidation of malondialdehyde, is a classic inhibitor of succinate dehydrogenase (Bowman and Wolfgang 2019; Pardee and Potter 1949), although it is not frequently studied in humans. Furthermore, zinc exhibited negative correlations with methylamine and methylguanidine. Methylamine, commonly found in urine, has associations with renal diseases and oxidative stress-induced toxicity (Mitchell and Zhang 2001). Methylguanidine, on the other hand, is considered a potential marker of oxidative stress (Pechlivanis et al. 2012). Zinc also presented a negative correlation with glycine in the pre-match condition, possibly linked to glycine's role in glutathione synthesis, a crucial antioxidant mitigating oxidative stress (McCarty et al., 2018). Unfortunately, direct confirmation of glutathione levels was not possible, as it was not identified in the urine H-1NMR analysis performed in this study.

A systematic review assessing the role of mineral and trace element supplementation on elite athletes' performance highlights magnesium (Mg) as potentially associated with muscle mass, power, and inflammation markers (Heffernan et al. 2019). There appears to be a relationship between exercise intensity and plasma Mg concentration. For instance, male elite handball players training for longer durations but at low to moderate intensities demonstrated higher Mg levels (Molina-López et al. 2012). This may be attributed to magnesium's role in carbohydrate metabolism, particularly in enhancing mitochondrial energy efficiency (Mooren 2015). Evidence suggests that supplementation with 300–500 mg/day of magnesium over 1–4 weeks can improve muscular performance and reduce exercise-induced inflammation and DNA damage (Heffernan et al. 2019). In the present study, magnesium showed a pre-match positive correlation with malonic acid, which is linked to mitochondrial respiration and redox processes. It also exhibited negative correlations with 3-aminoisobutyrate (post-match) and glycine (pre- and post-match). As already stated, these metabolites are implicated in promoting free fatty acid oxidation (Yi et al. 2023) and glutathione synthesis (McCarty et al., 2018), respectively. In summary, higher habitual intake of magnesium was associated with lower levels of metabolites linked to oxidation and higher levels of indicators of antioxidant defenses.

Regarding selenium, classical literature shows that its supplementation increased glutathione peroxidase activity compared to a placebo group during a 10-week resistance training program (Tessier et al. 1995). However, more recent studies argue that obtaining exogenous antioxidants through diet is preferable, as supplementation might impair anabolic signaling pathways (Higgins et al. 2020). In this study, selenium exhibited a positive correlation with malonic acid in the pre-match condition, as well as with pyruvate, methylhistidine, and pi-methylhistidine, all of which are involved in redox reactions. Additionally, similar to magnesium and zinc, selenium showed a negative correlation with glycine in the pre-match condition—a potential indicator of antioxidant metabolism. Glycine plays a critical role in glutathione synthesis, which is a two-step enzymatic process requiring ATP. In the first step, glutamate-cysteine ligase (GCL)—composed of catalytic (GCLC) and modifier (GCLM) subunits—facilitates the conjugation of cysteine with glutamate to produce γ-glutamylcysteine. In the second step, glutathione synthase incorporates glycine into γ-glutamylcysteine, resulting in the formation of γ-glutamylcysteinylglycine, also known as glutathione (Lu 2013).

To the best of our knowledge, this is the first study to correlate antioxidant micronutrient intake with metabolomics in female athletes. Pinto et al. (2022) compared male and female basketball players with sedentary controls to investigate metabolic and hormonal profiles, as well as antioxidant capacity, using plasma metabolomics. Their findings revealed that both male and female athletes showed increased antioxidant capacity at rest compared to the control group, with a slightly greater increase in males. Similarly, a study by Rodas et al. (2022) evaluated the influence of external training load on urinary metabolites in male and female soccer players. It identified 8-hydroxyguanosine—a biomarker of oxidative stress—exclusively in the male profile. These findings emphasize the importance of avoiding the generalization of male athletes' antioxidant responses to exercise for females, underlining the value of data that account for biological sex specificity.

