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1

SCOPING REVIEW OPEN ACCESS

Dietary Determinants Associated with Low Energy Availability among Athletes: A Scoping Review

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Abstract:

Introduction: Globally, a high prevalence of Low Energy Availability (LEA) (< 30 kcal·kg^{-1} FFM) is observed among competitive athletes. A comprehensive review of various factors associated with dietary intake will provide a better perception of management strategies for improving food intake and population-specific areas of future research. Thus, this study is aimed at identifying the diverse factors that influence dietary energy intake in relation to Energy Availability (EA) among male and female athletes who engage in training and competition across various sports.

Methods: Five search engines were searched using nine keywords, and original papers were extracted spanning over two decades (2003-2023). A predetermined participant-concept-context criterion was used for the inclusion of studies on competitive athletes.

Results: A total of 1462 studies were identified, of which 53 were deemed suitable for inclusion in this review. LEA was prevalent among 24% of male and 58% of female athletes globally and in 87.5% of adolescents in India.

Discussion: LEA was influenced by factors classified in six themes: training/performance demands, psychosocial/cultural influences, dietary practices/nutritional beliefs, environmental/logistical/educational factors, physiological considerations, and methodological issues, requiring culturally tailored biomarkers.

Conclusion: The significant prevalence of LEA globally necessitates culturally tailored causal research and biomarker-informed, standardised Randomized Controlled Trial (RCT) interventions that address multifaceted determinants to effectively prevent LEA.

Keywords: Low energy availability, Dietary intake, Energy intake, Determinants, Athletes.

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1. INTRODUCTION

The theoretical framework for physiological dysregulation and negative health and performance outcomes caused by low energy intake relative to energy expenditure in exercising humans is given in the models of Female Athlete Triad (FAT) and Relative Energy Deficiency in Sports (REDs) [1, 2]. Energy Availability (EA), a core component of REDs in exercising populations, as defined by Loucks in 2020, is the daily amount of energy available to sustain all physiological functions outside of exercise, given as *the difference between*

Energy Intake (EI) and Exercise Energy Expenditure (EEE), expressed relative to an individual's Lean Body Mass (LBM) [1, 3]. Low Energy Availability (LEA) (EA < 30 kcal/kg FFM) during periods of high energy expenditure results from concomitant low EI, which may or may not be accompanied by eating disorders in athletes [4, 5].

Research across various countries has identified several factors contributing to low EI among athletes. These factors include time constraints, financial limitations, inadequate cooking skills, the pressure to maintain a sport-appropriate physique among Australians [6], and training and sport-specific requirements as reviewed in research from the US and Europe [7], although their association with LEA is yet to be established. Current evidence provides country-specific and setting-specific determinants for low EI leading to LEA, reporting several factors in the domains of social and environment, among which "food availability", "socio-economic status", "pressure from coaches", "body shaming", "competitiveness between teammates", and "inadequate dietary intake" emerge as key factors associated with LEA [8, 9]. However, no comprehensive review covering the global aspects of diet associated with LEA among competitive athletes is yet available.

Hence, this scoping review has been planned to identify the various determinants of dietary energy intake associated with EA in male and female athletes training for and competing in different sports. This review will provide an overview of the numerous factors linked with inadequate food intake among athletes with LEA around the world. This data synthesis will offer up-to-date, concise information on the dietary determinants linked to LEA. The findings will be valuable for future global research and in developing dietary strategies to prevent REDs in elite athletes.

2. METHODS

This review followed the scoping review protocol proposed by Arksey & O'Malley in 2005 for data selection [10]. The guidelines for the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) were used for reporting of the study [11].

2.1. Eligibility Criteria

Participants: Studies included ensured that the athletic populations were professional, elite, or competing. All competitive athletes, irrespective of their age, gender, and sport, were included, while recreational and injured athletes were excluded.

Concept: Studies that measured EA among competitive athletes and reported any "dietary determinant", operationally defined as "any factor that influenced EI", were included. Other factors reported in these studies were also summarized.

Context: All studies reporting determinants of LEA conducted during any phase of the athlete's career: training, competition, and/or recovery were included. Athletic phases were not restricted to gaining insight into myriad dietary determinants of LEA among competitive athletes.

Original research, reported in English with a primary, quantitative, qualitative, observational, case-study, or interventional study design, was considered for inclusion. Those not meeting the described Participant—Concept—Context (PCC) criteria were excluded.

2.2. Search Strategy

Available and relevant databases and a grey literature source were searched to identify the full published articles. The research was undertaken on five databases in the following order: Web of Science, SCOPUS, PubMed, ProQuest Dissertations and Theses Global, and Google Scholar. All articles published from January 2003 to July 2023 were included. The search strategy used keywords to download all available research on the topic. The keywords used were "Energy Availability", "Athlete", "Energy", "Diet", "Food", "Intake", "Choice", "Habit", and "Practice". The search terms were combined with Boolean operators (AND and OR), and truncation and wildcard symbols were also used (Appendix **1**). Search strings were saved for reference.

2.3. Selection of Relevant Studies

The studies from the databases were downloaded into Microsoft Excel 2023 and collated into one spreadsheet. Later, the duplicates were removed, and studies were screened and selected based on inclusion criteria by two independent reviewers, SG and PRL. The disagreements were resolved by consensus following discussion between reviewers. Inaccessible studies were removed after contacting authors by email, with no response. As a consensus amongst reviewers, no article was rejected due to quality because it captured the maximum number of potential determinants for future research.

2.4. Data Extraction and Reporting

The studies selected were organized in a tabular form with information about the author(s) and year of publication, study design, sample size, gender, age, performance level, sport, origin of study, competitive phase, energy availability methodology, energy availability assessment method, energy availability cutoff, energy intake assessment method, energy expenditure assessment method, resting metabolism assessment method, body composition assessment method, reporting of energy availability, and concluded dietary determinants.

3. RESULTS

The identification of studies yielded 1462 studies, out of which 53 were found eligible for inclusion in this review. The reasons for exclusion are presented in Fig. (**1**). The final studies given in Table **1** include 45 primary research studies and 8 theses. The study design as given by the authors was cross-sectional (n = 22) [12-33], observational (n = 9) [13, 34-41], interventional (n = 4) [23, 25, 31, 42], pilot (n = 1) [43], case study (n = 1) [35], and descriptive (n = 2) [44, 45].

