Regulatory Toxicology and Pharmacology 169 (2026) 106106

Contents lists available at ScienceDirect

Regulatory Toxicology and Pharmacology

journal homepage: www.elsevier.com/locate/yrtph

Contamination and adulteration of food supplements: Risk perception and regulatory awareness in recreational athletes

Sofia Lopes [a], Madalena Cunha [b], Ana S. Fernandes [a], Nuno G. Oliveira [c], Cíntia Ferreira-Pêgo [a,1], João G. Costa [a,*,1]

[a] CBIOS, Universidade Lusófona's Research Center for Biosciences and Health Technologies, 1749-024 Lisboa, Portugal
[b] School of Health Sciences and Technologies, Universidade Lusófona, 1749-024 Lisboa, Portugal
[c] Research Institute for Medicines (iMed.ULisboa), Faculty of Pharmacy, Universidade de Lisboa, 1649-003 Lisboa, Portugal

ARTICLE INFO

Handling Editor: Dr. Martin van den Berg

Keywords:
Food supplements
Safety perception
Contamination
Adulteration
Toxicological risk
Recreational athletes

ABSTRACT

There is growing concern about the toxicological risks resulting from the contamination and adulteration of food supplements (FS), which may pose significant health hazards. Heavy metals, undeclared pharmaceuticals, stimulants, and other contaminants have been identified in FS. This study evaluated recreational athletes' perceptions and awareness of FS safety, including contamination risk and potential health consequences. A cross-sectional study was conducted among 303 gym-goers, using structured face-to-face interviews. Approximately 72% of participants reported FS use, predominantly men. Most respondents perceived themselves as informed, yet 95% were unable to identify the regulatory definition of FS correctly. Nearly half demonstrated limited awareness of market control and regulatory oversight. Differences emerged between FS users and non-users. As such, non-users showed greater awareness of potential interactions with medicines and were more likely to attribute broader functional roles to FS and expressed greater concern regarding overdose risk. In turn, users recognised the possibility of undeclared or prohibited substances more frequently. Contaminated FS were most often associated with cardiovascular, hepatic, and hormonal concerns. Overall, recreational athletes demonstrated substantial knowledge gaps regarding FS safety and regulation. These findings highlight the need for targeted education and risk communication strategies aligned with toxicological evidence to support safer supplementation practices.

1. Introduction

A well-balanced diet and adequate training are typically considered essential components of a healthy lifestyle (Finamore et al., 2022). In practice, a proper diet provides the nutrients required for optimal physiological function and overall health. However, depending on life stage and lifestyle demands, achieving the recommended levels of certain substances may not always be feasible (Ofoedu et al., 2021). In such circumstances, individuals often use food supplements (FS) to complement dietary intake (Costa et al., 2019).

In the first half of the twentieth century, formulations enriched with vitamins, minerals or macronutrients were introduced as FS (Jędrejko et al., 2021). These products were primarily directed towards populations with increased nutritional requirements, including pregnant and breastfeeding women, children, and older adults (Costa et al., 2019; Jędrejko et al., 2021).

Currently, athletes represent one of the primary consumer groups targeted by the FS industry, demonstrating broader and more diverse consumption patterns than the general population (Cohen et al., 2018; Martínez-Sanz et al., 2017; Ruano and Teixeira, 2020). This trend was underscored by Tscholl et al. (2010), who reported consumption of 6523 units among 3887 athletes, corresponding to an average of 1.7 supplements per athlete. We recently reported similar results among Portuguese gym-goers: nearly three-quarters of the participants reported consuming FS or sports food, averaging 1.6 products per athlete (Lopes et al., 2024).

Despite limited and heterogeneous evidence supporting claimed benefits and safety, athletes frequently use FS for overall health, recovery (Cohen et al., 2018; Edenfield, 2020; Mallick et al., 2023), perceived performance enhancement (Cohen et al., 2018; Edenfield,

* Corresponding author.
E-mail address: jgcosta@ulusofona.pt (J.G. Costa).
[1] Both authors contributed equally to the senior authorship.

https://doi.org/10.1016/j.yrtph.2026.106106
Received 7 March 2026; Received in revised form 8 April 2026; Accepted 21 April 2026
Available online 22 April 2026

2020; Harty et al., 2018; Martínez-Sanz et al., 2017), injury prevention (Cohen et al., 2018), weight control (Mallick et al., 2023; Rodriguez-Lopez et al., 2022), and dietary compensation (Cohen et al., 2018; Edenfield, 2020; Lopes et al., 2024; Mallick et al., 2023). Regulatory advances have not consistently kept pace with the rapid expansion of the FS market (Costa et al., 2019; Incze and Katz, 2018), creating ongoing challenges for regulatory oversight and risk management. Uncertainty regarding product composition led some authors (Cohen, 2009) to describe the American supplement market as "American roulette", highlighting concerns about undeclared or hazardous substances. Nevertheless, consumer confidence persists, often based on the assumption that FS undergo rigorous safety evaluations (Cohen, 2009; Denham, 2017).

From a regulatory perspective, manufacturers are primarily responsible for ensuring the quality and safety of FS (Mathews, 2018). In most regulatory settings, national authorities do not require formal pre-market approval or routine safety testing, leaving compliance responsibility with manufacturers (Mathews, 2018). Although no mandatory pre-market quality, safety, or functional testing is required, manufacturers are expected to comply with established standards such as Good Manufacturing Practices (GMP), which aim to ensure product quality and consistency (Incze and Katz, 2018; Kozhuharov et al., 2022; Mathews, 2018). Regulatory authorities retain the capacity to conduct post-market inspections and audits of manufacturing facilities, providing an additional layer of oversight (Mathews, 2018). Regulatory frameworks for FS differ considerably across jurisdictions. Within the EU, FS are regulated primarily under Directive 2002/46/EC (European Parliament and Council, 2002a), which harmonises labelling and permitted vitamins and minerals but delegates authority over dosage levels and other substances to individual Member States. Portugal transposed this Directive via Decree-Law No. 136/2003, subsequently updated by Decree-Law No. 118/2015. In the United States, the Dietary Supplement Health and Education Act does not require pre-market approval, placing the burden of safety on the FDA only after market entry (Incze and Katz, 2018). The United Kingdom retained equivalent provisions post-Brexit through the Nutrition (Amendment etc.) (EU Exit) Regulations 2019, though maximum levels remain unharmonised (UK Government - Department of Health and Social Care, 2024). This shared absence of mandatory pre-market safety evaluation across major markets creates structural conditions under which contamination and adulteration may remain undetected until post-market surveillance identifies a safety signal. Under such conditions, FS may be susceptible to contamination or intentional adulteration (Incze and Katz, 2018; Kozhuharov et al., 2022; Mathews, 2018). Contamination refers to the unintended presence of undeclared or harmful substances introduced during manufacturing, storage, or distribution (Costa et al., 2019; Mathews, 2018). Potential sources include cross-contamination, poor hygiene practices, or inadequate raw material quality (Costa et al., 2019; Moret et al., 2011; Walpurgis et al., 2020). Identified contaminants include microbiological, chemical, and physical hazards (Costa et al., 2019; Walpurgis et al., 2020). Adulteration, in contrast, involves the deliberate inclusion of undeclared substances to enhance commercial value or to create the appearance of therapeutic or performance benefits in violation of regulatory standards (Kozhuharov et al., 2022; Moret et al., 2011). Common reported adulterants include pharmaceuticals, anabolic agents, stimulants, and compounds capable of altering nutritional profiles (Costa et al., 2019; Gabriels et al., 2015; Tscholl et al., 2010), raising significant toxicological and regulatory concerns.

