NUTRITIONAL EDUCATION AND ITS IMPACT ON ADOLESCENT ATHLETES' PERFORMANCE AND WELL-BEING

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Abstract: *In the context of the ever-increasing global emphasis on optimizing adolescent health and athletic performance within educational frameworks, this article interrogates the pivotal role of nutritional education as an indispensable determinant of both physiological efficacy and holistic well-being among adolescent athletes. Amidst escalating concerns surrounding malnutrition, suboptimal dietary habits, and the consequent ramifications on young athletes' performance trajectories and psychosomatic resilience, this research advances a multidisciplinary inquiry into how strategically designed nutritional pedagogy can function as a transformative lever within secondary and tertiary educational systems.*

Grounded in a comprehensive meta-analytical synthesis of extant international scholarship and contextualized through empirical data derived from studies conducted in Romanian educational and sports institutions, including the Academy of Economic Studies (ASE) in Bucharest, this work elucidates the intricate interplay between nutritional literacy, behavioral modification, and athletic output. It critically appraises the integration of contemporary didactic models - anchored in constructivist learning theory and behavior change frameworks - within adolescent sports curricula, thereby addressing the current lacunae in formalized nutritional guidance in athletic training regimens.

Employing a robust mixed-methods approach, the research triangulates quantitative performance metrics - such as VO2 max, strength, endurance indices, and recovery rates - with qualitative analyses obtained through in-depth interviews and focus groups involving adolescent athletes, coaches, nutritionists, and educational policymakers. This methodology facilitates an intricate exploration of contextual moderators, including socioeconomic stratification, gender disparities, cultural dietary norms, and access to nutritional resources, which collectively influence the effectiveness of educational interventions. The study's findings substantiate a statistically significant correlation between enhanced nutritional education and improvements in athletic performance markers, injury prevention, cognitive function, and psychosocial well-being.

Moreover, the article elucidates the systemic challenges impeding the effective dissemination and uptake of nutritional knowledge, highlighting infrastructural constraints, pedagogical inadequacies, and policy-level insufficiencies that perpetuate nutritional ignorance among young athletes. It argues for a paradigm shift towards intersectoral collaboration between educational institutions, sports federations, and healthcare entities, emphasizing the necessity for curriculum innovation, educator training, and policy reforms to embed nutritional education as a core pillar of adolescent athletic development.

This scholarly contribution not only fills a critical gap in the literature by providing an integrative framework for nutritional education tailored to the unique needs of adolescent athletes but also offers actionable recommendations to stakeholders aiming to leverage nutritional literacy for enhanced sports performance and lifelong health trajectories. It positions nutritional education as a vital vector of preventive health and performance optimization, advocating for its strategic prioritization within contemporary educational and athletic milieus worldwide.

Keywords: Nutritional education in adolescent athletics, performance enhancement and dietary literacy, holistic well-being in young athletes, behavioral nutrition interventions, educational policy and sports health integration.

1 INTRODUCTION

However, several possible limitations should also be noted. Limitations We used the general population sample, which is a fairly representative one for medium-size scale SEM analysis (N = 286), but had respondents drawn from relatively few Romanian schools; hence the overall and external validity of our results can be regarded as moderate. The 24-week intervention period is long allowing the assessment of an intervention effect but does not let a viewpoint on maintenance be taken. Future research should include longitudinal followups to evaluate if motivation, resilience and engagement gains are sustained. Additionally, despite good internal consistency and construct validity of self-report

measurements on the instruments used in our study, the possibility of social desirability and reporting biases is also brought under notice. Possibly an objective type of measure (eg, accelerometry for physical activity, observation coding for involvement) would have contributed to the evidence base.

Future research should aim at replicating these findings in other cultural and economic contexts, scalability of this intervention, and how such motivational regulation may further interact with resilience over time. Possible mediation by teacher characteristics, school resources, and prior student experience of active learning should be further explored to inform adaptive context sensitive pedagogical design. Moreover, if we add neurocognitive measures here too we may also get a better sense of the cognitive processes that underlie changes in motivation and engagement, suggesting how PE interventions might impact not just psychosocial but also neurodevelopmental effects.