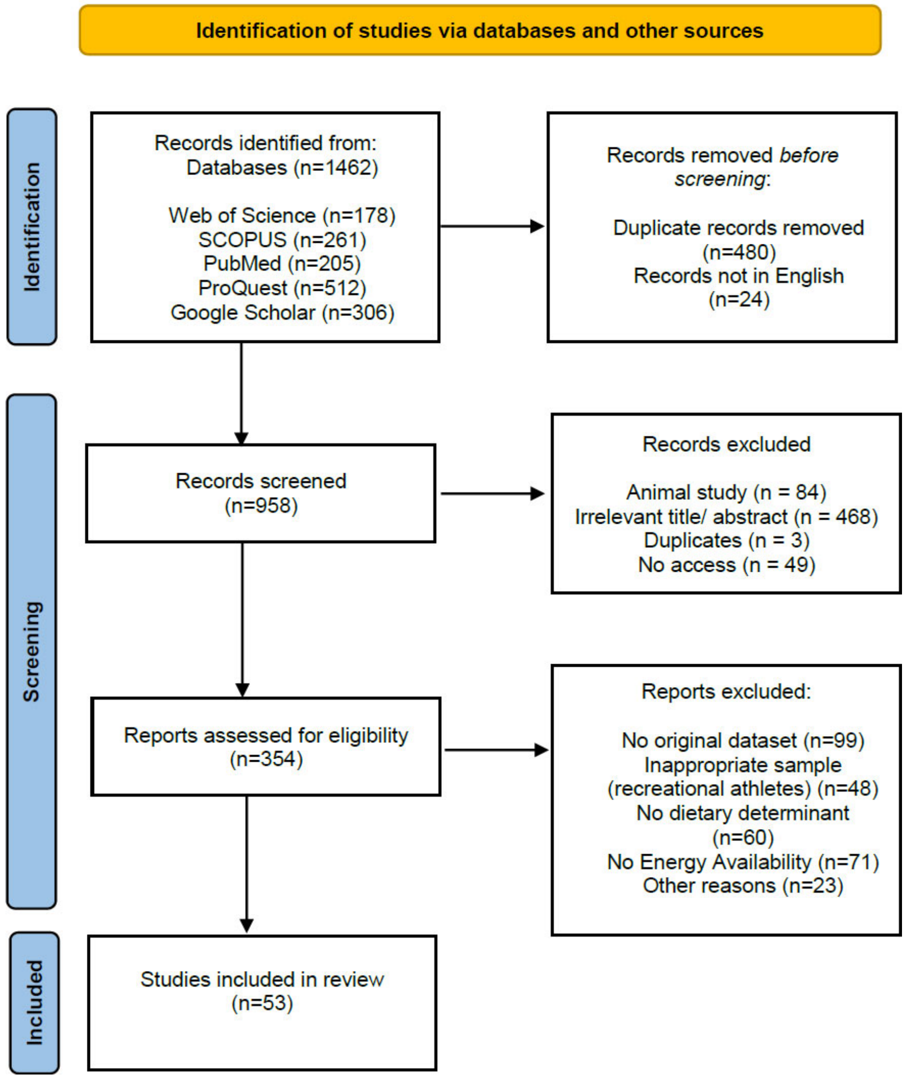

Fig. (1). PRISMA flow diagram of the study selection process.

Table 1. Data extraction.

Author(s) and Year	(Melin *et al.*, 2016)	(Cherian *et al.*, 2018)	(Silva & Paiva, 2015)	(Hertig-Godeschalk *et al.*, 2023)	(Ong & Brownlee, 2017)	(Coelho *et al.*, 2013)	(Logue *et al.*, 2019)
Reference	[12]	[13]	[56]	[43]	[60]	[14]	[15]
Study design	Cross-sectional	Cross-sectional and observational	NA	Pilot	NA	Cross-sectional controlled	Cross-sectional
POPULATION							
Sample size	n=25	n=40	n=67	n=14	n=11	n=24	n=833
Gender	Female	Male (n=21) Female (n=19)	Female	Male (n=6) Female (n=8)	Female	Female	Female
Age (years)	18 to 38	Under-12 and Under-16	18.7 ± 2.9	34 ± 9	21 to 26	12 to 19	18 and above
Performance level (as described by authors)	National	National	International	Elite	Elite	Competitive and sedentary control group	International (n=162), National (n=155), Competitive (n=281), Recreational (n=235)
Sport(s)	Weight-sensitive endurance	Soccer	Rhythmic Gymnastics	Multiple wheelchair	Dragon boat race	Tennis	38 different sports
CONTEXT							
Origin	Denmark	India	Portugal	Switzerland	Singapore	Brazil	Ireland
Competitive phase	During training	Pre competition	Pre competition	Pre competition and Competition	During training	Training	NA
CONCEPT							
Energy Availability assessment method	Calculated using EI, EEE and FFM	EI – EEE Represented in terms of kcal·kg−1 fat-free mass	EI - EEE Normalised to FFM	EI - EEE Relative to the FFM	EI (kJ) - EEE (kJ))/FFM (kg)	EI - EEE Normalized to FFM	LEAF-Q
Energy Availability cutoff (in study)	LEA = <30 kcal (125 kJ)/kg FFM/day; Reduced EA = <45 kcal (188 kJ)/kg FFM/day	LEA = <30 $kcal·kg^{-1}$ FFM; Adequate EA = ≥30 $kcal·kg^{-1}$ FFM	LEA = <45 kcal/kg FFM/day	LEA = ≤30 kcal/kg FFM/day	EA detrimental to health = <125.5 kJ/kg body fat-free mass/day; EA maintain normal physiological functions = ≥188 kJ/kg/day	LEA <45 kcal/kg FFM/day	At risk of LEA = score ≥8
Energy Intake assessment method	7-day weighed food records	3-days 24-hour dietary recall	24 hr dietary recall	3-days weighed food intake diaries	3-day food dairy	3-day food records	NA
Exercise Energy Expenditure assessment method	MET values of physical activities (Ainsworth compendium 2011)	Portable metabolic analyzer	MET values of physical activities (Ainsworth compendium 2011)	Recommendations of Conger and Basset	SensewearTM armband	Using the compendium of energy expenditures for youth (Ridley, Ainsworth, & Olds, 2008)	NA
Author(s) and Year	(Melin *et al.*, 2016)	(Cherian *et al.*, 2018)	(Silva & Paiva, 2015)	(Hertig-Godeschalk *et al.*, 2023)	(Ong & Brownlee, 2017)	(Coelho *et al.*, 2013)	(Logue *et al.*, 2019)

(Table 1) contd.....

Author(s) and Year	**(Melin *et al.*, 2016)**	**(Cherian *et al.*, 2018)**	**(Silva & Paiva, 2015)**	**(Hertig-Godeschalk *et al.*, 2023)**	**(Ong & Brownlee, 2017)**	**(Coelho *et al.*, 2013)**	**(Logue *et al.*, 2019)**
Resting Metabolic Rate assessment method	NA	NA	Cunningham equation	NA	Wong, J. E. *et al.*, for Southeast Asian athletes	NA	NA
Body Composition assessment method	DXA	Skinfold measurements and Body plethysmography	Bio-impedance analysis	DXA	Portable Bioelectrical impedance monitor	DXA	NA
OUTCOME							
Energy Availability reported	LEA = 3 subjects Reduced EA = 11 subjects	LEA = 5 boys; U16=4 LEA = 11 girls; U16=7	LEA below 45 kcal/kg FFM/day = 37.3% gymnasts EA below 30 kcal/kg FFM/day = 44.8% of gymnasts	All of the athletes experienced LEA for at least one day	Energy availability <188 kJ/kg FFM/day = 8 Energy availability <125.5 kJ/kg FFM/day = 6	Low energy availability = 91.7% of athletes Low energy availability = 71.4% of controls	At risk = Almost 40% (39.7%, n = 331)
Dietary determinants concluded	Training load, Energy Density, Weight cutting, Appetite, Meal composition	Energy Density, Age, Meal timing, Ad libitum intake, Food familiarity	Competitive Phase	Refuelling resources, Training load, Meal timing, Meal composition, Body image	Weight cutting, Competitive phase (preparation)	Weight cutting, Disordered Eating, Training load, Meal composition	Restrictive diets, Meal composition

Abbreviations: NA= Not Available.
EI= Energy Intake.
EEE= Exercise Energy Expenditure.
FFM= Fat Free Mass.
LEAF-Q= Low Energy Availability-Questionnaire.
EA= Energy Availability.
MET= Metabolic Equivalent of Task.
DXA= Dual-Energy X-ray Absorptiometry.

Author(s) and Year	**(Magee *et al.*, 2020)**	**(Matt *et al.*, 2022)**	**(Traversa *et al.*, 2022)**	**(Vescovi & Van Heest, 2016)**	**(Macuh *et al.*, 2023)**	**(Taylor *et al.*, 2022)**	**(Otte *et al.*, 2023)**
Reference	[34]	[16]	[46]	[35]	[61]	[36]	[17]
Study design	Observational	Cross-sectional	NA	Observational case Study	NA	Observational	Cross-sectional observational
POPULATION							
Sample size	n=18	n= 41+31	n=15	n=1	n=23	n=10	n=19
Gender	Female	Female (n=41+19) and Male (n=12)	Female	Female	NA	Male	Female
Age (years)	19.2 ± 1.1	14 to 17	20.5 ± 0.4	19	18 to 31	22 ± 8	24 ± 5
Performance level (as described by authors)	National Collegiate	High School Competitive	University Union	Junior Elite	Professional	Elite	Competitive
Sport(s)	Soccer	Endurance running	Rugby	Triathlon	Football	Road-cycling	Football
CONTEXT							
Origin	US	US	Canada	Canada	Slovenia	UK	Australia

(Table 1) contd.....