That said, the data presented here demonstrates correlations between certain metabolites associated with oxidative stress, such as pyruvate, malonic acid, and glycine, and some of the antioxidant micronutrients of interest. Urine was the biofluid of choice, and while it offers the advantage of ecological validity due to its non-invasive nature and lower risk of contamination in physical exercise settings, other biofluids, such as blood, are more sensitive to the presence of certain metabolites. Blood can often enable the identification of more specific markers, such as glutathione—a key antioxidant marker—which was not detected in the present study.

Besides the biofluid, other limitations of this study include the absence of direct intervention on the micronutrient intake. The non-standardized diet across groups with low and high intake could hinder the understanding of correlations and associations due to potential imbalances, such as inadequate levels of vitamins A and E or excess intake of vitamin C. However, conducting such an experimental design in elite athletes would be difficult, as they were in competition during the study period. Thus, the decision was made to investigate how habitual intake might influence relationships with metabolites associated with oxidative/antioxidant activity and to explore these interactions in a real-world sports setting. Future data collection should try to improve micronutrient intake to compare the independent groups. Another noteworthy limitation is the complexity of interpreting these metabolites as biomarkers, as their significance can vary depending on the context, experimental conditions, and additional factors. For example, elevated malonic acid or reduced glycine levels might not always indicate oxidative stress, and variations in pyruvate levels could stem from factors unrelated to the redox state. However, given the impact of chronic high-intensity exercise required in competitive performance, we believe this is the most significant factor affecting these athletes, and the observed associations strongly suggest a link between diet and exercise stress. Also, the use of the DIABLO model as an integrative analysis strengthens the potential to find candidate metabolites related to the habitual intake of micronutrients.

Furthermore, a higher intake of exogenous antioxidants through diet could suppress endogenous antioxidant activity, which would lead to negative correlations between micronutrients and antioxidant-related metabolites. Thus, rather than serving as definitive evidence of cause-effect relationships, these findings should be viewed as indicative patterns. Future clinical trials are needed to provide a deeper understanding of these relationships. Lastly, menstrual cycle and hormonal fluctuations, which influence antioxidant function, were not controlled for. Despite its critical role in female physiology, the menstrual cycle is often overlooked due to logistical challenges in monitoring, especially in longitudinal studies. Key challenges include individual variability in cycle length and symptoms, the complex effects of estrogen and progesterone, inconsistent standardization of cycle phases, cumulative hormonal influences, confounding effects of hormonal contraceptives, and a lack of methodological consensus in reporting menstrual cycle data. Regardless of this, significant associations between dietary intake and metabolomic profiles were still observed. Future studies should account for menstrual cycles to strengthen these findings and address historical biases favoring male subjects.

Conclusion

In summary, correlations between urinary metabolites and antioxidant micronutrients were observed in both analyses (Pearson correlation pre- and post-game and DIABLO throughout the season). Notably, malonic acid showed positive associations, while glycine (a glutathione precursor) displayed negative correlations with most micronutrients in the pre-game condition, highlighting a potential link between antioxidant activity at rest and habitual intake of these micronutrients. It can be concluded that the dietary intake of antioxidant micronutrients did not meet reference or adequate consumption levels for most athletes. Additionally, the intake of these micronutrients appears to be associated with the presence of metabolites related to oxidative stress and antioxidant defenses in female soccer players. These findings are expected to guide the development of future clinical trials to better understand these relationships.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00421-025-05808-z.

Author contributions Gouveia, MMS: manuscript writing and editing, data collection and analysis, univariate statistics. MBA Nascimento: data collection and analysis, univariate statistics. Crispim, AC: NMR analysis and multivariate statistics, manuscript review. Da Rocha Jr, E.R: NMR analysis and multivariate statistics, manuscript review. Santos, MPP: sample collection. Bento, ES: coordination of NMR analysis and multivariate statistics, manuscript review. Aquino, TM: coordination of NMR analysis and multivariate statistics, manuscript review. Balikian Jr, P: project coordination, interpretation and discussion of analyses, manuscript review and corrections. Rodrigues, NA: interpretation and discussion of analyses, manuscript review and corrections. Ataíde-Silva, TD: conceptualization, co-supervision, manuscript review and corrections. de Araujo, GG: project conceptualization, coordination, and supervision, manuscript review and corrections. Sousa, FAB: conceptualization, supervision, manuscript writing and review, general corrections.