From a toxicological perspective, contaminants and adulterants in FS can lead to unintended exposure to biologically active substances. The health implications depend on the specific agent, dose, and pattern of use, and may range from acute adverse effects to longer-term cumulative toxicity (Cohen, 2009; Skalicka-Woźniak et al., 2017). The most relevant classes of contaminants identified from both the literature review and notifications on the Rapid Alert System for Food and Feed (RASFF) portal, the EU's 24-h early-warning network for food and feed safety risks, established under Regulation (EC) No. 178/2002 (European Parliament and Council, 2002b), were metals, mycotoxins, pesticides, persistent organic pollutants (dioxins and PCBs), and medicines (e.g. phosphodiesterase-5 inhibitors, sibutramine, and their analogues). It is important to note that many of these substances are indeed present in FS used by recreational athletes (Cohen, 2009; Skalicka-Woźniak et al., 2017). These toxicant classes are associated with recognised target-organ effects: metals are mainly associated with renal and neurological toxicity, with possible hepatic and cardiovascular effects; mycotoxins with hepato- and nephrotoxicity and carcinogenicity; pesticide residues with neurotoxicity and endocrine effects; persistent organic pollutants with endocrine, immune and carcinogenic outcomes; and undeclared pharmacologically active substances with acute cardiometabolic or neuropsychiatric events, particularly in polypharmacy or high-risk individuals (Costa et al., 2019). In these contexts, FS-drug interactions may further modify toxicity profiles and clinical outcomes (Beirão et al., 2025).

Recently, we characterised FS consumption patterns in the same gym-based cohort, identifying a high prevalence of use and predominant supplementation practices among recreational athletes (Lopes et al., 2024). This behavioural context defines the exposure setting for FS use and is accompanied by a limited understanding of supplement composition, dosage, and potential adverse effects. The present study extends this framework by examining gym users' perceptions and awareness of FS contamination and adulteration. It pursues three primary objectives: (i) to characterise the level of knowledge and awareness of FS contamination and adulteration among recreational athletes in a gym-based setting; (ii) to compare risk perception, regulatory awareness, and perceived health consequences of contamination between FS users and non-users; and (iii) to examine associations between sociodemographic variables, including sex, age, and educational level, and risk perception scores. Given the absence of validated instruments for this specific domain and the limited prior literature, the study is primarily exploratory and comparative in design.

2. Methodology

2.1. Study design and population

The present analysis employed a cross-sectional study design conducted across multiple gyms in Lisbon (Portugal), with participant recruitment via face-to-face interviews conducted between March and May 2023. A convenience sampling approach was used. The final sample comprised 303 adults of both sexes, aged from 18 to 76 years (mean age 30.82 ± 12.84 years). Inclusion criteria required participants to be at least 18 years old, able to understand and communicate in Portuguese, and engaged in recreational physical activity. For the purposes of this study, 'recreational athletes' were operationalised as individuals who attend commercial gyms and engage in physical exercise on a recreational (non-competitive, non-federated) basis, irrespective of training frequency or modality. Further details regarding the study population and methodology have been previously reported (Lopes et al., 2024).

The sample size was estimated using the formula: $n = z^2 \times p\,(1 - p)/W^2$, where n represents the required sample size, z corresponds to the standard normal distribution (defined as 1.96 for a 95% confidence level), p denotes the estimated prevalence of FS use based on prior Portuguese data, and W represents the acceptable margin of error (5%). The p used in the sample calculation was derived from the most recent national data reported in the Fitness Barometer Portugal 2022, developed by Portugal Ativo and the Center for Economic and Institutional Studies of the Autonomous University of Lisbon, which estimated 691,656 active gym members in Portugal (Pedragosa et al., 2022). As no official prevalence data were available specifically for the Lisbon region, the national estimate was retained. To account for potential regional variability, the margin of error was conservatively increased to 6%. The resulting minimum sample size was 267 participants.

The study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki (World Medical Association, 2024) and received approval from the Ethics Committee of the School of Health Sciences and Technologies, Lusófona University (EC. ECTS/P12-23), approved on 28 March 2023. Before participation, oral informed consent was obtained from all participants.

2.2. Study instruments

The data collection instrument was adapted from published questionnaires (Alhakbany et al., 2022; Ruano and Teixeira, 2020; Sadek et al., 2022). Since no validated tool specifically addressing the perceived contamination risk of FS was available, the research team incorporated additional items. A pilot test with 10 individuals was conducted beforehand to assess questionnaire clarity and comprehensibility.

The questionnaire consisted of four sections. The first section collected sociodemographic characteristics, including age, sex, education, employment status, residence, marital status, monthly income, health status, medication use, and smoking habits. Self-reported body mass and height were used to calculate body mass index (BMI) according to Quetelet's formula [body mass (kg)/height^2 (m^2)] (Garrow and Webster, 1985). The second section covered exercise-related data, including gym membership duration, exercise frequency, training duration (both in and out of the gym), and training goals. The third section explored safety-related behaviours and perceptions concerning FS use, including FS use status, label-reading practices, perceived product value, purchase priorities, awareness of contaminant classes and other substances potentially present in FS, and perceived health risks associated with FS use. Finally, the fourth section evaluated knowledge and risk perception.

The participants initially answered an open-ended question to assess their understanding of the regulatory definition of FS. Afterwards, the participants were acquainted with a standardised clarification of the FS definition based on Directive 2002/46/CE and Portuguese Decree-Law N° 118/2015 ("*Foodstuffs intended to supplement the typical diet, consisting of a concentrated source of a nutrient or of other substances that have a nutritional or physiological effect, in a simple or combined form, commercialised in dosed formulas, capsules, tablets, pills and other similar forms, bags of powder, vials of liquid, dropper bottles and other similar forms of liquids and powders, which is taken in small, quantified amounts*"). To ensure a consistent frame of reference, participants only proceeded to the remaining items of the questionnaire after this clarification. Subsequent questions assessed concerns and beliefs regarding FS use, including whether FS may replace a healthy diet, interact with medications, cause adverse or toxic effects, be contaminated, or pose overdose risks, as well as perceptions of market regulation and control. Response formats included "Yes/No/I don't know" options, with one item rated on a four-point adequacy scale (non-existent, insufficient, sufficient, excessive). Multiple responses were permitted where applicable. The questionnaire comprised 36 questions.

2.3. Perception score

As no validated questionnaires adequately addressing this topic were available in the literature, a perception score was developed for this study. To quantify participants' perceived knowledge and awareness of potential FS contamination or adulteration, a nine-item, non-validated scoring instrument was used. Each item was scored as 0 (incorrect or unmet criterion) or 1 (correct or met criterion), yielding a total score ranging from 0 to 9 points that operationalised participants' ability to recognize FS-related safety risks (Table 1). The resulting score was subsequently used in exploratory analyses of associations with participant characteristics.

Table 1
Knowledge and risk perception items related to food supplements (FS).

Item	Classification (+1 point)
1. Correctly identifies the regulatory definition of FS.	Yes
2. Believes that FS can replace a balanced diet.	No
3. Recognises that FS may interact with medicines.	Yes
4. Acknowledges the potential for toxic or harmful effects associated with FS.	Yes
5. Recognises that FS could be contaminated or contain undeclared substances.	Yes
6. Perceives the risk of contamination in FS to be higher than medicines.	Yes
7. Recognises that excessive intake of FS may lead to serious health consequences.	Yes
8. Perceives the FS market as adequately regulated.	No
9. Perceives the level of regulatory control of FS on the market as sufficient.	No

2.4. Statistical analysis

Statistical analysis was performed using IBM SPSS Statistical Package for Social Sciences version 22.0 (IBM Corp., Chicago, IL, USA). Normality of continuous variables was verified, using the Kolmogorov-Smirnov test for $n > 50$ and the Shapiro-Wilk test for $n \leq 50$. Parametric or nonparametric tests were subsequently selected based on data distribution. Categorical variables were presented as percentages and frequencies, whereas continuous variables were expressed as mean ± standard deviation (SD) or median with interquartile range (IQR), as appropriate. Associations between categorical variables were analysed using the Chi-squared test, Fisher's exact test, and Monte Carlo simulation, depending on expected frequencies. Continuous variables were compared between categorical groups using the Student's t-test, the Mann-Whitney *U* test, or the Kruskal-Wallis test, depending on distributional assumptions.

To explore the relationships between individual knowledge and risk perception items and the overall score, linear regression models were estimated with the perception score as the dependent variable and questionnaire items as independent variables. Internal consistency of questionnaire sections was evaluated using Cronbach's alpha: $\alpha = 0.630$ for the general safety concerns section and $\alpha = 0.510$ for the knowledge and risk perception section (excluding the definition item). The latter value indicates moderate internal consistency, which is considered acceptable for exploratory research purposes. All statistical tests were two-tailed, with a statistical significance level set at $p < 0.05$.