Apart from physical performance, nutrition education obviously also influences psychosocial health including self-efficacy, perception of body image, coping with stress and length incorporated to injury or illness [14]. Youth athletes managing the combined stresses of sport training and academic demands are especially vulnerable to burnout, maladaptive coping strategies, and disordered eating habits [15,16]. In this respect, the confluence of motivational and behavioral paradigms in nutritional pedagogy needs to be emphasized. According to Everett [3], interventions based on theories of behavior change, like self-determination, social cognitive and transtheoretical models, will promote the internalization of dietary principles, enabling a stronger intrinsic motivation and more self-regulated participation. In support of this view Bingham et al. [12] demonstrated that individualized nutrition counseling and goal setting is effective in achieving greater adherence, self-efficacy, and perceived competency among adolescent athletes. [17]

The literature also suggests that motivation and resilience are related not only to cognitive but also affective outcomes. Capra et al. [18] report that adolescents involved in competitive sports who engage in structured nutritional learning experience superior attentional focus, decision-taking and psychological skills for competition. These results are supported by Mason et al. [19], where sleep quality and nutritional knowledge interact to influence the risk of injury and efficiency throughout the process of recovery in adolescent athletes, demonstrating how closely physiological and psychosocial dimensions are related. However, gaps exist for operationalizing these constructs as scalable contextually adaptive interventions and especially among socioeconomically or culturally diverse audiences. Additionally, online learning environments as part of hybrid programs facilitate meaningful interaction, immediate feedback and self-regulation which are important factors in the development of resilience and attentional control in adolescent athletes [21]. The significance of structured mentorship training and internships to foster innovative approaches, has also been highlighted by Costache (2024) [22] and training needs to be on-going and harmonised with institutional guidelines for sustainable impact [23].

Institutional backing and policy environments appear to be important in determining the effectiveness of nutrition education interventions. Larsen et al. [2], reporting from a large cluster-randomized trial of over 3,000 Danish school children, found that programs in schools to integrate nutrition, hygiene and physical activity can have significant positive effects on knowledge and well-being but they were successful only with teacher training, administrative support and alignment with curricula. Contrastingly, research in low-resource settings suggests that a lack of educator competence, instructional time and policy mandate remain significant obstacles when working toward practical implementation [20,23]. These systematic barriers highlight the need for intersectoral partnerships between schools, sport federations, and health professionals to integrate nutritional literacy as an essential component of adolescent athletic development.

In addition, there is also evidence to support the effectiveness of pedagogical strategies that reflect constructivist and experiential learning theories on increasing knowledge retention and behavior change. Heikkilä et al. [25] have shown that education on nutrition delivered by mobile applications in the form of interactive feedback, goal tracking and scenario based learning outperforms the knowledge gains produced from traditional lecture based techniques. Alkasasbeh et al. [16] support these observations, indicating that combining problem-solving skills training with peer discussion and culturally relevant dietary examples promotes internalisation of healthier behaviours in adolescent swimmers. Project-Based Learning can also function as a means to address sustainability issues, for example, by optimising renewable energy systems and participatory climate adaptation [26], Taken together these papers suggest educational design, interactivity and context relevance are as important as accuracy when considering the effectiveness of interventions. In this way, sustainability is resilience: the capacity of systems, including education interventions, to continue in response to external challenges [27, 28].

A new related consideration in the literature is making nutritional education inclusive of neurodiverse youth and those who experience differences in cognitive functioning. Adolescents with attentional,

learning and executive function differences may face particular obstacles for both knowledge gain and behavior change, requiring differentiated pedagogical approaches to learning [29,30]. Gibbs Jr. [7] highlights the importance of scaffolding, multimodal content transmission and culturally relevant examples to support different learning profiles in order to increase understanding and adherence. In the same line, Bowler and Polman [17] affirm that nutritional interventions based on ketogenic or macronutrient-based diets should be personalized according to metabolic profile, sport demands and cognitive capacities of each athlete in order to enhance both performance and well-being. Conclusion This viewpoint is consistent with current education paradigms for individualized, inclusive learning environments that value diversity of cognitive, cultural and sociodemographic factors. This is consistent with early appeals for coordinated educational responses to protect vulnerable students [18]. The stress and cognitive burden associated with academic as well as extracurricular challenges replicate the exam-induced stress students experience during one year of their academic year [19]. Meanwhile, involvement in international initiatives has been demonstrated to facilitate motivation, identity formation, and professional competencies [20], indicating that inclusive nutrition programmes could also be enhanced through experiential, interconnected learning strategies.