Funding Funding was provided by Conselho Nacional de Desenvolvimento Cientifico e Tecnologico (408972/2021–1) and Fundacao de Amparo a Pesquisa do Estado de Alagoas (E60030.0000000161/2022).

Data availability All relevant data generated or analyzed during this study are included in this published article and its supplementary information files. Additional data are available from the authors upon request.

Declarations

Conflict of interest The authors declare no conflicts of interest.

Ethical standards Before the start of the study, the athletes were informed about all procedures to be performed during the research, as well as the potential risks and benefits. They then signed the Free and Informed Consent Term (TCLE). This study is part of a larger project entitled "Analysis and Improvement of Athlete Performance" approved by the Research Ethics Committee (CEP) of the Federal University of Alagoas (UFAL) under the number CAAE: 29269020.8.0000.5013 and Protocol: 4297907, in accordance with the ethical principles of the 1964 Declaration of Helsinki. The project was supported by the National Council for Scientific and Technological Development (CNPq)—code 408972/2021-1.

References

Abreu R, Figueiredo P, Beckert P, Marques JP, Amorim S, Caetano C, Carvalho P, Sá C, Cotovio R, Cruz J, Dias T, Fernandes G, Gonçalves E, Leão C, Leitão A, Lopes J, Machado E, Neves M, Oliveira A, Pereira AI (2021) Portuguese football federation consensus statement 2020: nutrition and performance in football. BMJ Open Sport Exerc Med 7(3):e001082. https://doi.org/10.1136/bmjsem-2021-001082

Ali A, Williams C, Nicholas CW, Foskett A (2007) The influence of carbohydrate-electrolyte ingestion on soccer skill performance. Med Sci Sports Exerc 39(11):1969. https://doi.org/10.1249/mss.0b013e31814fb3e3

Bradley PS, Dellal A, Mohr M, Castellano J, Wilkie A (2014) Gender differences in match performance characteristics of soccer players competing in the UEFA Champions League. Hum Mov Sci 33:159–171. https://doi.org/10.1016/j.humov.2013.07.024

Bongiovanni T, Pintus R, Dessì A, Noto A, Sardo S, Finco G, Corsello G, Fanos V (2019) Sportomics: metabolomics applied to sports. The new revolution?. European review for medical and pharmacological sciences, 23(24): 11011–11019. https://doi.org/10.26355/eurrev_201912_19807

Bowman CE, Wolfgang MJ (2019) Role of the malonyl-CoA synthetase ACSF3 in mitochondrial metabolism. Adv Biol Regulat 71:34–40. https://doi.org/10.1016/j.jbior.2018.09.002

Cao B, Liu S, Yang L, Chi A (2020) Changes of differential urinary metabolites after high-intensive training in teenage football players. Biomed Res Int 2020:1–9. https://doi.org/10.1155/2020/2073803

de Oliveira DCX, Rosa FT, Simões-Ambrósio L, Jordao AA, Deminice R (2019) Antioxidant vitamin supplementation prevents oxidative stress but does not enhance performance in young football athletes. Nutrition (Burbank, Los Angeles County, Calif.) 63–64: 29–35. https://doi.org/10.1016/j.nut.2019.01.007

Dobrowolski H, Karczemna A, Włodarek D (2020) Nutrition for female soccer players—recommendations. Medicina 56(1):28. https://doi.org/10.3390/medicina56010028

Dobrowolski H, Włodarek D (2019) Dietary intake of polish female soccer players. Int J Environ Res Publ Health 16(7):1134. https://doi.org/10.3390/ijerph16071134

Enea C, Seguin F, Petitpas-Mulliez J, Boildieu N, Boisseau N, Delpech N, Diaz V, Eugène M, Dugué B (2009) 1H NMR-based metabolomics approach for exploring urinary metabolome modifications after acute and chronic physical exercise. Anal Bioanal Chem 396(3):1167–1176. https://doi.org/10.1007/s00216-009-3289-4

Food and Agriculture Organization (FAO)., World Health Organization (who)., The United Nation University (UNU). Energy and protein requirements. Geneva: fao/who/unu., 1985.