3. Results

Overall, 303 recreational athletes were included in the study [median age: 26.00 (IQR: 16.00) years; FS users: 71.95%]. Men (56.11%), single individuals (77.89%), graduated (54.79%), employed participants (67.00%), participants with a monthly family income between €1000 and €3000 (53.14%), and non-smokers (64.69%) constituted the majority of respondents. Table 2 summarises the general characteristics of the study population. The median height was 1.72 (IQR: 0.13) m, the median body mass was 70.00 (IQR: 18.00) kg, and the median BMI was 23.51 (IQR: 4.04) kg/m^2. FS users were more frequently men ($p = 0.003$) and had significantly greater height and body mass than FS non-users.

FS knowledge and purchasing behaviours stratified by FS use are presented in Table 3. Most participants reported reading FS labels habitually. Non-users placed greater value on professional counselling, while FS users prioritised product quality ($p = 0.007$). Notably, safety was rarely cited as a purchasing criterion in either group (Table 3).

Remarkably, only 4.95% of participants correctly identified the regulatory definition of FS (Table 4), indicating limited objective knowledge about these products. Demographic characteristics of

Table 2
Sociodemographic and lifestyle characteristics of participants according to food supplements use.

	Total Population (n = 303)	FS non-users (n = 85)	FS users (n = 218)	p-value
Sex, % (n)				
Men	56.11 (170)	42.35 (36)	61.47 (134)	**0.003** [b]
Women	43.89 (133)	57.65 (49)	38.53 (84)	
Age, years	26.00 (16.00)	27.00 (22.00)	26.00 (14.00)	0.073 [a]
Height, m	1.72 (0.13)	1.68 (0.13)	1.73 (0.15)	**0.008**[a]
Body mass, kg	70.00 (18.00)	66.00 (18)	72.00 (17.25)	**0.006**[a]
BMI, kg/m^2	23.51 (4.04)	23.31 (4.33)	23.53 (3.89)	0.253 [a]
Marital status, % (n)				
Single	77.89 (236)	69.41 (59)	81.19 (177)	0.084 [b]
Married	15.51 (47)	21.18 (18)	13.30 (29)	
Divorced	6.60 (20)	9.41 (8)	5.50 (12)	
Educational level, % (n)				
Undergraduate	45.21 (137)	45.88 (39)	44.95 (98)	0.884 [b]
Graduate	54.79 (166)	54.12 (46)	55.05 (120)	
Occupation, % (n)				
Non-worker	5.61 (17)	9.41 (8)	4.13 (9)	0.178 [b]
Worker	67.00 (203)	62.35 (53)	68.81 (150)	
Student	27.39 (83)	28.24 (24)	27.06 (59)	
Monthly family income, % (n)				
< €1000	8.58 (26)	8.24 (7)	8.72 (19)	0.177 [b]
€1000-3000	53.14 (161)	56.47 (48)	51.83 (113)	
> €3000	31.68 (96)	24.71 (21)	34.40 (75)	
Smoking status, % (n)				
Non-Smoker	64.69 (196)	61.18 (52)	66.06 (144)	0.658 [b]
Ex-Smoker	17.16 (52)	17.65 (15)	16.97 (37)	
Smoker	18.15 (55)	21.18 (18)	16.97 (37)	

Data are presented as a percentage (n) for categorical variables and median (IQR) for continuous variables. Group comparisons were performed using [a] Mann-Whitney U test or [b] Chi-square test, as appropriate. Abbreviations: BMI, body mass index; FS, food supplements.

Table 3
Behaviours and perceptions related to food supplements use.

	Total Population (n = 303)	FS non-users (n = 85)	FS users (n = 218)	p-value
FS label reading, % (n)				
No	31.02 (94)	29.41 (25)	31.65 (69)	0.705 [a]
Yes	68.98 (209)	70.59 (60)	68.35 (149)	
Feels well-informed about FS, % (n)	45.88 (139)	17.65 (15)	56.88 (124)	**< 0.001**[a]
Purchase priorities, % (n)				
Counselling	24.09 (73)	37.65 (32)	18.81 (41)	**0.007** [b]
Safety	1.32 (4)	0.00 (0)	1.83 (4)	
Brand	10.89 (33)	11.76 (10)	10.55 (23)	
Price	16.83 (51)	11.76 (10)	18.81 (41)	
Quality	46.87 (142)	38.83 (33)	50.00 (109)	

Data are presented as percentages (n) for categorical variables. Group comparisons were performed using [a] Chi-squared test or [b] Monte Carlo test, as appropriate. Abbreviations: FS, food supplements.

participants who failed to identify the regulatory definition of FS correctly are presented in Fig. 1, with younger participants (18–25 years) and FS users being most frequently represented.

Significant differences in beliefs were observed across demographic groups, as shown in Table 4. When compared with FS users, non-users were more likely to believe that FS could replace a healthy diet ($p = 0.024$), to recognize potential interactions between FS and medicines ($p = 0.045$), and to express concern about the possibility of overdose-related harm ($p = 0.010$). Non-users were less likely than FS users to perceive market control as adequate ($p = 0.044$). Furthermore, men were more likely to consider contamination risk higher in FS than in medicines ($p = 0.034$) and to perceive market control of FS as sufficient ($p = 0.019$). Regarding educational level, graduated participants perceived a higher risk of contamination of FS than of medicines ($p = 0.043$). Participants aged 26-40 years were significantly more likely to believe that FS may be contaminated or contain undeclared substances. The mean score for knowledge and risk perception of FS was 4.70 ± 1.36 out of 9 points. The perception score was not significantly associated with FS use, sex, educational level, or age.

Perceptions regarding FS market control and regulation are illustrated in Fig. 2. Approximately 22.00% and 26.50% of participants expressed scepticism regarding adequate control and regulation, respectively, while a large fraction of the participants (46.54% and 40.92%) reported a lack of knowledge about these topics.

The perceptions of contaminant and adulterant classes among FS users and non-users are presented in Fig. 3. Non-users were more likely to believe that FS could be contaminated, whereas a higher percentage of users perceived a lower likelihood of contamination (52.94% vs 45.41%, respectively). Additionally, non-users most frequently identified industrial pollutants as the principal class of potential contaminants, followed by nutritional modifiers and heavy metals. FS users more often referred to nutritional modifiers, pesticides, and industrial pollutants as the predominant contaminant or adulterant categories. Regarding the least frequently perceived class of contaminants or adulterants, both groups identified doping substances. However, this perception was less common among FS users (15.15%) compared with non-users (28.89%).

Significant demographic differences were observed in perceived potential health risks associated with contaminated and adulterated FS (Table 5). Men more frequently associated contamination with renal effects ($p = 0.026$), whereas women were more likely to identify cardiovascular ($p = 0.006$) and hepatic ($p = 0.013$) effects. Furthermore, participants with a higher educational level were more likely to recognize potential carcinogenic effects than those without an academic background ($p = 0.010$). The same tendency regarding carcinogenic effects was observed in older participants ($p = 0.018$), who also demonstrated greater concern about potential hepatic effects ($p = 0.019$). The linear regression analysis of categorical predictors associated with this knowledge and perception score is shown in Table 6. Participants with a graduate level scored on average 0.341 points higher than those without a graduate level. Additionally, occupational status was associated with higher perception scores: workers ($B = 0.814$; CI: 0.128–1.501; $p = 0.009$) and students ($B = 0.904$; CI: 0.228–1.580; $p = 0.020$) had higher perception scores than non-working participants.

A linear regression model of individual item scores showed that seven out of nine questionnaire items were significantly associated with higher knowledge and risk perception of the FS score (Table 7). Correct identification of the regulatory definition of FS ($B = 1.158$; CI: 0.461–1.855; $p = 0.001$), recognition that FS cannot replace a balanced diet ($B = 1.177$; CI: 0.572–1.783; $p < 0.001$), awareness of interaction with medicines ($B = 1.402$; CI: 1.136–1.668; $p < 0.001$), belief in possible contamination ($B = 1.538$; CI: 1.284–1.792; $p < 0.001$), perception of higher contamination risk ($B = 1.436$; CI: 1.168–1.704; $p < 0.001$), awareness of overdose harm ($B = 1.302$; CI: 0.994–1.609; $p < 0.001$), and perception of insufficient market control ($B = 1.768$; CI: 1.479–2.058; $p < 0.001$) were all positively associated with a higher total perception score, indicating greater overall awareness of FS-related risks.