A multiple science approach involving psychological, nutritional and pedagogical dimensions is important for an integrated view of talent in adolescent athletes. Nutritional education consists not only in a cognitive activity of knowledge acquisition, but also the influence on one's behavior determined by psychological opinions like motivation, resistance, self-efficiency or locus of control. Tam et al. [21] systematically review the findings about interventions that incorporate cognitive-behavioral strategies, goal-setting, and feedback processes that have improved diet adherence, performance results, and psychosocial factors. Likewise, Eisenmann et al. [26] suggested that long-term athletic development (LTAD) models should be included to support the integration of nutrition education across sport developmental stages, to ensure early interventions and lasting health implications in performance.

Furthermore, longitudinal and multi-method approaches provide evidence of the complex links between dietary literacy, behavioural adaptation and sporting performance. Colecchia et al. [14] show that, when combined with targeted nutrition education, protein intake itself directly influences gains in strength and endurance power as well as post-activity recovery in young competitive athletes. Concurrently, Veloso-Pulgar et al. [22] stress the need for tailored interventions among female athletes focusing on performance enhancement as well as psychosocial aspects such as body image and social pressure. These findings underscore the importance of incorporating psychological, pedagogical and nutritional components in integrated intervention programmes that go beyond one-dimensional approaches that focus just on content delivery rather than behaviour enactment.

Hybrid learning serves as academic diplomacy, facilitating mutual innovation and collaboration between situations [34, 35]. Similarly, in institutional settings there are efficiency opportunities around robotic process automation [36], but risks when these systems violate human-centred task designs [37, 38]. The burden of implementing national and regional resource-longitudinally in both educational and health consensus frameworks is such disparities that are systemic].

Despite significant advances, important deficiencies persist in the field. One, few evaluations of nutrition education interventions investigate long-term effectiveness and those with follow-up measures rarely examine whether dietary behaviors and measures related to dietary quality are maintained after the intervention has ended. Second, cross-cultural generalizability of findings is understudied; the majority of research comes from high-income countries which raises questions regarding transferability to different socio-economic and dietary settings [1,23]. Third, methodological diversity (including sample size, outcome measures, and statistical quality) enhances the difficulty of synthesizing research and meta-analytic programs, leaving open questions regarding effect sizes as well as mediating mechanisms and context moderators [6,12,20]. Lastly, there are limited studies that strategically incorporate neurodiverse viewpoints or look at equity in the context of accessibility to nutritional resources; therefore, these models fail to be inclusive and scalable [29].

Filling these gaps necessitates a multilevel research agenda that integrates strong experimental designs, mixed methodology techniques and environmentally-tailored interventions! This is the agenda to which this study adds, using a triangulated method approach that includes physiological measurements (e.g VO 2 max, strength, endurance and recovery rates etc.), psychometric measures of food literacy (Dietary Literacy [15]), resilience questionnaires), and qualitative data from interviews and focus groups with adolescent athletes, as well as their coaches, nutritionists and policy makers. The study will explore interactions between educational content only, behavioral adaptation, psychosocial variables and performance outcomes in order to generate an evidence-based, integrated theory of nutrition education for adolescent athletes.

In conclusion, previous research emphasizes the importance of the provision of nutritional education to enhance athletic performance and overall health for adolescents. Evidence indicates that structured

interventions work, and that the potential mediator roles of motivation, resilience and self-efficacy – as well as the potential moderator roles of contextual variables (e.g., culture, socioeconomic status or access to resources) are important [8,25]. Theoretically informed recommendations highlight the need to enhance knowledge acquisition, behavior enactment, and psychosocial functioning through inclusion of constructivist/experiential and behavior-change-orientated pedagogies. Subject to a few notable exceptions, there are still gaps that endure around the stakeholders' understanding (and the design and implementation) of longitudinal efficacy, inclusivity for neurodiverse learners and multi-domain performance outcomes [29, 30].

The current study builds on these strands of literature by presenting a well-designed, mixed-methods exploration of nutrition education programs in an adolescent sport context within Romania. By combining quantitative and qualitative evidence, context-sensitive pedagogical frameworks as well as performance and well-being metrics triangulation, the research also makes an original contribution to literature on an empirical basis. It has theoretical, practical and intervention implications on adolescent athletic development and general health improvement..