Author(s) and Year	(Magee *et al*., 2020)	(Matt *et al*., 2022)	(Traversa *et al*., 2022)	(Vescovi & Van Heest, 2016)	(Macuh *et al*., 2023)	(Taylor *et al*., 2022)	(Otte *et al*., 2023)
Competitive phase	Season midpoint	Beginning of season	Practice Day, Recovery Day and Game Day	Training	Preparation	Pre-season training	Pre-season
CONCEPT							
Energy Availability assessment method	EI - EEE Expressed as kcals per kilogram of FFM; LEAF-Q	NA	(EI - EEE)/kg FFM	EI - EEE expressed as kcal/kg FFM/day	EI (kcal) - EEE (kcal) / FFM (kg)	EI – Net EEE / FFM	LEAF- Q
Energy Availability cutoff (in study)	LEA = <30 kcal/kg of FFM; At LEA risk = Score ≥8 on LEAF-Q	LEA = <30 kcal/kgFFM/day; Suboptimal EA (male) = 30-45 kcal/kgFFM/day; EA = >45 kcal/kgFFM/day	Optimal EA = >45 kcal/kg FFM/day; Moderate EA = 30–45 kcal/kg FFM/day; Poor EA = <30 kcal/kg FFM/day	LEA = <30 kcal/kgFFM/day	Clinically LEA = <30 kcal/kg FFM Subclinical LEA = 30 - 40 kcal/kg FFM Optimal or high EA = >40 kcal /kg FFM	NA	At LEA risk = Score ≥8 on LEAF-Q
Energy Intake assessment method	4-day diet logs	2005 FFQ and 2014 FFQs	7-day dietary record	3–5 days diet logs	3-day food diaries	7 days remote food photography method (RFPM)	3-day weighed food records
Exercise Energy Expenditure assessment method	Wearable monitoring devices	Actiheart heart rate monitors	Based on lab study performed by Nyman & Spriet in 2021	Heart rate monitor	MET values of physical activities (Ainsworth compendium 2011)	MET values of physical activities (Ainsworth compendium 2011)	Global Positioning System (GPS) monitors
Resting Metabolic Rate assessment method	NA	NA	Harris-Benedict equation	Harris-Benedict equation	NA	Harris-Benedict equation	NA
Author(s) and Year	(Magee *et al*., 2020)	(Matt *et al*., 2022)	(Traversa *et al*., 2022)	(Vescovi & Van Heest, 2016)	(Macuh *et al*., 2023)	(Taylor *et al*., 2022)	(Otte *et al*., 2023)
Body Composition assessment method	Air displacement plethysmography	DXA and BIA	Bioelectrical impedance analysis (BIA)	DXA	BIA	Assumed 13% body fat	Portable BIA
OUTCOME							
Energy Availability reported	LEA in 66.7% athletes (23.0 ± 5.7 kcals/kg FFM); Non-LEA in 6 athletes (36.4 ± 7.3 kcals/kg FFM); At LEA risk = 56.3% of athletes	EA (<30) = 36 athletes (female=33; male=3) EA (30-44.99) = 18 athletes EA (>45 kcal/kgFFM/day) = 16.4% of the total sample	Mean EA over the 7-day period was: Forwards = 29.0 ± 3.7 (kcal/kg/FFM/day); Backs = 33.3 ± 3.5 (kcal/kg/FFM/day); 86% of players did not achieve optimal EA	Energy availability observed = <30 kcal/kg FFM/d	Energy availability = 29 kcal/kg FFM	EA = (−)21.9 to 76.0 kcal · kg FFM^{-1} · day^{-1}	At risk of LEA = 42% athletes
Dietary determinants concluded	Refuelling resources, Nutritional knowledge, Performance level	Gender, Disordered Eating	Playing position, Competitive phase, Appetite, Training load, External stress	Inadvertent undereating, Training load, Time constraints, Convenience, Appetite	Food beliefs, Training load, Supplement use	Appetite, Weight cutting, Training load, Nutritional knowledge, Time constraints, Intake assessment, Food choices, Competitive phase (training day)	Competitive phase, Nutritional knowledge, Time constraints, Training load, Appetite, Gut health, Employment status (time), Convenience

Abbreviation: BIA= Dual-Energy X-ray Absorptiometry.

(Table 1) contd.....

Author(s) and Year	**(L. C. de Souza *et al.*, 2023)**	**(Silva *et al.*, 2018)**	**(Dasa *et al.*, 2023)**	**(Jesus *et al.*, 2022)**	**(Condo *et al.*, 2019)**	**(Zabriskie *et al.*, 2019)**	**(Robbeson *et al.*, 2013)**
Reference	[18]	[19]	[37]	[38]	[20]	[47]	[21]
Study design	Cross-sectional	Cross-sectional	Prospective observational	Observational	Cross-sectional	NA	Cross-sectional descriptive
POPULATION							
Sample size	n=24	n=82	n=51	n=88	n=30	n=20	n=16
Gender	Female	Female (n=61) and Male (n=21)	Female	Male (n=64) and Female (n=24)	Female	Female	Female
Age (years)	19.5 ± 1.3	12.8 ± 3.1	22 ± 4	16 to 35	18 to 35	20.4 ± 1.8	18 to 30
Performance level (as described by authors)	National Collegiate	Competitive	Elite	National and International	Elite	National Collegiate	University and higher
Sport(s)	Acrobatics & Tumbling (A&T)	Acrobatic gymnastics (ACRO)	Football	Basketball (n = 29), Handball (n = 7), Volleyball (n = 9), Swimming (n = 18), and Triathlon (n = 25)	Australian Rules Football	Lacrosse	Track and field
CONTEXT							
Origin	US	Portugal	Norway	Portugal	Australia	US	South Africa
Competitive phase	Training	Competition	Training and Match	Preparation and Competition	Pre-season	Entire season	In season
CONCEPT							
Energy Availability assessment method	TEI – EEE / FFM	EI - EEE Normalised to FFM	[EI – EEE] / FFM	EI (in kcal) − EEE (in kcal)/ FFM (in kg)	LEAF-Q	(EI – AEE)/kg FFM	Mean daily EI (kcal) - Mean daily estimated EEE (kcal)/ FFM (kg)
Energy Availability cutoff (in study)	LEA = <30 kcals·FFM^{-1}	Low energy availability LEA = <45 kcal/kg FFM/day	LEA = <30 kcal/kg FFM/day	Clinical LEA = <30 kcal/kg FFM for both sexes; Subclinical LEA = 30–40 kcal/kg FFM for males or 30–45 kcal FFM for females; Optimal EA = ≥40 kcal/kg FFM for males and ≥45 kcal/kg FFM for females	At risk LEA = score ≥8; Not at-risk LEA = score ≤7	Clinical LEA = <30 kcal/kg FFM	Low estimated EA = <30 kcal/kg FFM/day; Healthy estimated EA = ≥45 kcal/kg FFM/day
Energy Intake assessment method	3-day dietary recall	3-day food records	3 (24-hour) diet recalls	NA	3 (24 h) dietary recalls	4-day dietary record	4 (24-hour) dietary recalls
Exercise Energy Expenditure assessment method	Proposed by Beermann, 2020	MET values of physical activities (Ainsworth compendium 2011)	DLW and GPS data	DLW and MET values of physical activities (Ainsworth compendium 2011)	NA	Physical activity monitor	MET values of physical activities (Ainsworth compendium 2011)
Author(s) and Year	(L. C. de Souza *et al.*, 2023)	(Silva *et al.*, 2018)	(Dasa *et al.*, 2023)	(Jesus *et al.*, 2022)	(Condo *et al.*, 2019)	(Zabriskie *et al.*, 2019)	(Robbeson *et al.*, 2013)
Resting Metabolic Rate assessment method	Cunningham equation	Cunningham equation	Cunningham equation; Harris-Benedict equation	Indirect calorimetry	NA	Cunningham equation; Schofield equation	NA

(Table 1) contd.....