4. Discussion

The use of FS by recreational athletes is a hot topic that should be approached from multiple perspectives. FS may support training adaptation and recovery when appropriately used (Martínez-Sanz et al., 2017; Rodriguez-Lopez et al., 2022; Walpurgis et al., 2020). However, their widespread use raises safety concerns, particularly given documented contamination and adulteration, which could compromise product quality and pose potential health risks (Costa et al., 2019). This duality between perceived benefit and toxicological uncertainty

Table 4
Knowledge and risk perception of food supplements across participant categories.

	Total Population (n = 303)	FS use			Sex			Education level			Age			
		No (n = 85)	Yes (n = 218)	p-value	Men (n = 170)	Women (n = 133)	p-value	Undergraduate (n = 137)	Graduate (n = 166)	p-value	18-25 years (n = 148)	26-40 years (n = 88)	41-80 years (n = 67)	p-value
1. Correctly identifies the regulatory definition of FS, %	4.95	4.70	5.00	0.902	5.90	3.80	0.398	5.80	4.20	0.517	7.43	3.41	1.49	0.126
2. Believes that FS can replace a balanced diet, %	6.60	11.76	4.59	**0.024**	5.29	8.27	0.300	7.30	6.02	0.656	6.08	6.82	7.46	0.927
3. Recognises that FS may interact with medicines, %	55.78	62.35	53.21	**0.045**	52.35	60.15	0.125	48.18	62.05	0.052	54.05	60.23	53.73	0.909
4. Acknowledges the potential for toxic or harmful effects associated with FS, %	98.02	97.64	98.17	0.771	97.65	98.50	0.599	97.08	98.80	0.286	96.62	98.86	100.00	0.205
5. Recognises that FS could be contaminated or contain undeclared substances, %	47.53	52.94	45.41	0.238	44.71	51.13	0.267	45.25	49.40	0.472	41.22	59.09	46.27	**0.028**
6. Perceives the risk of contamination in FS to be higher than medicines, %	40.59	37.65	41.74	0.514	45.88	33.83	**0.034**	34.31	45.78	**0.043**	37.84	47.73	37.31	0.270
7. Recognises that excessive intake of FS may lead to serious health consequences, %	71.62	82.35	67.43	**0.010**	70.59	72.93	0.653	71.53	71.69	0.976	72.97	73.86	65.67	0.468
8. Perceives FS market as adequately regulated, %	32.68	28.24	34.40	0.555	37.06	27.08	0.177	32.85	32.53	0.998	32.43	29.55	37.31	0.591
9. Perceives the level of regulatory control of FS on the market as sufficient, %	27.06	18.82	30.28	**0.044**	32.35	20.30	**0.019**	29.93	24.70	0.308	30.41	19.32	29.85	0.151
Total score[a]	4.70 (1.36)	4.75 (1.35)	4.68 (1.36)	0.746	4.73 (1.32)	4.66 (1.41)	0.590	4.57 (1.34)	4.81 (1.37)	0.115	4.64 (1.38)	4.94 (1.36)	4.51 (1.28)	0.131

Data are presented as percentages for categorical variables and mean (SD) for continuous variables. Group comparisons were performed using the Chi-square test and Mann-Whitney U or Kruskal-Wallis tests, as appropriate. Abbreviations: FS, food supplements. [a] Score ranged from 0 to 9 points.

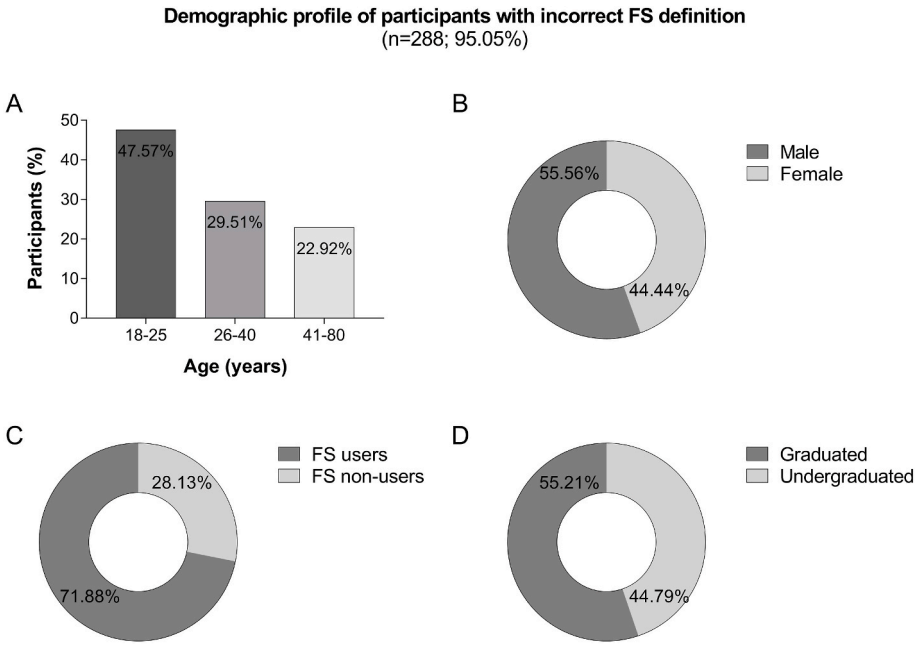

Fig. 1. Demographic distribution of participants with incorrect food supplements (FS) definition by (A) age, (B) sex, (C) FS use, and (D) educational level.

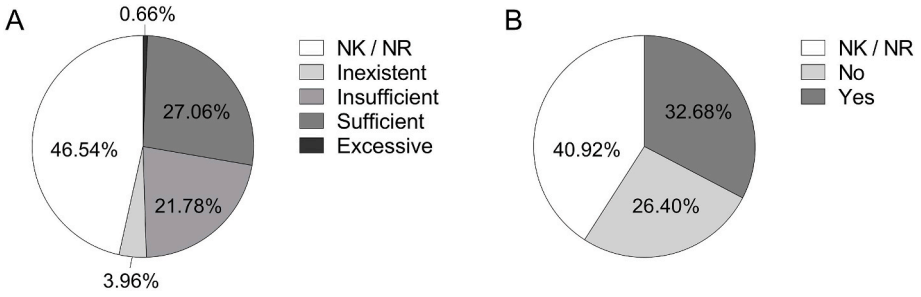

Fig. 2. Participant awareness of (A) control and (B) regulation of the food supplements market.
Abbreviations: NK/NR, Not known/No response.

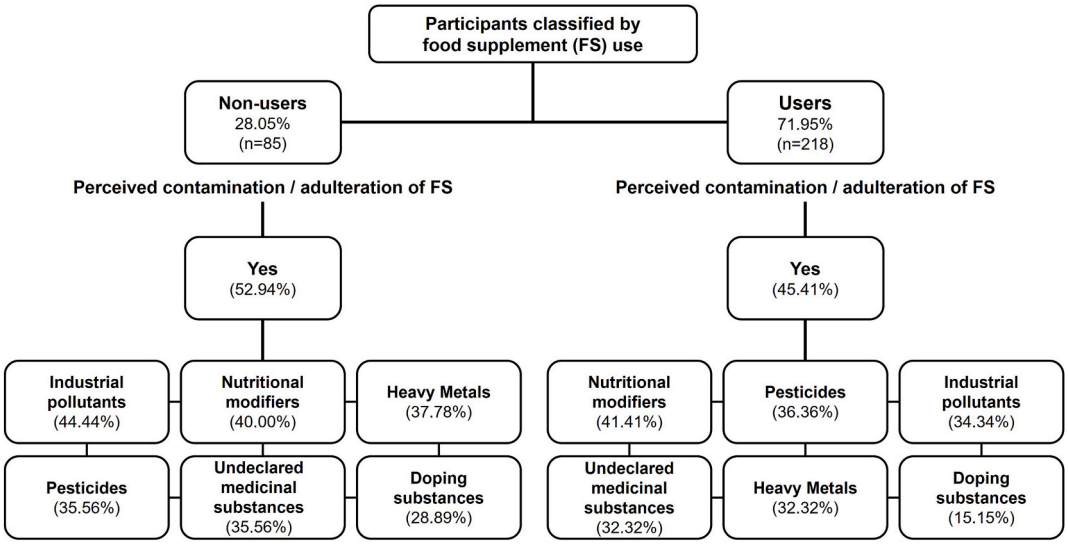

Fig. 3. Perceptions of food supplements users and non-users regarding major contaminant and adulterant classes.

underlines the present study's focus on safety perception in gym environments.