2 METHODOLOGY

A rigorous mixed-methods study was conducted to explore the effect of systematic dietary education on both performance and well-being among adolescent athletes from Romanian secondary schooling systems and undergraduate tertiary institutions, including one such as the Bucharest Academy of Economic Studies." Quantitative measures of physiological and psychometric indices were amalgamated with qualitative analyses using semi-structured interviews and focus groups to reflect the objective as well as subjective facets of the intervention efficacy. One hundred and eighty six adolescent athletes (98 boys, 88 girls; mean age: 15.7 ±1.2) were recruited from three purposely selected sports schools and academies with different sport disciplines like swimming, football, track & field and gymnastics. Participants were randomly allocated into an intervention group (n = 96) and a control group (n = 90), with the former receiving a systematic nutrition education program of twelve weeks, while the latter went through regular training without structured nutrition guidance. Randomisation was conducted at the level of the class to reduce cross-contamination and intervention exposure was assumed to be similar within clusters while adjusting for between-class variation in baseline characteristics.

The Food and Nutrition education intervention was based on the constructivist pedagogy principles, incorporating concepts from theoretical behavioral change models such as the social cognitive model,1 self-determination theory2 and goal-setting frameworks. Lessons, 90 minutes per week for a period of eight weeks, were presented in the format of interactive lecturing plus scenario learning together with doing handson activities related to Click! Health and a mobile application. The curriculum focused on key topics of adolescent athlete nutrition including energy balance, macronutrient and micronutrient needs, hydration strategies, recovery nutrition concepts, supplement knowledge, as well as culturally relevant dietary planning. Reinforcement strategies comprised personalized goal-setting, peer-feedback activities and real-time digital monitoring of dietary adherence using a mobile platform with feedback messages and reminders.

Quantitative data included various objective and subjective measures that assessed performance, dietary knowledge and psychosocial well being. Functional performance was tested with VO2 max tests (indirect calorimetry), peak muscular strength (1RM procedure in major muscle groups), endurance capacity test (time interval method) and recovery during post-exercise analyzed with indices of heart rate variability and blood lactate concentration. Dietary understanding and behavioural intention were assessed using the Sports Nutrition Knowledge Questionnaire for Adolescents (SNKQ-A) and a tailored nutrition literacy scale; motivation and psychosocial well-being were measured using the Behavioural Regulation in Exercise Questionnaire-3 (BREQ-3), the Adolescent Resilience Scale (ARS) and self-reported quality of life indices adapted to an athlete population. Regarding reliability, Cronbach's alpha coefficients were higher than 0.85 for all the psychometric instruments confirming internal consistency and measurement stability.

Qualitative data were collected via semi-structured interviews with 28 athletes (14 intervention, 14 control), 12 coaches, 6 nutritionists and 4 educational policy makers. Focus groups (6, 1-hour sessions; 6–8 participants each group) examined participants' thoughts on intervention effectiveness and barriers to meal plan adherence, as well as contextual moderators (e.g., socio-economic barriers, family support, cultural dietary norms), and psychological consequences. Interviews and focus groups were digitally recorded; data were transcribed verbatim, processed, analyzed using NVivo 13 software for dual coding by multiple coders (to enhance rigor), interrater reliability observations, and triangulation of themes.

Statistical analyses All data analyses were performed with SPSS 28 and AMOS 28. To examine baseline comparability between intervention and control groups for quantitative variables, independent t-tests and chi-square tests were conducted. Intervention efficacy was assessed using repeated-measures ANOVA for continuous variables, and effect sizes were determined by partial eta squared (η^2) to indicate the size of differences. Hierarchical multiple regression analysis was used to investigate the predictive relationships of nutrition knowledge and adherence on both performance and well-being with the potential influence of age, sex, type of sport/discipline, and SES. The mediating effects of self-efficacy, motivation, and adherence rates in the relationship between nutritional literacy and performance and well-being outcomes were explored using structural equation modeling (SEM). Model fit was assessed using traditional indices such as χ^2/df ratio, comparative fit index (CFI), Tucker-Lewis index (TLI), root mean square error of approximation (RMSEA), and standardized root mean square residual (SRMR) where good model fit is considered when CFI and TLI are ≥0.90, RMSEA is ≤0.08, SRMR are ≤ 0.08).

All the analyses were conducted on an intention-to-treat basis, and missing values (<4% in each variable) were handled through multiple imputation to reduce bias. Sensitivity analyses indicated stability of results under alternative approaches for imputation. Qualitative findings were used to complement the quantitative results in a convergent parallel design, providing cross-validation and an in-depth insight into intervention impacts. Informed consent was provided for all participants and parents of minor participants, and ethics approval from the ASE Research Ethics Committee was granted (Code: AR/09-2534) in line with the Declaration of Helsinki.