Author(s) and Year	**(L. C. de Souza *et al.*, 2023)**	**(Silva *et al.*, 2018)**	**(Dasa *et al.*, 2023)**	**(Jesus *et al.*, 2022)**	**(Condo *et al.*, 2019)**	**(Zabriskie *et al.*, 2019)**	**(Robbeson *et al.*, 2013)**
Body Composition assessment method	DEXA	Skinfold thicknesses and BIA	DEXA	Air displacement plethysmograph	NA	DEXA scan	DEXA
OUTCOME							
Energy Availability reported	LEA = 58.3%, n = 14 student-athletes	Female adolescent gymnasts EA = 32.8 ± 9.4 kcal/kg FFM/day; Female children EA = 45.8 ± 8.7 kcal/ kg FFM/day; Male gymnasts EA = 45.1 ± 14.7 kcal/kg FFM/day; Male children EA = 53.8 ± 9.1 kcal/kg FFM/day	LEA on training days = 23% of the players; LEA on match days = 36% of the players	Clinical low EA at the preparatory phase = Eleven athletes (12.5%)	At risk of LEA = 30% of players	EA (phase 1) = 30.4 ± 11.0 kcal/kg FFM; EA (phase 2) = 26.2 ± 10.5 kcal/kg FFM; EA (phase 3) = 22.9 ± 8.5 kcal/kg FFM; EA (phase 4) = 28.7 ± 9.5 kcal/kg FFM; EA (phase 5) = 28.9 ± 9.2 kcal/kg FFM	Low estimated EA = Eleven athletes (73.3%)
Dietary determinants concluded	Training load, Meal composition (low CHO)	Training load	Competition phase, Food beliefs, Training load	Type of sport, Weight cutting, Competition phase	Restrictive diet, Food beliefs, Nutritional knowledge, Estimated energy requirements, Training load, Food intolerances	Availability, Travel, Competition phase, Training load, Time constraints, Convenience, Education level	Disordered eating, Weight cutting, Body image

Abbreviations: TEI= Total Energy Intake.
DLW= Doubly Labeled Water.
DEXA= Dual-Energy X-ray Absorptiometry.

Author(s) and Year	**(Reed *et al.*, 2014)**	**(Jurov *et al.*, 2021)**	**(Reed *et al.*, 2013)**	**(Stenqvist *et al.*, 2020)**	**(Joaquim *et al.*, 2018)**	**(Schaal *et al.*, 2017)**	**(Cook & Dobbin, 2022)**
Reference	[48]	[22]	[49]	[42]	[57]	[53]	[39]
Study design	NA	Cross-sectional controlled laboratory	NA	Prospective intervention	NA	NA	Observational cohort
POPULATION							
Sample size	Pre-season n=19; Mid-season n=15; Post season n=17	n=12	n=19	n=20	n=17	n=9	n=36
Gender	Female	Male	Female	Male	Male (n=9) and Female (n=8)	Female	Male
Age (years)	18 to 21	18 to 35	18 to 21	18 to 50	26 (6.17)	20.4 ± 0.4	23.1 ± 3.9
Performance level (as described by authors)	National Collegiate	Trained (n =3), Well-trained (n = 4) and Professional athletes (n = 5)	National Collegiate	Regional and National	Elite	National	Elite (National and International)

(Table 1) contd.....

Author(s) and Year	**(Reed *et al.*, 2014)**	**(Jurov *et al.*, 2021)**	**(Reed *et al.*, 2013)**	**(Stenqvist *et al.*, 2020)**	**(Joaquim *et al.*, 2018)**	**(Schaal *et al.*, 2017)**	**(Cook & Dobbin, 2022)**
Sport(s)	Soccer	Endurance	Soccer	Cycling	Paralympic track and field	Synchronized swimming	Cycling
CONTEXT							
Origin	US	Slovenia	US	Norway	Brasil	France	UK
Competitive phase	Pre-season, Mid-season, and Post season	Training	Pre-season, Mid-season, and Post season	Training	Pre-competitive and Competitive training	Pre competition	Preparatory
CONCEPT							
Energy Availability assessment method	EA = EI - EEE relative to kilograms of LBM (kcal. kg^{-1} LBM)	EA = (EI-EEE)/ FFM	EA = EI - EEE relative to kilograms of LBM (kcal. kg^{-1} LBM)	EA = (EI [kcal] - EEE [kcal])/(FFM [kg])/day	EA = EI (kcal) - EEex(kcal)/ FFM (kg)	EA = EI - ExEE normalizing the resulting value to lean body mass	EAy = (EI − EEE) / eLBM
Energy Availability cutoff (in study)	LEA = <30 kcal. kg^{-1} LBM; Higher EA = ≥30 kcal. kg^{-1} LBM,	Optimal EA = ≥40 kcal/kg FFM/day	LEA = <30 kcal. kg^{-1} LBM; Higher EA = ≥30 kcal. kg^{-1} LBM,	LEA = <30 kcal·kg^{-1} FFM·day^{-1}	Adequate EA = ≥45kcal/kgFFM/day; Reduced EA = 30 to 45kcal/kgFFM/day; LEA = ≤30kcal/kgFFM/day	Energy balanced state EA = 45 kcal.kg/LBM/day; LEA = <30 kcal.kg/LBM/day	EA (healthy physiological functioning) = ~45 kcal·kg LBM^{-1}·day^{-1}; EA (impaired physiological functioning) = <30 kcal·kg LBM^{-1}·day^{-1}
Energy Intake assessment method	3-day diet logs	Dietary diaries for 7 consecutive days	3-day diet logs	4 four consecutive days weighed and registered dietary inatkes	4 consecutive days digital worksheet and a photographic record	4 consecutive days food photographs	3 consecutive days food records
Author(s) and Year	(Reed *et al.*, 2014)	(Jurov *et al.*, 2021)	(Reed *et al.*, 2013)	(Stenqvist *et al.*, 2020)	(Joaquim *et al.*, 2018)	(Schaal *et al.*, 2017)	(Cook & Dobbin, 2022)
Exercise Energy Expenditure assessment method	Polar Team2 software, Heart rate monitors, and purposeful exercise logs	Wearable heart rate monitors	Polar Team2 software, Heart rate monitors, and purposeful exercise logs	MET values of physical activities (Ainsworth compendium 2011)	Multidirectional accelerometer	Heart rate monitor	MET values of physical activities (Ainsworth compendium 2011)
Resting Metabolic Rate assessment method	World Health Organization equation	Indirect calorimetry: Harris-Benedict equation was used	World Health Organization equation	Indirect calorimetry; Cunningham equation	NA	NA	Harris-Benedict equation
Body Composition assessment method	DXA	Bioelectrical impedance device	DXA	DXA	Skinfold measures	Skinfold measurement	Boer formula for men
OUTCOME							
Energy Availability reported	LEA (preseason) = 5 of 19 (26%); LEA (midseason) = 5 of 15 (33%); LEA (postseason) = 2 of 17 (12%)	EA = 29.5 kcal/kg FFM/ day	LEA (preseason) = 5 of 19 (26%); LEA (midseason) = 5 of 15 (33%); LEA (postseason) = 2 of 17 (12%)	Markers associated with LEA found low T3, lowered RMR, and increased cortisol	LEA (day 1) = 17.6% of athletes; LEA (day 2) = 33.3% of athletes; LEA (day 3) = 33.3% of athletes; LEA (day 4) = 8.3% of athletes	Baseline EA = 25.0 ± 3.2 kcal.kg/LBM/day; IT_{WK2} EA = 22.3 ± 1.9 kcal.kg/LBM/day; IT_{WK4} EA = 18.0 ± 2.8 kcal.kg/LBM/day	EA (rest day) = 44 ± 14 kcal·kg LBM^{-1}·$day^{-1;}$ EA (training days) = 16 ± 18 kcal·kg LBM^{-1}·$day^{-1;}$ Mean EA = 25 ± 13 kcal·kg LBM^{-1}·day^{-1}

(Table 1) contd.....

Author(s) and Year	(Reed *et al.*, 2014)	(Jurov *et al.*, 2021)	(Reed *et al.*, 2013)	(Stenqvist *et al.*, 2020)	(Joaquim *et al.*, 2018)	(Schaal *et al.*, 2017)	(Cook & Dobbin, 2022)
Dietary determinants concluded	Energy density, Meal composition, Weight cutting	Weight cutting, Training load	Body image, Meal composition, Training load, Inadvertent undereating, Meal preparation (Food availability), Appetite	Training load, Inadvertent undereating, Meal composition	Taste, Athlete-guide, Disability	Appetite, Hormone, Gut health, External stress (social and environmental), Weight cutting, Type of sport, Competition phase, Training load	Training load, Eating disorder

Abbreviation: LBM= Lean Body Mass.