Approximately 72% of participants reported using FS, suggesting an upward trend compared with earlier Portuguese studies that reported

Table 5
Perceived potential health effects associated with contaminated and adulterated food supplements.

Perceived potential health effects	Total Population (n = 303)	FS use			Sex			Educational level			Age			
		No (n = 85)	Yes (n = 218)	p-value	Men (n = 170)	Women (n = 133)	p-value	Undergraduate (n = 137)	Graduate (n = 166)	p-value	18-25 years (n = 148)	26-40 years (n = 88)	41-80 years (n = 67)	p-value
Carcinogenic effects	27.72 (84)	22.35 (19)	29.82 (65)	0.192	24.47 (45)	29.32 (39)	0.582	20.44 (28)	33.74 (56)	**0.010**	20.27 (30)	34.09 (30)	35.82 (24)	**0.018**
Renal effects	38.94 (118)	31.76 (27)	41.28 (90)	0.126	44.12 (75)	31.58 (42)	**0.026**	37.96 (52)	39.16 (65)	0.831	39.60 (59)	45.46 (40)	26.87 (18)	0.057
Cardiovascular effects	44.88 (136)	45.88 (39)	44.04 (96)	0.772	37.65 (64)	53.38 (71)	**0.006**	42.34 (58)	46.39 (77)	0.480	39.87 (59)	46.59 (41)	52.24 (35)	0.216
Hepatic effects	43.89 (133)	41.18 (35)	44.95 (98)	0.552	37.65 (64)	51.88 (69)	**0.013**	40.88 (56)	46.39 (77)	0.336	35.81 (53)	50.00 (44)	53.73 (36)	**0.019**
Hormonal disturbances	49.83 (151)	49.41 (42)	49.54 (108)	0.984	47.65 (81)	51.88 (69)	0.465	48.18 (66)	50.60 (84)	0.674	51.35 (76)	53.41 (47)	40.30 (27)	0.222

Data are presented as percentages (n) for categorical variables. Group comparisons were performed using the Chi-square test. Abbreviations: FS, food supplements.

Table 6
Linear regression analysis of categorical predictors associated with the knowledge and risk perception of food supplements score.

	Perception Score	
	B (95% CI)	p-value
Sex		
Men	1.00 (REF)	-
Women	−0.068 (−0.378–0.242)	0.667
Age (continuous)	−0.006 (−0.018–0.006)	0.312
Number of FS intake	−0.044 (−0.196–0.107)	0.564
FS use		
No	1.00 (REF)	-
Yes	0.024 (−0.455–0.504)	0.920
Education level		
Undergraduate	1.00 (REF)	-
Graduate	0.341 (0.017–0.664)	**0.039**
Occupation		
Non-Worker	1.00 (REF)	-
Worker	0.814 (0.128–1.501)	**0.009**
Student	0.904 (0.228–1.580)	**0.020**
Feels well-informed about FS		
No	1.00 (REF)	-
Yes	−0.030 (−0.339–0.279)	0.849

Data expressed as B (95% CI). Abbreviations: B, regression coefficient; CI, confidence interval; REF, Reference - baseline category for categorical predictors; FS, food supplements.

Table 7
Linear regression analysis of perception questionnaire items associated with higher knowledge and risk perception of food supplements score.

	Response scored as correct	B (95% CI)	p-value
Questionnaire item			
1. Correctly identifies the regulatory definition of FS.	Yes	1.158 (0.461–1.855)	**0.001**
2. Believes that FS can replace a balanced diet.	No	1.177 (0.572–1.783)	**< 0.001**
3. Recognises that FS may interact with medicines.	Yes	1.402 (1.136–1.668)	**< 0.001**
4. Acknowledges the potential for toxic or harmful effects associated with FS.	Yes	1.054 (−0.044–2.152)	0.060
5. Recognises that FS could be contaminated or contain undeclared substances.	Yes	1.538 (1.284–1.792)	**< 0.001**
6. Perceives the risk of contamination in FS to be higher than medicines.	Yes	1.436 (1.168−1.704)	**< 0.001**
7. Recognises that excessive intake of FS may lead to serious health consequences.	Yes	1.302 (0.994–1.609)	**< 0.001**
8. Perceives FS market as adequately regulated.	No	−0.135 (−0.484−0.213)	0.445
9. Perceives the level of regulatory control of FS on the market as sufficient.	No	1.768 (1.479–2.058)	**< 0.001**

Data expressed as B (95% CI). Abbreviations: B, regression coefficient; CI, confidence interval; FS, food supplements.

consumption rates of 43-66% (Ruano and Teixeira, 2020; Sousa et al., 2013). Such high prevalence implies repeated exposure and therefore increases the cumulative probability of encountering contaminated or adulterated products. From a toxicological perspective, frequent FS consumption represents a recurrent exposure scenario in which variability in product quality may lead to intermittent contact with

undeclared substances, increasing the likelihood of cumulative toxicological burden over time (Costa et al., 2019).

In line with prior literature (Goston and Correia, 2010; Jawadi et al., 2017; Sousa et al., 2013), men used FS more frequently, contributing to differences in anthropometrics between users and non-users. These differences likely reflect training goals and body composition patterns rather than intrinsic biological determinants of supplementation behaviour. In this previously characterised cohort, FS users were primarily motivated by muscle gain, whereas non-users reported well-being as their primary motivation (Lopes et al., 2024). Goal-oriented supplementation may increase vulnerability to products marketed with exaggerated or misleading benefits (Jarthon and Durand, 2017). Training frequency also differed between groups (Lopes et al., 2024), corroborating previous observations (Goston and Correia, 2010; Jawadi et al., 2017; Lacerda et al., 2015). Higher exercise volume may increase perceived nutritional demands and encourage FS use (Cohen et al., 2018; Incze and Katz, 2018), although perceived requirements do not necessarily reflect physiological deficiencies, reinforcing the need for evidence-based guidance.

Although many participants reported reading labels, purchasing priorities rarely included safety, and approximately half of the participants perceived themselves as adequately informed. However, perceived knowledge did not translate into regulatory understanding, as 95% of participants failed to identify the legal definition of FS, consistent with reported knowledge gaps in gym-based populations (Alhakbany et al., 2022; Sadek et al., 2022). Jawadi et al. (2017), in a cross-sectional study among 299 gymnasium users in Riyadh, Saudi Arabia, found a FS prevalence of 37.8%, predominantly among men, with information sourced primarily from online sources (38.0%) and coaches (35.4%), while physicians and dietitians were rarely consulted. This reliance on non-specialist sources was also documented by Alhakbany et al. (2022) among Saudi adults attending fitness centres, where over 20% of participants perceived protein supplements as entirely risk-free, and more than one-third either did not know the associated risks or could not identify them specifically. Sadek et al. (2022), studying 455 Lebanese athletes, reported that more than 90% did not believe FS should undergo safety testing before marketing, while approximately 55% were unaware of possible FS-drug interactions, a proportion strikingly similar to that observed in our study. Across these geographically and culturally diverse settings, the recurrence of inflated self-perceived knowledge alongside documented regulatory ignorance and limited risk awareness suggests a structural pattern in gym-based populations that transcends national context, reinforcing the need for standardised, toxicologically informed education strategies. Misclassification of FS (e.g., as powdered protein products) may narrow risk appraisal and underestimate formulation diversity. Misconceptions that FS can prevent or treat diseases may promote inappropriate self-directed use, particularly when consumers substitute professional advice with supplementation practices (European Commission, 2016a). Importantly, safety frameworks assume regulatory compliance, and the EC report concludes that horizontal food legislation provides sufficient guarantees for FS safety (European Commission, 2016b). However, these safeguards may be undermined by non-compliance and adulteration, which remain documented in international markets (Costa et al., 2019; Tucker et al., 2018).