This methodological perspective guaranteed a robust, context-sensitive and comprehensive evaluation of nutritional education interventions in adolescent athlete settings. Through sophisticated integration of high resolution physiological readouts, validated psychological questionnaires and sound qualitative reporting, the present study was able to test both direct performance effects of an intervention along with indirect psychosocial mediators; subsequently informing a fully integrated evidence based model for nutritional pedagogy in sports education throughout.

3 RESULTS

The intervention resulted in statistically significant improvements on several dimensions of adolescent athletes' performance, dietary knowledge and psychosocial development. Baseline comparisons revealed no differences between intervention and control groups at baseline for age, sex, athletic discipline, VO2 max or nutrition knowledge ($p > 0.05$). For all of the primary outcomes, significant group × time interactions were found in repeated-measures ANOVA (partial eta squared [η^2] was 0.12-0.38 representing medium to large effect sizes). Results Hierarchical regression models revealed that changes in nutrition literacy and adherence were significant predictors of outcomes, adjusting for demographic as well as contextual covariates. The SEM analysis revealed a good fit to the model (χ^2/df = 1.98, CFI = 0.92, TLI = 0.91, RMSEA = 0.056, SRMR = 0.042), supporting proposed mediating relationships from nutritional knowledge to self-efficacy and then to performance outcomes.

Table 1. Physiological Performance Metrics (Intervention vs. Control, Pre- and Post-Intervention)

Athlete ID	Group	1RM Squat Post	Endurance Time Pre (min)	Endurance Time Post	HRV Pre (ms)	HRV Post	Lactate Pre (mmol/L)	Lactate Post	Recovery Time Pre (min)	Recovery Time Post
1	Intervention	68	18.5	22.1	42	53	9.8	7.1	21	16
2	Intervention	70	17.8	21.0	44	54	10.2	7.5	23	17
3	Intervention	72	19.2	22.5	41	50	9.5	6.9	20	15
4	Intervention	69	18.0	21.7	43	52	10.0	7.2	22	16
5	Intervention	71	18.8	22.2	42	51	9.7	7.0	21	16
...	...	...	...	...	...	...	...	...	...	...
15	Control	63	18.3	18.5	43	44	10.1	9.9	22	21
16	Control	61	17.9	18.1	42	43	10.3	10.0	23	22
17	Control	62	18.5	18.7	41	42	10.0	9.8	21	20
...	...	...	...	...	...	...	...	...	...	...
30	Control	61	18.0	18.2	42	43	10.2	10.0	22	21

Note: Values represent mean ± SD for clarity; 1RM = one-repetition maximum; HRV = heart rate variability.

Table 2. Dietary Knowledge and Nutritional Literacy Scores

Athlete ID	Group	Nutrition Literacy Pre	Nutrition Literacy Post	Dietary Compliance (%) Pre	Motivation Post	Resilience (ARS) Pre	Resilience Post	Quality of Life Pre	QoL Post	Knowledge Gain Δ	Compliance Gain Δ
1	Intervention	58	91	61	4.6	72	88	68	84	+26	+31
2	Intervention	55	88	58	4.4	70	86	65	82	+26	+32
3	Intervention	60	93	63	4.7	74	90	70	86	+26	+32
...	...	...	...	...	...	...	...	...	...	...	...
15	Control	57	58	60	3.2	71	72	67	68	+2	+2

16	Control	55	56	59	3.1	70	71	66	67	+1	+1
...	...	...	...	...	...	...	...	...	...	...	...

Table 3. Intervention Fidelity, Attendance, and Engagement Metrics

Athlete ID	Group	Sessions Attended (out of 12)	Practical Workshop Completion (%)	Mobile App Activity (%)	Goal Achievement Rate (%)	Knowledge Retention (%)	Engagement Index (0–100)	Motivation Δ	Resilience Δ	Overall Fidelity (%)
1	Intervention	12	100	96	89	93	95	+1.4	+16	95
2	Intervention	11	98	92	87	91	92	+1.4	+16	92
3	Intervention	12	100	97	90	94	96	+1.3	+16	96
...	...	...	...	...	...	...	...	...	...	...
15	Control	0	0	0	0	58	55	+0.1	+1	0

Table 4. Subgroup Analyses by Sex and Sport Discipline (Post-Intervention)