Author(s) and Year	(Egger & Flueck, 2020)	(Viner *et al.*, 2015)	(Jurov *et al.*, 2021)	(Kinoshita *et al.*, 2021)	(Torstveit *et al.*, 2019)	(Jurdana *et al.*, 2022)	(Kettunen *et al.*, 2021)
Reference	[54]	[58]	[23]	[24]	[25]	[59]	[55]
Study design	NA	NA	Intervention cross-sectional controlled laboratory	Cross-sectional	Cross-sectional intervention	Prospective	NA
POPULATION							
Sample size	n=14	n=10	n=12	n=18	n=53	n=10	n=19
Gender	Male (n=8) and Female (n=6)	Male (n=6) and Female (n=4)	Male	Female	Male	Male	Female
Age (years)	18 to 60	29 to 49	NA	15 to 19	18 to 50	15 to 30	Under-18
Performance level (as described by authors)	Elite (National)	Competitive	National and Professional	Competitive high school	Regional competitive	Competitive Elite	National
Sport(s)	Wheelchair	Endurance cycling	Cycling, Triathlon, Endurance	Middle- or Long-distance running	Endurance (Cycling, Triathlon, Long-distance running)	Cycling	XC Skiers
CONTEXT							
Origin	Switzerland	US	Slovenia	Japan	Norway	Slovenia	Finland
Competitive phase	Pre-season	Training and Competition	NA	Training	Training	Competitive training	Preparation
CONCEPT							
Energy Availability assessment method	(EI - EEE)/kg FFM	{EI – [EEE – (RMR/min × exercise min)]} ·FFM $(kg)^{-1}$·day^{-1}	(EI-EEE)/FFM	EI - EEE Adjusted for fat free mass (FFM)	EI - EEE Relative to fat free mass (FFM)	EI - EEE Relative to FFM	EI - EEE Expressed in kcal/kg fat-free mass $(FFM)^{-1}$/day $(d)^{-1}$
Energy Availability cutoff (in study)	Optimal EA = ≥45 kcal kg^{-1} FFM day^{-1}; Suboptimal EA = 30 kcal kg^{-1}FFM day^{-1} to 45 kcal kg^{-1}FFM day^{-1}; LEA = ≤30 kcal kg^{-1}FFM day^{-1}	LEA = <30 kcal·kg FFM^{-1}·day^{-1}	LEA being = <30 kcal/kg FFM/day	LEA = <30 kcal·kg^{-1} FFM·d^{-1}; Optimal EA = 45 kcal·kg^{-1} FFM·d^{-1}	LEA = <30 kcal/kg FFM/day	LEA = 30 kcal/kg FFM/day	LEA = <30 kcal/kgFFM^{-1}/d^{-1}; Optimal EA = >45 kcal/kgFFM^{-1}/d^{-1}

(Table 1) contd.....

Author(s) and Year	(Egger & Flueck, 2020)	(Viner *et al.*, 2015)	(Jurov *et al.*, 2021)	(Kinoshita *et al.*, 2021)	(Torstveit *et al.*, 2019)	(Jurdana *et al.*, 2022)	(Kettunen *et al.*, 2021)
Energy Intake assessment method	Weighed 7-consecutive day food diary	3 days·month^{-1}	7 consecutive days food diaries	7-day dietary records	3 or 4 consecutive days food logs	3-day food diaries and photographic records	48-hour food logs
Exercise Energy Expenditure assessment method	Recommendations by Conger & Bassett, 2011	MET values of physical activities (Ainsworth compendium 2011)	Wearable heart rate monitors	Wearable HR monitor	Heart rate monitor	MET values of physical activities (Ainsworth compendium 2011)	Equations by Charlot, 2014
Author(s) and Year	(Egger & Flueck, 2020)	(Viner *et al.*, 2015)	(Jurov *et al.*, 2021)	(Kinoshita *et al.*, 2021)	(Torstveit *et al.*, 2019)	(Jurdana *et al.*, 2022)	(Kettunen *et al.*, 2021)
Resting Metabolic Rate assessment method	Metabolic cart; Equation for SCI by Pelly, 2017	Cunningham equation	Indirect calorimetry	Whole room calorimeter; Cunningham's equation	Ventilated hood; Cunningham equation	Handheld indirect calorimeter	Cunningham equation
Body Composition assessment method	DXA	DXA	Bioelectrical impedance	DXA	DEXA	BIA	Bioimpedance measurement
OUTCOME							
Energy Availability reported	LEA = 73% of the days in female athletes LEA = 30% of the days in male athletes	LEA (Pre-season) = 70% athlete; LEA (Competition) = 90% athlete; LEA (Off-season) = 80% athlete	EA reduced by 50%	LEA = 6 of the 18 participants	EA (Lower EXDS) = 41.0 ± 11.0 kcal/kg FFM/day; EA (Higher EXDS) = 35.1 ± 10.3 kcal/kg FFM/day	EA = 35 kcal/kg FFM	Suboptimal EA at HOME = 89% of athletes; Suboptimal EA at CAMP = 58% of athletes; LEA at HOME = 5 (26%) athletes; LEA at CAMP = 7 (37%) athletes
Dietary determinants concluded	Weight cutting, Competition phase, Training load, Gender	Food beliefs, Restrictive diets, Weight cutting (Body composition management), Competition phase, Energy Density, Meal composition	Training load	Body image, Ad libitum intake	Eating disorder, Body image	Type of sport, Competitive phase, Training load, Residence, Meal composition (Macronutrient intake)	Nutritional knowledge, Meal composition (macronutrient intake), Resource availability (prepared meal), Training load, Residence

Author(s) and Year	(Kuikman *et al.*, 2021)	(Wright *et al.*, 2014)	(Hoch *et al.*, 2009)	(Torres-McGehee *et al.*, 2021)	(Simič *et al.*, 2022)	(McGuire *et al.*, 2023)
Reference	[50]	[26]	[27]	[28]	[29]	[62]
Study design	Survey	Cross-sectional descriptive	Prospective cross-sectional	Cross-sectional	Cross-sectional	NA
POPULATION						
Sample size	n=642+257	n=22	n=80+80	n=121	n=27	n=20
Gender	Female (n = 642) and Male (n = 257)	Female	Female	Female	Male (n=13) and Female (n=14)	Male
Age (years)	18 above	18 to 30	13 to 18	19.8 ± 2.0	13 to 18	18 to 40

(Table 1) contd.....