Our data also show a perceptual gradient between FS users and non-users: users tended to express more favourable beliefs regarding supplementation, whereas non-users more frequently recognised interactions with medicines and expressed concerns regarding overdose harm. This patternmay reflect the influence of marketing and availability cues, and aligns with evidence that food-drug interaction risks remain insufficiently recognised in professional training and practice (Beirão et al., 2025). Advertising often emphasises performance and aesthetic benefits while minimising potential risks, which may contribute to an inflated perception of safety, particularly when products are framed as “natural” (Druker and Gesser-Edelsburg, 2017; Goston and Correia, 2010). Furthermore, widespread availability may strengthen implicit assumptions of oversight (Cohen, 2009), potentially distancing consumer expectations from toxicological realities.

A more nuanced finding concerns how FS users and non-users conceptualise contamination. Non-users predominantly associated contamination with industrial or environmental pollutants, whereas users more often referred to undeclared or illegal compounds that alter product composition. These contrasting perceptions likely reflect selective awareness rather than incorrect beliefs *per se*. From a toxicological perspective, both categories correspond to documented risks. Industrial contaminants such as heavy metals, pesticide residues, or mycotoxins are linked to renal, hepatic, neurological, or cardiovascular toxicity (Costa et al., 2016, 2019; Naz et al., 2024). Conversely, undeclared pharmacologically active substances, including anabolic agents, stimulants, or prescription drugs, are recurrently reported and may lead to acute toxicity, endocrine disruption, or cardiometabolic complications (Skalicka-Woźniak et al., 2017; Tsarouhas et al., 2018). Importantly, neither group demonstrated comprehensive awareness across the full toxicological spectrum, indicating fragmented risk perception that may be shaped by partial information.

Participants most frequently identified endocrine, cardiovascular, hepatic, and renal harms as plausible outcomes. Toxicological evidence supports these target-organ concerns: FS may be adulterated with anabolic-androgenic agents and stimulants, and contaminated with industrial chemicals and residues, which are associated with recognised organ-specific toxicities, including hepatic injury, cardiovascular events, endocrine disruption, and renal impairment (Cohen, 2009; Costa et al., 2019; Skalicka-Woźniak et al., 2017). Regarding specific adulterant classes, analysis of the RASFF portal for the period 2011–2022 identified phosphodiesterase-5 inhibitors as the most frequently notified pharmaceutical adulterant (235 records), followed by stimulants, including 1,3-dimethylamine (97 records) and synephrine (53 records), as well as anorexics, anabolics, and prohormones. Over 65% of these notifications were classified as serious risks (Amidžić et al., 2023). Undeclared anabolic-androgenic agents and stimulants are of particular concern in gym-based populations, given their association with acute cardiometabolic events, endocrine disruption, and, in the case of certain stimulants, severe hepatotoxicity leading to organ failure (Skalicka-Woźniak et al., 2017). The alignment between perceived harms and known toxicological targets suggests partial concordance, but lower contamination awareness among users indicates a gap between potential exposure and risk recognition.

Demographic patterns suggest that cognitive and experiential factors influence risk perception. Men expressed greater concern about renal effects, which may reflect awareness of high-protein supplementation practices (Goston and Correia, 2010; Lopes et al., 2024; Ruano and Teixeira, 2020), although current evidence does not support consistent harm in healthy individuals (Van Elswyk et al., 2018). Women more frequently identified cardiovascular and hepatic concerns, consistent with the liver's detoxification role (Barcelos et al., 2020; Trefts et al., 2017) and potential exposure to undeclared stimulant active substances (Corcoran, 2025). Education level also influenced perceived risk: participants with higher levels of education more frequently recognised carcinogenic concerns, possibly reflecting higher health literacy and improved access to scientific and regulatory information (Hahn and Truman, 2015). Older participants more often recognised hepatic and carcinogenic risks (Guido and Mileti, 2022), whereas younger individuals may prioritise rapid performance outcomes over long-term safety implications (Geller et al., 2015; Kim et al., 2018). These patterns underscore the need for tailored risk communication approaches.

Given the limited literature specifically addressing perceived FS contamination, the present work contributes a behavioural toxicological perspective in real-world gym settings. Although exploratory, this approach enabled a structured assessment of awareness relevant to consumer vulnerability. However, the total perception score showed limited discriminatory capacity across participant subgroups, likely

reflecting response clustering (e.g., near-universal endorsement of "possible harms") and uncertainty regarding regulation. This distinction suggests that general concern about adverse effects does not necessarily translate into regulatory understanding.

Based on these findings, educational programs should guide consumers towards safer, evidence-based FS use (Heaney et al., 2011), including improved understanding of dosage, interactions, adverse effects, and realistic alternatives to unnecessary supplementation (Walpurgis et al., 2020). The fragmented risk awareness documented in this and comparable studies underscores the need for structured intervention at three complementary levels. At the regulatory level, competent authorities, including the National Authority of Medicines and Health Products (INFARMED) nationally, the European Food Safety Authority (EFSA) at the European level, and the Food and Drug Administration (FDA) in the United States, retain post-market surveillance powers that represent a critical line of defence given the shared absence of mandatory pre-market safety evaluation across these jurisdictions. Strengthening these frameworks through more systematic market monitoring, harmonised nutrivigilance reporting, and transparent dissemination of safety notifications to consumers could meaningfully reduce the circulation of unsafe products (Amidžić et al., 2023; Costa et al., 2019). At the professional level, the recurrent finding across gym-based studies that coaches and online sources overwhelmingly dominate as information channels, while pharmacists, physicians, and dietitians remain marginalised (Jawadi et al., 2017; Sadek et al., 2022), signals an urgent need to integrate evidence-based FS counselling into the routine practice of healthcare professionals, who are well-positioned to deliver targeted interventions on contamination risk, drug interactions, and unsafe supplementation practices (Beirão et al., 2025). At the consumer level, given that safety was cited as a purchasing criterion by fewer than 2% of participants in the present cohort, gym-based education and point-of-sale risk communication represent pragmatic and scalable preventive strategies, particularly when tailored to the demographic profile of the predominant FS consumer group. At the policy level, persistent challenges include fragmented oversight of production and marketing, inconsistent quality assurance, and widespread misinformation. Gaps in professional knowledge may further compound these issues (Cohen et al., 2018; Sadek et al., 2022; Walpurgis et al., 2020).

From a regulatory toxicology perspective, these findings highlight the importance of strengthening institutional oversight and consumer monitoring frameworks to improve early detection of unsafe products. Authentication or certification schemes designed to verify product quality and safety may enhance transparency and reduce the circulation of non-compliant products, although harmonised implementation may be constrained by Member States' economic and regulatory capacities (Cohen et al., 2018). Importantly, toxicology-oriented consumer education also represents a preventive strategy, as improving understanding of exposure pathways, dosage, and adverse effects may reduce unsafe practices and consequent exposure.

Nevertheless, some limitations must be acknowledged. The convenience sampling strategy and cross-sectional design may limit generalisability and preclude causal inference. These constraints may affect the strength and scope of inference rather than invalidate the observed associations. Furthermore, interviews conducted in gym settings restricted objective measurements due to logistical constraints. The interview-based data collection format, while enabling structured face-to-face administration, may be susceptible to social desirability bias, with participants potentially overstating their knowledge of FS safety and regulation. An additional limitation is the absence of validated instruments specifically addressing perceptions of FS contamination or adulteration, necessitating the development of an exploratory questionnaire. The resulting perception score demonstrated moderate internal consistency (Cronbach's $\alpha = 0.510$), and findings derived from it should be interpreted with appropriate caution. Future validation studies would strengthen interpretability and enable cross-study comparability.

Despite these limitations, the findings highlight a critical intersection between consumer perception, regulatory awareness, and potential toxicological risk. Understanding how gym-goers perceive FS safety provides an essential foundation for designing preventive strategies, reinforcing the need for education, regulatory transparency, and continued toxicological surveillance. Ultimately, aligning consumer awareness with documented toxicological realities may reduce exposure to unsafe products and support safer supplementation practices, representing a meaningful contribution to public health and sports nutrition safety.

5. Conclusion

FS use was highly prevalent in this gym-based population, yet perceived knowledge frequently did not correspond to accurate regulatory understanding. Although many participants reported feeling informed, 95% were unable to correctly identify the regulatory definition of FS, and substantial proportions demonstrated limited awareness of market control and regulatory oversight, highlighting a gap between confidence and comprehension. Differences between FS users and non-users further revealed contrasting beliefs regarding safety, drug interactions, overdose risks, and contamination sources, suggesting that behavioural choices may be shaped by variable risk perception.