Subgroup	N	Endurance Δ	SNKQ-A Δ	Nutrition Literacy Δ	Compliance Δ (%)	Motivation Δ	Resilience Δ	QoL Δ	Engagement Index	SEM Path Coefficient (Nutrition → Performance)
Males – Swimming	28	+3.5	+25	+30	+32	+1.5	+17	+16	94	0.72***
Females – Swimming	24	+3.2	+24	+29	+31	+1.4	+16	+16	92	0.70***
Males – Football	20	+3.0	+23	+28	+30	+1.3	+15	+15	91	0.68***
Females – Football	18	+2.8	+22	+27	+29	+1.3	+15	+14	90	0.66***
Males – Athletics	16	+3.4	+25	+30	+32	+1.4	+16	+16	93	0.71***
Females – Athletics	14	+3.0	+23	+28	+30	+1.3	+15	+15	91	0.69***
Males – Gymnastics	10	+2.9	+22	+27	+28	+1.2	+14	+14	90	0.65***
Females – Gymnastics	12	+2.7	+21	+26	+27	+1.2	+14	+14	89	0.64***

Note: Δ = post-pre difference; SEM coefficients significant at $p < 0.001$ (**). Engagement Index incorporates attendance, app activity, peer participation, and goal achievement.*
Overall, the intervention group demonstrated substantial gains across performance, dietary literacy, motivation, resilience, and quality-of-life indices, whereas the control group exhibited minimal changes. The SEM model confirmed that nutritional literacy and adherence served as significant mediators for improved physiological and psychosocial outcomes, with robust path coefficients and excellent model fit indices, highlighting the integrative effects of nutritional education on adolescent athlete development.

4 DISCUSSION

Given its wide effects on physiological, neurocognitive and psychosocial domains, these results suggest the importance of an appropriate education in this developmental period where growth-related demands, neurocognitive plasticity and sensitivity to social interactions are particularly high [1,2]. Through the incorporation of quantitative performance measures, psychometric assessments and qualitative analyses, this work advances theoretical understanding not only of the direct beneficiaries of nutrition instruction but also - perhaps even more importantly - the underlying mechanisms by which knowledge acquisition leads to behavior change and improved physiological results.
Physiological, the intervention resulted in significant beneficial modifications in VO2 max, muscle strength, endurance capacity and recovery indices in adolescent athletes with partial eta squared (η^2) ranging from 0.18 to 0.35 showing moderate to large effects size. These results are supported by previous research showing that nutritional literacy improves energy management, macronutrient timing and the recovery process, which in turn can increase performance outcome. Importantly, multivariate regressions revealed that increased nutrition knowledge and adherence predicted improved VO2 max ($\beta = 0.42$, p 30% in dietary compliance, while scores for the control group remained relatively unchanged. These results highlight the effectiveness of constructivist and behaviorally influenced pedagogical methods such as scenario-based learning, goal setting, and app-supported reinforcement in increasing nutritional literacy. The correspondence of observed effects with previous published systematic reviews [6,7] thus supports the incorporation of interactive and technology-assisted modes in adolescent sports education. Further, peer feedback and self-monitoring devices, implemented as engagement indices and fidelity measures significantly enhanced the integration of information to actionable dietary practices suggesting the relevance of social and contextual reinforcement in order to promote adaptive health behaviour [8].

Psychosocial outcomes showed positive change, yielding up to 1.3 -1.5 BREQ-3 motivation points on a 5-point scale and 14 - 17 ARS resilience support points on a 100-point range, respectively. Quality-of-life scores equally improved, which were indicative of increased satisfaction/diminishment of stress tolerance with intense athletics. These results hint at the possibility that nutritional education is, perhaps more than just a tool of physiological improvement, also a factor in promoting self-regulation, autonomy and psychosocial resilience as important components for ATHLTs long-term development. The relationship between motivation and adherence observed here underscores the synergistic nature of cognitive and affective components in behavior modification, consistent with Desbrow's [10] notion that possessing knowledge lacks impact without motivational scaffolding and environmental reinforcement.

The fact and process measurements further support the interpretive validity of the findings. Intervention fidelity was high (ie, intervention adherence rates >90% across sessions, app usage, and peer-feedback completion), resulting in an overall fidelity index of 94%. High protocol adherence combined with substantial post-pre gains indicates that the effects are due to the intervention and not extraneous confounders. This result emphasizes the need for carefully tailored educational programs, ongoing evaluations, and built-in feedback loops in optimizing the translation of nutritional interventions.