Author(s) and Year	(Kuikman *et al.*, 2021)	(Wright *et al.*, 2014)	(Hoch *et al.*, 2009)	(Torres-McGehee *et al.*, 2021)	(Simič *et al.*, 2022)	(McGuire *et al.*, 2023)
Performance level (as described by authors)	Recreational (n = 148/62), Collegiate (n = 217/38), National (n = 156/90), and International athletes (n = 119/66)	University (provincial or national level)	Varsity athletes (n=80) and sedentary students/controls (n=80)	Collegiate athletes and performing artists	Competitive	Elite inter-county
Sport(s)	Cycling, long-distance running = 84% (n = 565/188), Soccer, rugby = 8% (n = 32/38), Sprinting, shot-putting = 5% (n = 30/16) ; and Archery, equestrian = 1% (n = 11/0)	Field hockey (n = 9) and netball (n = 13)	Track (n=24), cross-country (n=25), volleyball (n=13), basketball (n=14), soccer (n=24), tennis (n=7), swimming (n=17), golf (n=3) and softball (n=6)	Equestrian (n=28), soccer (n=20), beach volleyball (n=18), softball (n=17), volleyball (n=12), and ballet (n=26).	Climbing	Gaelic football
CONTEXT						
Origin	Canada	Australia	US	US	Slovenia	Ireland
Competitive phase	Training and Competition	Training	NA	Training	Training (selection)	Pre-season and In-season
CONCEPT						
Energy Availability assessment method	LEA (females) = LEAF-Q LEA (males) = Non validated questionnaire	mean EI (kcal) – mean estEEE (kcal)/ FFM (kg)	DI - EEE	[EI - EEE]/kg/FFM	EI - EEE / FFM	EI - EEE Relative to kilograms of lean body mass per day
Energy Availability cutoff (in study)	At risk LEA = score ≥8	Low estEA = <30 kcal/kg FFM/day; Optimal estEA = ≥45 kcal/kg FFM/day	LEA = <45 kcal/kg/LBM.	LEA = ≤30 kcal/kg of fat-free fat mass	Optimal EA = 45 kcal/kg FFM/day; Reduced EA = 30–45 kcal/kg FFM/day	High EA = >40 kcal.kg $LBM^{-1}.d^{-1}$; Optimal EA = ≥40 kcal.kg $LBM^{-1}.d^{-1}$; Subclinical EA = 30 - 40 kcal.kg $LBM^{-1}.d^{-1}$; Clinical EA = <30 kcal.kg $LBM^{-1}.d^{-1}$
Author(s) and Year	(Kuikman *et al.*, 2021)	(Wright *et al.*, 2014)	(Hoch *et al.*, 2009)	(Torres-McGehee *et al.*, 2021)	(Simič *et al.*, 2022)	(McGuire *et al.*, 2023)
Energy Intake assessment method	NA	3-day diet record	3-day food diary	7 consecutive days	3-day food records	3 consecutive days photographed diary
Exercise Energy Expenditure assessment method	NA	MET values of physical activities (Ainsworth compendium 2011)	Ainsworth compendium of physical activity (1993, 2000, 2008)	SenseWear Armband with an accelerometer	MET values of physical activities (Ainsworth compendium 2000)	MET values of physical activities (Ainsworth compendium 2011)
Resting Metabolic Rate assessment method	NA	Cunningham equation	NA	Indirect calorimetry	An integrated software	Cunningham equation
Body Composition assessment method	NA	DEXA	DXA	DEXA	BIA	Skinfold measurements
OUTCOME						
Energy Availability reported	Likelihood of being at risk of LEA was 2.5 times for female athletes compared to controls	Low estEA (24± 12 kcal/kg fat-free mass/day) = 59% of the athletes	LEA in athletes = 36% LEA in sedentary/ control subjects = 39%	LEA = 81% (n=98) participants	Average EA = 27.5 ± 9.8 kcal/kg FFM/day	LEA (at pre-season) = 65% LEA (at in season) = 70%

(Table 1) contd.....

Author(s) and Year	(Kuikman *et al.*, 2021)	(Wright *et al.*, 2014)	(Hoch *et al.*, 2009)	(Torres-McGehee *et al.*, 2021)	(Simič *et al.*, 2022)	(McGuire *et al.*, 2023)
Dietary determinants concluded	Performance level, Disordered eating, Athlete support	Weight cutting (dieting), Training load, Body image, Environment familiarity, External stress (media, peer)	Inadvertent undereating, External stress (culture and media)	Type of sport (clothing), External stress, Competitive phase, Time availability, Team support, Weight cutting, Training load (unaccounted increased EEE)	Inadvertent undereating, Food group avoidance, Restrictive diets	Restrictive diets, Competitive phase

Author(s) and Year	(Imandel *et al.*, 2021)	(Halfacre Katharine L., 2020)	(Peterson *et al.*, 2018)	(Day, 2016)	(Brown *et al.*, 2013)	(Nalder, 2012)
Reference	[51]	[30]	[44]	[52]	[31]	[45]
Study design	NA	Cross-sectional	Descriptive	NA	Cross-sectional Intervention	Descriptive
POPULATION						
Sample size	n=92	n=9	n=81	n=25	n=29	Athlete (n=22) and non-athlete control (n=22)
Gender	Male	Male	Male (n=38) and Female (n=43)	Female	Female	Male
Age (years)	19.8 ± 1.4	24 to 35	18 to 25	19.5 ± 1.8	13 to 18	18 to 45
Performance level (as described by authors)	Collegiate	Professional (n=6) and amateur (n=3)	Collegiate	Collegiate	High School	Elite
Sport(s)	Cross-country and track and field	MMA fighters	Track and field, Football, Volleyball, Soccer, Golf, Basketball, and Tennis	Distance runners, sprinters, hurdlers, and jumpers	Track	Cycling
CONTEXT						
Origin	US	US	US	US	US	US
Competitive phase	Training	Competition (RWL)	NA	NA	Training	Training
CONCEPT						
Energy Availability methodology (described by)	Collegiate Professional Sports Dietitians Association, 2018	NA	Loucks & Thuma, 2003	Kopp-Woodroffe, 1999	Nattiv, 2007	Nattiv, 2007
Energy Availability assessment method	Food Energy Intake – Exercise Energy Expenditure = Energy Availability	ALEA = Defined by a negative value for TEA, which is the difference between caloric intake and TEE	DI – ExEE kcal/kg of LBM/day	average daily EI - daily EEE; Converted to an index of EA by dividing EA by kg of FFM	DI - EEE	mean EI – mean EEE normalized for FFM
Energy Availability cutoff (in study)	LEA = <30 kcal/kg fat-free mass per day; Energy balance = 45 kcal/kg fat-free mass per day	0 = Adequate Energy, TEA ≥ 0; 1 = ALEA, TEA < 0	LEA = <30 kcal/kg of LBM/day; Reduced EA = 30-45 kcal/kg of LBM/day; Adequate EA = ≥45 kcal/kg of LBM/day	EB = ≥45 kcals/kg of FFM/d; Below EB = <45 kcal/kg of FFM/d; Restricted EI = ≤30 kcal/kg of FFM/d	Optimal EA = ≥45 kcal/kg LBM; EA (bone turnover) = <45 kcal/kg LBM; EA (menstrual dysfunction) = <30 kcal/kg LBM; Moderate LEA = <45 but >30 kcal/kg LBM	Energy balance = >45 kcal-kg^{-1}FFM-d^{-1}; suppressed reproductive function and bone formation = <30 kcal-kg^{-1}FFM-d^{-1}

(Table 1) contd.....

Author(s) and Year	(Imandel *et al.*, 2021)	(Halfacre Katharine L., 2020)	(Peterson *et al.*, 2018)	(Day, 2016)	(Brown *et al.*, 2013)	(Nalder, 2012)
Author(s) and Year	(Imandel *et al.*, 2021)	(Halfacre Katharine L., 2020)	(Peterson *et al.*, 2018)	(Day, 2016)	(Brown *et al.*, 2013)	(Nalder, 2012)
Energy Intake assessment method	24-hour dietary recall	7-day food journals	3-days 24 h recall	3-day diet record	3 consecutive 24-hour diet recall	3-day food record
Exercise Energy Expenditure assessment method	MET values of physical activities (Ainsworth compendium 2011)	MET values of physical activities (Ainsworth compendium 2011)	Accelerometers and PA logs	Actigraph GTX3 triaxial accelerometer	MET values of physical activities (Ainsworth compendium 2011)	MET values of physical activities (Ainsworth compendium 2011)
Resting Metabolic Rate assessment method	NA	Cunningham equation	NA	NA	World Health Organization, 1985	Indirect calorimetry
Body Composition assessment method	Air displacement plethysmography or DXA	Skinfold measurements	DXA	Skinfold measurements	Bod Pod	Bioelectrical impedance
OUTCOME						
Energy Availability reported	EA <30.0 kcal/kgFFM/day = 35% (n=7)	Negative EA (fight week) = (n=8) 88.9% participants	LEA (males) = n=9; 23.7%; LEA (females) = n=5; 11.6%	Mean EA = 30.8 kcal/kg of FFM/d; EA < 45 kcal/kg of FFM/d = 92% (23 participants); EA < 30 kcal/kg of FFM/d = 52% (13 participants)	Moderate LEA = 50% (n = 11); EA > 45 kcal/kg LBM = 27.3% (n=6); EA < 30 kcal/kg LBM = 22% (n=5)	EA (cyclists) = 17.7 ± 8.9 $kcal\text{-}kg^{-1}$ $FFM\text{-}d^{-1}$; EA (controls) = 33.86 ± 9.8 $kcal\text{-}kg^{-1}$ $FFM\text{-}d^{-1}$; LEA (cyclists) = 91% (n=20); LEA (controls) = 41% (n=9)
Dietary determinants concluded	Dietary restraint	Weight cutting (RWL)	Inadvertent undereating	Time constraints, Body image (Attitude about body fat and its relation to performance)	Body image, External stress (media, society)	Restrictive diets, Weight cutting, Performance enhancement

Abbreviations: ALEA= Acute Low Energy Availability.
TEA= Total Energy Availability.
TEE= Total Energy Expenditure.