Sex- and education-related differences in perceived health consequences indicate that awareness of potential renal, cardiovascular, hepatic, or endocrine effects is interpreted through diverse experiential and cognitive perspectives. Men more often associated contamination with renal effects, while women more frequently identified cardiovascular and hepatic outcomes. Participants with higher education or active occupational engagement showed greater perception scores, reinforcing the role of health literacy in recognising contamination risks.

From a toxicological standpoint, contamination and adulteration of FS remain documented concerns with plausible systemic health implications. Aligning consumer awareness with established toxicological evidence is therefore essential to support safer supplementation practices. Educational strategies that improve understanding of dosage, interactions, and adverse effects may function as primary preventive tools, particularly in environments influenced by marketing pressures and heterogeneous regulatory enforcement. Strengthening transparency through certification or verification systems may enhance product safety. Integrating behavioural awareness with toxicological monitoring may support safer consumer practices and strengthen regulatory strategies aimed at improving the safety and transparency of the FS market.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used ChatGPT 5.2 to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

Funding

This research was funded by Fundação para a Ciência e a Tecnologia (FCT), Portugal, through UID/04567/2025 (DOI: 10.54499/UID/04567/2025), under the R&D unit CBIOS and UID/04138/2025 (DOI: 10.54499/UID/04138/2025), UID/PRR/04138/2025 (DOI: 10.54499/UID/PRR/04138/2025) and UID/PRR2/04138/2025 (DOI: 10.54499/UID/PRR2/04138/2025) under the R&D unit iMed.ULisboa. C.F.-P. was funded by the FCT Scientific Employment Stimulus contract DOI 10.54499/CEECINST/00147/2018/CP1498/CT0009.

CRediT authorship contribution statement

Sofia Lopes: Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Madalena Cunha:** Investigation, Methodology. **Ana S. Fernandes:** Writing – review & editing. **Nuno G. Oliveira:** Writing – review & editing. **Cíntia Ferreira-Pêgo:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Supervision, Validation, Writing – review & editing. **João G. Costa:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare no competing financial interests or personal relationships that could have influenced the work reported in this paper.

Acknowledgments

The authors would like to thank all the volunteers for participating in the study.

Data availability

Data will be made available on request.

References

Alhakbany, M.A., Alzamil, H.A., Alnazzawi, E., Alhenaki, G., Alzahrani, R., Almughaiseeb, A., Al-Hazzaa, H.M., 2022. Knowledge, attitudes, and use of protein supplements among saudi adults: gender differences. Healthcare (Basel) 10, 394. https://doi.org/10.3390/healthcare10020394.

Amidžić, M., Banović Fuentes, J., Banović, J., Torović, L., 2023. Notifications and health consequences of unauthorized pharmaceuticals in food supplements. Pharmacy 11, 154. https://doi.org/10.3390/pharmacy11050154.

Barcelos, R.P., Lima, F.D., Carvalho, N.R., Bresciani, G., Royes, L.F., 2020. Caffeine effects on systemic metabolism, oxidative-inflammatory pathways, and exercise performance. Nutr. Res. (N.Y.) 80, 1–17. https://doi.org/10.1016/J.NUTRES.2020.05.005.

Beirão, S., Costa, J.G., Ferreira-Pêgo, C., 2025. Assessing knowledge and awareness of Food and Drug Interactions among nutrition sciences students: implications for education and clinical practice. Nutr. Health 31, 995–1002. https://doi.org/10.1177/02601060241263409.

Cohen, P.A., 2009. American roulette–contaminated dietary supplements. N. Engl. J. Med. 361, 1523–1525. https://doi.org/10.1056/NEJMp0904768.

Cohen, P.A., Wen, A., Gerona, R., 2018. Prohibited stimulants in dietary supplements after enforcement action by the US food and drug administration. JAMA Intern. Med. 178, 1721–1723. https://doi.org/10.1001/jamainternmed.2018.4846.

Corcoran, J., 2025. Cardiovascular toxicity associated with supplement use. Clin. Toxicol. 63, 801–809. https://doi.org/10.1080/15563650.2025.2550983.

Costa, J.G., Saraiva, N., Guerreiro, P.S., Louro, H., Silva, M.J., Miranda, J.P., Castro, M., Batinic-Haberle, I., Fernandes, A.S., Oliveira, N.G., 2016. Ochratoxin A-induced cytotoxicity, genotoxicity and reactive oxygen species in kidney cells: an integrative approach of complementary endpoints. Food Chem. Toxicol. 87, 65–76.

Costa, J.G., Vidovic, B., Saraiva, N., do Céu Costa, M., Del Favero, G., Marko, D., Oliveira, N.G., Fernandes, A.S., 2019. Contaminants: a dark side of food supplements? Free Radic. Res. 53, 1113–1135. https://doi.org/10.1080/10715762.2019.1636045.

Denham, B.E., 2017. Athlete information sources about dietary supplements: a review of extant research. Int. J. Sport Nutr. Exerc. Metabol. 27, 325–334. https://doi.org/10.1123/ijsnem.2017-0050.

Druker, I., Gesser-Edelsburg, A., 2017. Identifying and assessing views among physically-active adult gym members in Israel on dietary supplements. J. Int. Soc. Sports Nutr. 14, 37. https://doi.org/10.1186/s12970-017-0194-7.

Edenfield, K.M., 2020. Sports supplements: pearls and pitfalls. Prim Care 47, 37–48. https://doi.org/10.1016/j.pop.2019.10.002.

European Commission, 2016a. Study on Food Intended for Sportspeople: Final Report. Directorate-General for Health and Food Safety. Publications Office of the European Union, Luxembourg. https://doi.org/10.2875/498189.

European Commission, 2016b. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: next Steps for a Sustainable European Future – European Action for Sustainability.

European Parliament and Council, 2002a. Directive 2002/46/EC of the European Parliament and of the Council of 10 June 2002 on the approximation of the laws of the Member States relating to food supplements. Off. J. Eur. Union L 183, 51–57.

European Parliament and Council, 2002b. Regulation (EC) no 178/2002 of the European Parliament and of the Council of 28 January 2002 laying down the general principles and requirements of food law, establishing the European Food Safety Authority and laying down procedures in matters of food safety. Official Journal of the European Communities L31, 1–24.

Finamore, A., Benvenuti, L., De Santis, A., Cinti, S., Rossi, L., 2022. Sportsmen's attitude towards dietary supplements and nutrition knowledge: an investigation in selected roman area gyms. Nutrients 14. https://doi.org/10.3390/NU14050945/S1.

Gabriels, G., Lambert, M., Smith, P., Wiesner, L., Hiss, D., 2015. Melamine contamination in nutritional supplements–Is it an alarm bell for the general consumer, athletes, and "Weekend Warriors". Nutr. J. 14, 69. https://doi.org/10.1186/s12937-015-0055-7.

Garrow, J.S., Webster, J., 1985. Quetelet's index (W/H2) as a measure of fatness. Int. J. Obes. 9, 147–153.

Geller, A.I., Shehab, N., Weidle, N.J., Lovegrove, M.C., Wolpert, B.J., Timbo, B.B., Mozersky, R.P., Budnitz, D.S., 2015. Emergency department visits for adverse events related to dietary supplements. N. Engl. J. Med. 373, 1531–1540. https://doi.org/10.1056/NEJMsa1504267.

Goston, J.L., Correia, M.I.T.D., 2010. Intake of nutritional supplements among people exercising in gyms and influencing factors. Nutrition 26, 604–611. https://doi.org/10.1016/j.nut.2009.06.021.

Guido, G., Mileti, A., 2022. Health choices and risk perception in elderly consumers: a systematic review. Health Market. Q. 39, 230–248. https://doi.org/10.1080/07359683.2021.1996307.

Hahn, R.A., Truman, B.I., 2015. Education improves public health and promotes health equity. Int. J. Health Serv. 45, 657–678. https://doi.org/10.1177/0020731415585986.

Harty, P.S., Zabriskie, H.A., Erickson, J.L., Molling, P.E., Kerksick, C.M., Jagim, A.R., 2018. Multi-ingredient pre-workout supplements, safety implications, and performance outcomes: a brief review. J. Int. Soc. Sports Nutr. 15, 41. https://doi.org/10.1186/s12970-018-0247-6.