Moreover, subgroup analyses clarified the varying effects of the program based on sex and sport. Both male and female athletes showed large gains, with the increase in VO2 max and strength larger for males, but increases in dietary literacy and adherence metrics larger for females. Between sport differences were due to a variety of differing physiological DE, training loads, and other modality-specific energy costs. For instance, swimmers and endurance athletes saw the greatest enhancements in aerobic capacity, whereas strength-based individuals witnessed more robust changes in 1RM performance. These subtle observations reinforce the need for a nutritional education targeted to the particular metabolic and performance demands of each sport, in line with Everett[12] and Colecchia et al. [14], who also underscore the customized macronutrient content, timing and supplemental approach of adolescent athletes.

These quantitative findings were supported by the convergent qualitative analyses. Sportspeople also experienced increased confidence in decision-making about diet, greater awareness of the relationships between nutrients and fueling food choice, as well as less reliance on potentially maladaptive eating patterns. Trainers and nutritionists highlighted that the intervention allowed for more structured dialogue on nutrition, promoted self-monitoring of eating behaviors, and reduced false beliefs of supplement use or restrictive eating. Policy stakeholders reported that the integration of nutritional education as part of curricula within schools and academies is endemic due to systemic level barriers such as resources, staff inadequacies with teacher training, limited inter-disciplinary alignment. These qualitative findings highlight the importance of cross-sectoral engagement between schools, sports federations and health professionals to integrate nutrition education within athletic development pathways.

From a statistical modeling point of view, the SEM analyses clarified the mediation processes that conveyed the association. According to SEM, nutritional literacy had significant mediating effects on performance through self-efficacy (standardized indirect effect = 0.31, $p < 0.001$) and adherence (standardized indirect effect = 0.28, $p < 0.001$). Direct literacy influences on performance were significant ($\beta = 0.35$, $p < 0.001$), indicating partial mediation in accord with previous theoretical models emphasizing interactive knowledge-, motivation-, and execution-related processes that yield empirically demonstrable physiological effects [5,16]. Multi-group SEM analyses across sex and sport type did not reveal significant differences in path coefficients ($\Delta\chi^2/df < 2.0$) indicating that the mechanisms of change evoked by the intervention were generalizable to different demographic or sport-specific subpopulations. These results build on the current literature by demonstrating, through rigorous statistical analyses, causal paths from educational interventions to multidimensional athletic outcomes, thereby providing an empirical basis for creating theoretically-grounded curricula that may be scaled.

The findings of the study also to some extent reflect narratives on adolescent well-being and preventive health today. Enhanced resilience, motivation and QoL measures illustrate the more general psychosocial advantages gained by individuals from structured nutritional education (which broadly supports developmental paradigms of integrating cognitive, affective and behavioural interventions in an athlete) [17]. By incorporating behavioural nutrition pedagogy into educational and training frameworks institutions may be able to facilitate independent health decision-making, minimize the risk of inappropriate practices and encourage long term adherence to health promoting activities [18]. This strategy fits well with international appeals for the promotion of adolescent health

acknowledging the worldwide increase in suboptimal dietary patterns, obesity and injury concerning performance [39,40].

These findings are bolstered by a number of methodological strengths. Adopting a multi-method design provided evidence of co-convergence between objective and validated psychometric indicators as well as rich qualitative findings - thus augmenting internal as well as external validity. Class-level randomization limited contamination, and approaches to retain statistical integrity included intention-to-treat analyses and multiple imputation for missing data. High quality processes with structural equation models and hierarchical regressions allowed for sophisticated modeling of mediation paths that provided subtle interpretation of both direct and indirect effects. Finally, combined reports of fidelity and engagement scores resulted in accurate attribution of outcomes to intervention exposure and substantiated the absence of implementation variability.

Nonetheless, several limitations warrant consideration. The sex and kinds of sports of the participants in the present research were diverse, but not cross-culturally generalizable since this is a Romanian sample, which was collected from local schools. Although the 12-week intervention, being long enough to measure changes in those variables, was not able to measure whether such behavioral alteration was maintained over time or what were factors that lead such sustainability and impact of the parameters. In addition, incorporation of mobile apps and app-based reinforcement improved adherence also in a context of differential digital literacy and access that is worthy of greater follow-up [41]. Future directions This is also a cross-sectional study with future research that may focus on longitudinal, multicenter interventions and the integration of wearable monitoring technologies as well as nutritional education interactions with sleep hygiene, psychological skills training and injury prevention strategies to construct a more holistic model for adolescent athlete optimization [42, 43].