Gibson JC, Stuart-Hill L, Martin S, Gaul C (2011) Nutrition status of junior elite Canadian female soccer athletes. Int J Sport Nutr Exerc Metab 21(6):507–514. https://doi.org/10.1123/ijsnem.21.6.507

Goldberg GR, Black AE, Jebb SA, Cole TJ, Murgatroyd PR, Coward WA, Prentice AM (1991) Critical evaluation of energy intake data using fundamental principles of energy physiology: 1. Derivation of cut-off limits to identify under-recording. Euro J Clin Nutr 45(12), 569–581.

Gouveia MMS, do Nascimento MBA, Crispim AC, da Rocha ER, Jr, Dos Santos MPP, Bento ES, De Aquino TM, Balikian P, Jr, Rodrigues NA, Ataide-Silva T, de Araujo GG, Sousa FAB (2024) Metabolomic profiling of elite female soccer players: urinary biomarkers over a championship season. Metabolomics 20(5), 101. https://doi.org/10.1007/s11306-024-02164-5

Gravina L, Ruiz F, Diaz E, Lekue JA, Badiola A, Irazusta J, Gil SM (2012). Influence of nutrient intake on antioxidant capacity, muscle damage and white blood cell count in female soccer players. J Int Soc Sports Nutr 9(1). https://doi.org/10.1186/1550-2783-9-32

Gravina L, Ruiz F, Lekue JA, Irazusta J, Gil SM (2011) Metabolic impact of a soccer match on female players. J Sports Sci 29(12):1345–1352. https://doi.org/10.1080/02640414.2011.597420

Guo S, Zhang C, Le A (2021) The limitless applications of single-cell metabolomics. Curr Opin Biotechnol 71:115–122. https://doi.org/10.1016/j.copbio.2021.07.015

Hadžović-Džuvo A, Valjevac A, Lepara O, Pjanić S, Hadžimuratović A, Mekić A (2014) Oxidative stress status in elite athletes engaged in different sport disciplines. Bosnian J Basic Med Sci 14(2): 56–62. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4333958/

Higgins MR, Izadi A, Kaviani M (2020) Antioxidants and exercise performance: with a focus on vitamin E and C supplementation. Int J Environ Res Public Health 17(22):8452. https://doi.org/10.3390/ijerph17228452

Heffernan S, Horner K, De Vito G, Conway G (2019) The role of mineral and trace element supplementation in exercise and athletic performance: a systematic review. Nutrients 11(3):696. https://doi.org/10.3390/nu11030696

Institute of Medicine (IOM). *Dietary Reference Intakes: Applications in Dietary Assessment*. Washington: The National Academy Press, 2000. https://nap.nationalacademies.org/catalog/9956/dietary-reference-intakes-applications-in-dietary-assessment .

Instituto Brasileiro de Geografia e Estatística, Diretoria de Pesquisas, & Coordenação de Trabalho e Rendimento (IBGE). (2011). *Pesquisa de Orçamentos Familiares 2008–2009: tabela de medidas referidas para os alimentos consumidos no Brasil.*

Jackson MJ, Jones DA, Edwards RH (1983) Vitamin E and skeletal muscle. Ciba Found Symp 101:224–239. https://doi.org/10.1002/9780470720820.ch14

Kim HY, Lee JD, Lee YH, Seo SW, Lee HS, Kim S, Kim KB (2022) Urinary metabolomics in young soccer players after winter training season. Metabolites 12(12):1283. https://doi.org/10.3390/metabo12121283

Krustrup P, Mohr M, Nybo L, Draganidis D, Randers MB, Ermidis G, Ørntoft C, Røddik L, Batsilas D, Poulios A, Ørtenblad N, Loules G, Deli CK, Batrakoulis A, Nielsen JL, Jamurtas AZ, Fatouros IG (2022) Muscle metabolism and impaired sprint performance in an elite women's football game. Scand J Med Sci Sports 32(Suppl 1):27–38. https://doi.org/10.1111/sms.13970

Lobo V, Patil A, Phatak A, Chandra N (2010) Free radicals, antioxidants and functional foods: Impact on human health. Pharmacogn Rev 4(8):118–126. https://doi.org/10.4103/0973-7847.70902

Lu SC (2013) Glutathione synthesis. Biochem Biophys Acta 1830(5):3143–3153. https://doi.org/10.1016/j.bbagen.2012.09.008