Author(s) and Year	(Reed, 2012)	(Moss *et al.*, 2020)	(Villa *et al.*, 2021)	(Muia *et al.*, 2016)	(Kalpana *et al.*, 2023)	(Fenton, 2022)
Reference	[32]	[63]	[40]	[9]	[41]	[33]
Study design	Cross-sectional	NA	Observational	NA	Observational	Cross-sectional
POPULATION						
Sample size	n=19	n=13	Pre-teen (n=17) and Teen (n=13)	n=61+49	n=52	n=24
Gender	Female	Female	NA	Female	Male	Male (n =10) and Female (n =14)
Age (years)	18 to 21	23.7 ± 3.4	9 to 12; 13 to 18	16 to 17	16 to 31	16 to 35
Performance level (as described by authors)	Collegiate	Professional	Elite	Competitive athlete (n=61) and non-athlete (n=49)	National	Amateur elite
Sport(s)	Soccer	Soccer	Gymnasts	Runners	Kho-Kho	Track
CONTEXT						
Origin	US	UK	Spain	East Africa	India	New Zealand

(Table 1) contd.....

Author(s) and Year	(Reed, 2012)	(Moss *et al.*, 2020)	(Villa *et al.*, 2021)	(Muia *et al.*, 2016)	(Kalpana *et al.*, 2023)	(Fenton, 2022)
Competitive phase	Pre, Mid, and Post season	In season (Training and competition)	Training	Training	Training	NA
CONCEPT						
Energy Availability assessment method	EI - EEE Relative to kilograms of lean body mass (kcal/kg LBM)	(EI − EEE)/ FFM	NA	Mean daily EI (kcal • d^{-1}) – Mean daily EEE (kcal • d^{-1}) / Fat-free mass $(kg)^{-1}$	EI - EEE Expressed as kcal per kg FFM	Female = LEAF-Q; Male = Gastrointestinal questions from the LEAF-Q, sexual desire inventory (SDI) and the androgen deficiency in aging males (ADAM)
Energy Availability cutoff (in study)	Low EA = <30 kcal/kg lean body mass	Optimal EA = >45 kcal·kg FFM^{-1}·day^{-1}; Reduced EA = 30-45 kcal·kg FFM^{-1}·day^{-1}; Low EA = <30 kcal·kg FFM^{-1}·day^{-1}	Optimal EA =r >45 kcal/kg FFM/day; Sub-clinical EA = 30–45 kcal/kg FFM/day; Extreme LEA = <10 kcal/kg FFM	Clinical LEA= <30 kcal • kg FFM^{-1} • d^{-1}; Subclinical LEA = 30–45 kcal • kg FFM^{-1} • d^{-1}; Optimal EA = ≥45 kcal • kg FFM^{-1} • d^{-1}	LEA = ≤25 kcal per kg FFM	At LEA risk (female) = score ≥8; At risk (male) = score ≥20
Energy Intake assessment method	3-consecutive days diet logs	5-day weighed food diary	7-day food diary	5-day diet record	1-day direct weighment plus recall method	NA
Exercise Energy Expenditure assessment method	Polar Team2 software, Heart rate monitors, and purposeful exercise logs	MET values of physical activities (Ainsworth compendium 2011)	ActiGraph accelerometer	MET values of physical activities (Ainsworth compendium 2000)	MET values of physical activities (Ainsworth compendium 2000)	NA
Author(s) and Year	(Reed, 2012)	(Moss *et al.*, 2020)	(Villa *et al.*, 2021)	(Muia *et al.*, 2016)	(Kalpana *et al.*, 2023)	(Fenton, 2022)
Resting Metabolic Rate assessment method	Indirect calorimetry; Harris-Benedict equation	Indirect calorimetry; Cunningham equation	World Health Organization (WHO) (2006)	Schofield equation	Cunningham equation	NA
Body Composition assessment method	DXA	DXA	Bioimpedance analysis	Skinfold measurements	Skinfold measurements	NA
OUTCOME						
Energy Availability reported	Low EA (pre-season) = 9 of 19 (47%); Low EA (mid-season) = 6 of 15 (40%); Low EA (post-season) = 2 of 17 (12%)	Optimal EA = 15% of players; Reduced EA = 62% of players; Low EA = 23% of players	Subclinical EA (Pre-Teen) = 12 (70.6%); LEA (Pre-Teen) = 2 (29.4%); LEA (Teen) = 13 (100%)	Clinical LEA = 17.9% (n = 10/56) of athletes; Clinical LEA = 2.2% (n = 1/45) of non-athletes; Subclinical LEA = 76% participants	LEA = 44% of players	At risk (female) = 8 At risk (male) = 5
Dietary determinants concluded	Competitive phase, Body image, Resource availability (Food availability, affordability), Appetite	Training load, Meal composition (Lack of periodization), Inadvertent undereating	Age, Athlete support	Meal composition, Appetite, Socio-economic status (financial affordability), Planned food plate, Attitude (care-free), Body image, Training load	Training load, Food environment, Inadvertent undereating	Body image, Weight cutting, Performance (under fuelling), Inadvertent undereating

3.1. Sample

The athletes in the studies were competing at high school (n = 3) [16, 24, 31], university (n = 16) [9, 18, 21, 26-28, 32, 34, 44, 46-52], national (n = 12) [12, 13, 15, 23, 38, 39, 41, 42, 50, 53-55], and international (n = 5) levels [15, 38, 39, 50, 56]. The sports played by athletes in the studies can be categorized into endurance (n = 25) [9,, 12, 16, 21-25, 27, 31, 33, 35, 36, 38, 39, 42, 44, 45, 50-52, 55, 57-59], team (n = 22) [13, 17, 20, 26-28, 32, 34, 37, 38, 41, 44, 46-50, 53, 60-63], skill games (n = 8) [18,, 19, 27, 28, 40, 44, 50, 56], and power (n = 2) [30, 50]. The majority of the studies were undertaken in the US (n = 16) [16, 18, 27, 28, 30-32, 34, 44, 45, 47-49, 51, 52, 58] and Slovenia (n = 5) [22, 23, 29, 59, 61]. Out of the 53 studies, eleven had an age group less than 18 years [9,, 13, 14, 16, 19, 24, 27, 29, 31, 40, 55], four studies belonged to the age group 16-30 years, while 37 had an age group greater than 18 years [12, 15, 17, 18, 20-22, 25, 26, 28, 30, 32-39, 41-54, 56-63].