Heaney, S., O'Connor, H., Michael, S., Gifford, J., Naughton, G., 2011. Nutrition knowledge in athletes: a systematic review. Int. J. Sport Nutr. Exerc. Metabol. 21, 248–261. https://doi.org/10.1123/ijsnem.21.3.248.

Incze, M., Katz, M.H., 2018. Regulating the dietary supplement industry: the taming of the slew. JAMA Intern. Med. 178, 1723. https://doi.org/10.1001/jamainternmed.2018.5097.

Jarthon, J.-M., Durand, C., 2017. Aging and resisting aging: fitness training as a means to do so. Loisir Soc. 40. https://doi.org/10.1080/07053436.2017.1328785.

Jawadi, A.H., Addar, A.M., Alazzam, A.S., Alrabieah, F.O., Al Alsheikh, A.S., Amer, R.R., Aldrees, A.A.S., Al Turki, M.A., Osman, A.K., Badri, M., 2017. Prevalence of dietary supplements use among gymnasium users. J. Nutr. Metab., 9219361 https://doi.org/10.1155/2017/9219361, 2017.

Jędrejko, K., Lazur, J., Muszyńska, B., 2021. Risk associated with the use of selected ingredients in food supplements. Chem. Biodivers. 18, e2000686. https://doi.org/10.1002/cbdv.202000686.

Kim, Y., Park, I., Kang, S., 2018. Age and gender differences in health risk perception. Cent. Eur. J. Publ. Health 26, 54–59. https://doi.org/10.21101/cejph.a4920.

Kozhuharov, V.R., Ivanov, K., Ivanova, S., 2022. Dietary supplements as source of unintentional doping. BioMed Res. Int. https://doi.org/10.1155/2022/8387271, 2022.

Lacerda, F.M.M., Carvalho, W.R.G., Hortegal, E.V., Cabral, N.A.L., Veloso, H.J.F., 2015. Factors associated with dietary supplement use by people who exercise at gyms. Rev. Saude Publica 49, 63. https://doi.org/10.1590/S0034-8910.2015049005912.

Lopes, S., Cunha, M., Costa, J.G., Ferreira-Pêgo, C., 2024. Analysis of food supplements and sports foods consumption patterns among a sample of gym-goers in Portugal. J. Int. Soc. Sports Nutr. 21, 2388077. https://doi.org/10.1080/15502783.2024.2388077.

Mallick, M., Camacho, C.B., Daher, J., El Khoury, D., 2023. Dietary supplements: a gateway to doping? Nutrients 15, 881. https://doi.org/10.3390/nu15040881.

Martínez-Sanz, J.M., Sospedra, I., Ortiz, C.M., Baladía, E., Gil-Izquierdo, A., Ortiz-Moncada, R., 2017. Intended or unintended doping? A review of the presence of doping substances in dietary supplements used in sports. Nutrients 9, 1093. https://doi.org/10.3390/nu9101093.

Mathews, N.M., 2018. Prohibited contaminants in dietary supplements. Sports Health 10, 19–30. https://doi.org/10.1177/1941738117727736.

Moret, S., Prevarin, A., Tubaro, F., 2011. Levels of creatine, organic contaminants and heavy metals in creatine dietary supplements. Food Chem. 126, 1232–1238. https://doi.org/10.1016/J.FOODCHEM.2010.12.028.

Naz, M., Ahmed, M., Aftab, F., Ali, M.A., Sanaullah, M., Ahmad, W., Alshammari, A.H., Khalid, K., Wani, T.A., Zargar, S., 2024. Contamination of trace, non-essential/heavy metals in nutraceuticals/dietary supplements: a chemometric modelling approach and evaluation of human health risk upon dietary exposure. Food Chem. Toxicol. 190, 114806. https://doi.org/10.1016/j.fct.2024.114806.

Ofoedu, C.E., Iwouno, J.O., Ofoedu, E.O., Ogueke, C.C., Igwe, V.S., Agunwah, I.M., Ofoedum, A.F., Chacha, J.S., Muobike, O.P., Agunbiade, A.O., Njoku, N.E., Nwakaudu, A.A., Odimegwu, N.E., Ndukauba, O.E., Ogbonna, C.U., Naibaho, J., Korus, M., Okpala, C.O.R., 2021. Revisiting food-sourced vitamins for consumer diet and health needs: a perspective review, from vitamin classification, metabolic functions, absorption, utilization, to balancing nutritional requirements. PeerJ 9, e11940. https://doi.org/10.7717/peerj.11940.

Pedragosa, V., Cardadeiro, E., Santos, A., 2022. Barómetro do fitness em Portugal. Fact sheet. Centro de Estudos Económicos e Institucionais, Universidade Autónoma de Lisboa 1–36.

Rodriguez-Lopez, P., Rueda-Robles, A., Sánchez-Rodríguez, L., Blanca-Herrera, R.M., Quirantes-Piné, R.M., Borrás-Linares, I., Segura-Carretero, A., Lozano-Sánchez, J.,

2022. Analysis and screening of commercialized protein supplements for sports practice. Foods 11, 3500. https://doi.org/10.3390/foods11213500.

Ruano, J., Teixeira, V.H., 2020. Prevalence of dietary supplement use by gym members in Portugal and associated factors. J. Int. Soc. Sports Nutr. 17, 11. https://doi.org/10.1186/s12970-020-00342-z.

Sadek, Z., Mohsen, H., Yazbek, S., Nabulsi, Z.A.A., Sarraj, A.R., Hoteit, M., 2022. Dietary supplements use among athletes in Lebanon: knowledge, attitudes, practices, and correlates. Foods 11. https://doi.org/10.3390/FOODS11101521.

Skalicka-Woźniak, K., Georgiev, M.I., Orhan, I.E., 2017. Adulteration of herbal sexual enhancers and slimmers: the wish for better sexual well-being and perfect body can be risky. Food and Chemical Toxicology, Second international symposium on phytochemicals in medicine and food (2-ISPMF) 108, 355–364. https://doi.org/10.1016/j.fct.2016.06.018.

Sousa, M., Fernandes, M.J., Moreira, P., Teixeira, V.H., 2013. Nutritional supplements usage by Portuguese athletes. Int. J. Vitam. Nutr. Res. 83, 48–58. https://doi.org/10.1024/0300-9831/a000144.

Trefts, E., Gannon, M., Wasserman, D.H., 2017. The liver. Curr. Biol. 27, R1147–R1151. https://doi.org/10.1016/j.cub.2017.09.019.

Tsarouhas, K., Kioukia-Fougia, N., Papalexis, P., Tsatsakis, A., Kouretas, D., Bacopoulou, F., Tsitsimpikou, C., 2018. Use of nutritional supplements contaminated with banned doping substances by recreational adolescent athletes in Athens, Greece. Food Chem. Toxicol. 115, 447–450. https://doi.org/10.1016/j.fct.2018.03.043.

Tscholl, P., Alonso, J.M., Dollé, G., Junge, A., Dvorak, J., 2010. The use of drugs and nutritional supplements in top-level track and field athletes. Am. J. Sports Med. 38, 133–140. https://doi.org/10.1177/0363546509344071.

Tucker, J., Fischer, T., Upjohn, L., Mazzera, D., Kumar, M., 2018. Unapproved pharmaceutical ingredients included in dietary supplements associated with US food and drug administration warnings. JAMA Netw. Open 1, e183337. https://doi.org/10.1001/jamanetworkopen.2018.3337.

UK Government - Department of Health and Social Care, 2024. Nutrition Legislation Information Sheet.

Van Elswyk, M.E., Weatherford, C.A., McNeill, S.H., 2018. A systematic review of renal health in healthy individuals associated with protein intake above the US recommended daily allowance in randomized controlled trials and observational studies. Adv. Nutr. 9, 404–418. https://doi.org/10.1093/advances/nmy026.

Walpurgis, K., Thomas, A., Geyer, H., Mareck, U., Thevis, M., 2020. Dietary supplement and food contaminations and their implications for doping controls. Foods 9, 1012. https://doi.org/10.3390/foods9081012.

World Medical Association, 2024. WMA Declaration of Helsinki: Ethical Principles for Medical Research Involving Human Participants.