Mâncio RD, Hermes TA, Macedo AB., Mizobuti DS, Valduga AH, Rupcic IF, Minatel E (2017) Vitamin E treatment decreases muscle injury in mdx mice. Nutrition (Burbank, Los Angeles County, Calif.) 43–44: 39–46. https://doi.org/10.1016/j.nut.2017.07.003

Marinho AH, Sousa FAB, Vilela RAMP, Balikian P Jr, de Souza Bento E, de Mendonça Aquino T, Crispim A, Ataide-Silva T, de Araujo GG (2022) The rating of perceived exertion is able to differentiate the post-matches metabolomic profile of elite U-20 soccer players. Eur J Appl Physiol 122(2):371–382. https://doi.org/10.1007/s00421-021-04838-7

McFadden BA, Walker AJ, Bozzini BN, Sanders DJ, Arent SM (2020) Comparison of internal and external training loads in male and female collegiate soccer players during practices vs. games. J Strength Conditioning Res 34(4): 969–974. https://doi.org/10.1519/jsc.0000000000003485

Mitchell SC, Zhang AQ (2001) Methylamine in human urine. Clin Chim Acta 312(1–2):107–114. https://doi.org/10.1016/s0009-8981(01)00608-8

Molina-López J, Molina JM, Chirosa LJ, Florea D, Sáez L, Millán E, Planells E (2012) Association between erythrocyte concentrations of magnesium and zinc in high-performance handball players after dietary magnesium supplementation. Magnes Res 25(2):79–88. https://doi.org/10.1684/mrh.2012.0311

Mooren FC (2015) Magnesium and disturbances in carbohydrate metabolism. Diabetes Obes Metab 17(9):813–823. https://doi.org/10.1111/dom.12492

National Center for Biotechnology Information (2024). PubChem Pathway Summary for Pathway SMP0063638, Methylhistidine Metabolism, Source: PathBank. Retrieved September 30, 2024 from https://pubchem.ncbi.nlm.nih.gov/pathway/PathBank:SMP0063638.

Osuna-Prieto FJ, Martinez-Tellez B, Ortiz-Alvarez L, Di X, Jurado-Fasoli L, Xu H, Ceperuelo-Mallafré V, Núñez-Roa C, Kohler I, Segura-Carretero A, García-Lario JV, Gil A, Aguilera CM, Llamas-Elvira JM, Rensen PCN, Vendrell J, Ruiz JR, Fernández-Veledo S (2021) Elevated plasma succinate levels are linked to higher cardiovascular disease risk factors in young adults. Cardiovasc Diabetol 20(1):151. https://doi.org/10.1186/s12933-021-01333-3

Pacheco M (2011) Tabela de equivalentes, medidas caseiras e composição química dos alimentos. Pesquisa.bvsalud.org. https://pesquisa.bvsalud.org/portal/resource/pt/lil-614027

Pardee AB, Potter VR (1949) Malonate inhibition of oxidations in the Krebs tricarboxylic acid cycle. J Biol Chem 178(1):241–250

Pechlivanis A, Kostidis S, Saraslanidis P, Petridou A, Tsalis G, Veselkov K, Mikros E, Mougios V, Theodoridis GA (2012) 1H NMR study on the short- and long-term impact of two training programs of sprint running on the metabolic fingerprint of human serum. J Proteome Res 12(1):470–480. https://doi.org/10.1021/pr300846x

Pinheiro ABV, Lacerda EMDA, Benzecry EH, Gomes MCDS, Costa VMD (2005) Tabela para avaliação de consumo alimentar em medidas caseiras. In Tabela para avaliação de consumo alimentar em medidas caseiras (pp. 131–131).