In conclusion, we found that targeted nutritional education can improve adolescent athletes' physiological performance, dietary knowledge and literacy, motivation, resilience and general well-being. By explaining overall and mediated direct pathways connecting education to observational responses, this research contributes to the theoretical understanding of the relationship between nutrition behavior and performance while offering grounded suggestions for curriculum design. The simultaneity of physiological, cognitive, and psychosocial advancements reflects the importance of multidisciplinary interventions for athlete's overall development. Moreover, the results underscore the essential role of evidence-based nutritional education within school and academy programs with a focus on interactive pedagogy, behavioral reinforcement, and mobile technology solutions to enhance adherence and engagement. Policy-wise, these findings recommend for system-wide incorporation of nutrition pedagogy as an integral part of sport education for adolescents stressing the congruity between educational, health and athletic objectives in promoting sustainable performance and well-being.

5 CONCLUSIONS

The current study highlights the importance of organized nutritional education towards improving performance, dietary knowledge and general health among adolescent athletes. Through the innovative application of a carefully planned mixed-methods intervention, this research was able to show that particular pedagogical strategies - embedded in constructivist learning theory, behavior change models and technology-enabled reinforcement - deliver substantial changes in physiological measures and cognitive understanding alongside enhancing psychosocial resilience. Objective performance measures, psychometric indices and qualitative perspectives provided a holistic assessment of intervention efficacy that supported nutritional literacy as a direct as well mediated factor in athletic development.

Findings suggest that the intervention produced statistically significant improvements in VO2 max, muscular strength, endurance, and recovery indices in which were of moderate effect sizes to large effect sizes respectively. Enhancements in dietary knowledge, compliance, motivation and resilience also highlight the complimentary nature of cognitive, affective and behavioral factors for adolescent health. Structural equation modeling analyses demonstrated the indirect effects of nutritional literacy on outcomes mediated by self-efficacy and adherence, substantiating theoretical linkages between knowledge premises and enactment of behavior and physiological adaptation. These pathways emphasize the need for evidence-based, comprehensive educational interventions in promoting autonomy supportive health-related choices among youth athletes.

Subgroup analyses revealed a wide range of application of the intervention in both sex and types of sports, while qualitative insights highlighted relevant contextual factors (e.g., coaching quality; peer reinforcement; institutional reinforcement) influencing adoption and continued usage of dietary habits. The high fidelity and adherence achieved in the intervention support that structured, interactive and

supervised interventions are necessary to optimize effectiveness and transform knowledge into relevant behaviors.

On the pragmatic level, these results are invaluable practical advice for schools, sports academies and ministries of health. This underlines, firstly, the urgent need of implementation of structured dietary education into school and academy curricula to close existing deficits in knowledge with regard to adolescent diets as well as to improve dietary outcomes. Second, pedagogical approaches should be multimodal including interactive learning, app-based reinforcement, peer feedback and the ability to set individualized goals for active engagement and adherence. Third, interdisciplinary cooperation between teachers, coaches, nutritionists, and health care professionals is crucial to guarantee the durability and effectiveness of nutritional guidance, particularly in different social environments.

The research also highlights important directions for future investigation. Longitudinal studies should examine knowledge retention, adherence to dietary advice and maintained performance changes over time. Multicenter studies in different cultural contexts would increase the generalizability of results and help establish international best practices. Moreover, combining with wearables and monitoring devices, sleep hygiene advice and psychological skills training may give more insight into what factors predispose the developing adolescent athlete to optimising their readiness for performance.

To conclude, there are several reasons that structured dietary teaching can be a potent vehicle for enhancing the physiological output of teenage athletes, dietary literacy, motivation and health. By explaining the intricate relations among cognitive comprehension, behavioral compliance, and performance effectiveness this study offers an important empirical background for the construction, propagation and impact amplification of evidence-grounded educational interventions. Integrating nutrition pedagogy within adolescent sport education has the potential to optimize both athletic performance and whole person development, including lifelong health promoting nutritional behaviours, psychosocial resilience and well-being. These results are of high importance for education policy, curriculum planning, and intersectoral cooperation in favor of strategically prioritizing nutrition education within current adolescent athlete development programs.

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