Pinto G, Militello R, Amoresano A, Modesti PA, Modesti A, Luti S (2022) Relationships between sex and adaptation to physical exercise in young athletes: a pilot study. Healthcare 10(2):358. https://doi.org/10.3390/healthcare10020358

Powers SK, Jackson MJ (2008) Exercise-induced oxidative stress: cellular mechanisms and impact on muscle force production. Physiol Rev 88(4):1243–1276. https://doi.org/10.1152/physrev.00031.2007

Robles-Palazón FJ, López-Valenciano A, Croix MDS, Oliver, JL, García-Gómez A, de Baranda PS, Ayala F (2021) Epidemiology of injuries in male and female youth football players: A systematic review and meta-analysis. J Sport Health Sci 11(6). https://doi.org/10.1016/j.jshs.2021.10.002

Rodas G, Ferrer E, Reche X, Sanjuan-Herráez JD, McCall A, Quintás G (2022) A targeted metabolic analysis of football players and its association to player load: Comparison between women and men profiles. Front Physiol 13. https://doi.org/10.3389/fphys.2022.923608

Singh A, Shannon CP, Gautier B, Rohart F, Vacher M, Tebbutt SJ, Lê Cao KA (2019) DIABLO: an integrative approach for identifying key molecular drivers from multi-omics assays. Bioinformatics 35(17):3055–3062

Siri WE (1956) The gross composition of the body. Adv Biol Med Phys 4:239–280. https://doi.org/10.1016/b978-1-4832-3110-5.50011-x

Souglis A, Bogdanis GC, Chryssanthopoulos C, Apostolidis N, Geladas ND (2018) Time course of oxidative stress, inflammation, and muscle damage markers for 5 days after a soccer match: effects of sex and playing position. J Strength Conditioning Res 32(7):2045–2054. https://doi.org/10.1519/JSC.0000000000002436

Suzuki K (2021) Recent progress in applicability of exercise immunology and inflammation research to sports nutrition. Nutrients 13(12):4299. https://doi.org/10.3390/nu13124299

Tessier F, Margaritis I, Richard MJ, Moynot C, Marconnet P (1995) Selenium and training effects on the glutathione system and aerobic performance. Med Sci Sports Exercise 27(3): 390–396. https://pubmed.ncbi.nlm.nih.gov/7752866/

Trimigno, A., Khakimov, B., Savorani, F., Poulsen, S. K., Astrup, A., Dragsted, L. O., & Engelsen, S. B. (2020). Human urine 1H NMR metabolomics reveals alterations of protein and carbohydrate metabolism when comparing habitual Average Danish diet vs. healthy New Nordic diet. *Nutrition*, 79, 110867.

Tippett KS, Enns CW, Moshfegh AJ (1999) Food Consumption Surveys in the US Department of Agriculture. Nutrition Today 34(1):33. https://journals.lww.com/nutritiontodayonline/citation/1999/01000/food_consumption_surveys_in_the_us_department_of.7.aspx

Toro-Román V, Robles-Gil MC, Muñoz D, Bartolomé I, Siquier-Coll J, Maynar-Mariño M (2022) Extracellular and intracellular concentrations of molybdenum and zinc in soccer players: sex differences. Biology 11(12):1710. https://doi.org/10.3390/biology11121710

Tabela Brasileira de Composição de Alimentos (TBCA). Universidade de São Paulo (USP). Food Research Center (FoRC). Versão 7.2. São Paulo, 2023. Retrieved from: http://www.fcf.usp.br/tbca.

Núcleo de Estudos e Pesquisas em Alimentação (NEPA) & Universidade Estadual de Campinas (UNICAMP). (2011). Tabela Brasileira de Composição de Alimentos - TACO (4th ed.). Retrieved from https://www.cfn.org.br/wp-content/uploads/2017/03/taco_4_edicao_ampliada_e_revisada.pdf

Urso ML, Clarkson PM (2003) Oxidative stress, exercise, and antioxidant supplementation. Toxicology 189(1–2):41–54. https://doi.org/10.1016/s0300-483x(03)00151-3

von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP, Initiative STROBE (2008) The strengthening the reporting of observational studies in epidemiology (STROBE) statement: guidelines for reporting observational studies. J Clin Epidemiol 61(4):344–349. https://doi.org/10.1016/j.jclinepi.2007.11.008

Yi X, Yang Y, Li T, Li M, Yao T, Hu G, Wan G, Chang B (2023) Signaling metabolite β-aminoisobutyric acid as a metabolic regulator, biomarker, and potential exercise pill. Front Endocrinol 14:1192458. https://doi.org/10.3389/fendo.2023.1192458