3.2. EA Methodology

The three main methods described for assessing EA used FFM in the majority (n = 45) of studies [9, 12-14, 18, 19, 21-29, 31, 32, 34-49, 52-63], while a few used LBM (n = 7) and LEAF-Q (n = 6) [15, 17, 20, 23, 32-34, 44, 48, 49, 50, 53, 62]. The cut-off used to classify athletes in the LEA category was < 30 kcal • kg FFM^{-1} • d^{-1} or ≤ 30 kcal • kg FFM^{-1} • d^{-1} in most studies (n = 35), while in some (n = 4) it was < 45 kcal • kg FFM^{-1} • d^{-1} [9, 12, 13, 14, 16, 18, 19, 21, 23-28, 32, 34, 35, 37-39, 42-44, 46-49, 51, 53-63]. The majority of studies (n = 26) utilized 3-day dietary recalls for energy intake assessment [13, 14, 17-20, 25-27, 29, 31, 32, 35, 37, 39, 43-45, 48, 49, 52, 58-62]. The exercise energy expenditure was assessed using MET values (n = 23) [9, 12, 14, 19, 21, 26, 27, 29-31, 36, 38, 39, 41, 42, 45, 51, 56, 58, 59, 61-63], wearable monitors (n = 21) [13, 16, 17, 22-25, 28, 32, 34, 35, 37, 40, 44, 47-49, 52, 53, 57, 60], DLW (n = 2) [37, 38], recommendations of Conger and Basset (n = 2) [43, 54], a lab study performed by Nyman & Spriet in 2021 (n = 1) [46], and equation by Charlot *et al*. 2014 (n = 1) [55, 64]. The predictive equations used for assessing resting metabolic rate were the Cunningham equation (n = 15) [18, 19, 24-26, 30, 37, 41, 42, 47, 55, 56, 58, 62, 63], the Harris and Benedict equation (n = 7) [22, 32, 35-37, 39, 46], World Health Organization equation (n = 4) [31, 40, 48, 49], the Schofield equation (n = 2) [9, 47], the equation for Southeast Asian athletes (n = 1) [60], equation for SCI (n =1) [54]. Indirect calorimetry (n = 11) was also used in studies to assess the resting metabolic rate [22-25, 28, 32, 38, 42, 45, 59, 63]. The body composition of the study participants was measured using Dual X-ray Absorptiometry (DXA) scans (n = 23) [12, 14, 16, 18, 21, 24-28, 32, 35, 37, 42-44, 47-49, 51, 54, 58, 63], Bioelectrical Impedance Analyser (BIA) (n=14) [16, 17, 19, 22, 23, 29, 40, 45, 46, 55, 56, 59-61], skinfold measurements (n = 9) [9, 13, 19, 30, 41, 52, 53, 57, 62], air plethysmography (n = 5) [13, 31, 34, 38, 51], and Boer's formula (n = 1) [39]. 40 out of 53 studies reported participants had EA < 30 kcal • kg FFM^{-1} • d^{-1} while four suggested athletes being at risk of LEA [9, 12, 13, 15-18, 20, 21, 22, 24, 26-29, 31-41, 43-49, 51-55, 57, 58, 60-63].

3.3. Dietary Determinants

Various determinants emerged in the review, which were categorized into themes as given in Table 2.

Table 2. Categorisation of determinants into themes.

Theme	Key Determinants
1. Training and Performance Demands	- Increased training loads - Athletic season/periodization - Sport-specific requirements (*e.g.*, weight-class, aesthetics)
2. Psychosocial and Cultural Influences	- Body image concerns - Media and sporting culture pressures - Gender-related vulnerabilities (especially in female athletes) - Psychological stress
3. Dietary Practices and Nutritional Beliefs	- Restrictive diets (*e.g.*, paleo, gluten-free) - Carbohydrate and macronutrient misconceptions - Meal timing constraints - Voluntary intake restriction
4. Environmental, Logistical, and Educational Factors	- Time constraints (academic/workload) - Food availability and affordability - Nutrition knowledge - Parental or coach influence - Access to support staff
5. Physiological considerations	- Appetite suppression from training/intensity - Hormonal influences (*e.g.*, ghrelin)
6. Methodological Considerations	- Underreporting or altered behaviour during assessments

3.3.1. Training and Performance Demands

Elevated training loads without a proportional increase in EI resulted in LEA in 27 studies [9, 12, 14, 17-20, 22, 23, 26, 28, 35-37, 39, 41-43, 46, 47, 49, 53-55, 59, 61, 63], with a 42% frequency among Australian AFLW females during preseason [17]; 44% Indian Kho-Kho males due to inadvertent undereating [41]. Phases of training affected EA, which decreased to 4.2 kcal·kg^{-1} FFM·day^{-1} in multi-sport populations [47], interfacing with weight-cutting practices during particular seasons (n = 16) *via* dietary restriction for performance or body image considerations [12, 14, 21, 22, 26, 28, 30, 33, 36, 38, 45, 48, 53, 54, 58, 60]. The phases of the athletic season (n = 15) affected dietary intake by elevating energy expenditure [17, 28, 32, 36-38, 46, 47, 53, 54, 56, 58-60, 62], resulting in food shortages due to travel, and imposing time limits (90% competition LEA). Conversely, inadequate nutritional periodisation during load variations and the miscalculation of requirements resulted in inadvertent undereating (n = 9) [27, 29, 33, 35, 41, 42, 44, 49, 63]. Sport-specific requirements, such as weighing in or conforming to clothing in weight-class/aesthetic disciplines (n = 4) [28, 38, 53, 59], led to dietary restriction, with Indian junior males displaying 67.5% LEA from unadjusted demands [13].

3.3.2. Psychosocial and Cultural Influences

Body image concerns resulted in calorie restriction and exercise reliance (n = 11; 40% LEAF-Q at-risk Irish women) [9, 15, 21, 24-26, 31-33, 43, 49, 52], exacerbated by media and sports culture influences, as well as psychological stress leading to undereating (n = 6) [26-28, 31, 46, 53]. Females were more susceptible to disordered eating and had lower EI than males (55% daily LEA *vs*. 35%; 2.5-fold risk) [16, 50], particularly in US high school endurance runners and Canadian aesthetic groups, where cultural stressors converged with training requirements to maintain restraint.

3.3.3. Dietary Practices and Nutritional Beliefs

The macronutrient composition (n = 12) affected energy density and satiety (n = 4) [9, 12, 13, 15, 18, 42, 43, 48, 49, 55, 58, 59, 63], while misconceptions regarding low-carbohydrate diets for weight management (n = 4) and restrictive diets (n=6; *e.g.*, gluten-free/paleo, food group avoidance) limited intake (30% suboptimal EA among Australian rugby females) [15, 20, 29, 37, 45, 58, 61, 62]. Meal timing constraints associated with training schedules (n = 2) reduced EI even in ad libitum conditions [13, 43], indicating a correlation between nutritional attitudes and performance-driven under-eating across genders, with female-dominant samples showing the highest reduction.

3.3.4. Environmental, Logistical, and Educational Factors

Time limitations due to academic or professional commitments (n = 6) resulted in convenience eating, adversely affecting nutritional adequacy (81% of suboptimal EI among collegiate athletes) [17, 28, 35, 36, 47, 52], further compounded by inadequate knowledge (n = 5); 66.7% of youth in the US/ Finland) [17, 20, 34, 36, 55]. The influence of parents and coaches impacted dietary intake among youth (29.4% pre-teen LEA) [40], whereas food availability and affordability varied according to socioeconomic status, travel conditions, and performance level—elite athletes accessed superior nutrition in contrast to amateurs [28, 40, 50, 57]. Familiarity with the food environment, taste, and buffet/low-calorie planning all had an impact on EI [9, 26, 36, 41, 57], but collegiate class schedules limited eating windows.

3.3.5. Physiological Considerations

Increased training, meal composition, and gastro-intestinal health resulted in appetite suppression and lower EI (n = 9) [9, 12, 17, 32, 35, 36, 46, 49, 53]. Ghrelin levels increased as a result of compensatory intake attempts among females [53]. Rest-training energy availability discrepancies (44 *vs*. 17.7 kcal·kg^{-1}FFM·day^{-1}) highlighted the relationship between training and physiology, particularly in mixed and male cohorts [39, 45].

3.3.6. Methodological Considerations

Underreporting or assessment-induced intake alterations biased results (70-90%; 3-7 day recalls/diaries), inflating LEA through heterogeneous cutoffs (< 30-45 kcal·kg^{-1} FFM·day^{-1}), EEE records inaccuracies, and cross-sectional predominance confound gender/country-specific interpretations without validation with gold methods [36].

4. DISCUSSION

LEA, defined as < 30 kcal·kg^{-1} FFM·day^{-1} [65], manifests globally at 24% among male athletes and 58% among females. This trend is reinforced by recent data indicating 63% RED-S risk and associated performance impairments such as diminished endurance and agility [66]. Despite high rates of LEA, few studies have comprehensively identified all evidence-based dietary factors that promote LEA. Future research using multi-method cohort designs that include biomarkers (*e.g.*, reduced fT3, oestradiol) is recommended to examine dietary components that are specific to culture, gender, and age, allowing for customized interventions, as also demonstrated in recent cohorts.

Training and performance demands significantly hinder EI, with heightened EEE showing strong correlations with LEA, attributed to inadequate periodisation, travel disruptions, appetite suppression, and socio-economic barriers [36, 37]. Prevalence reported in recent studies indicates LEA among 11–67% of athletes during off-season and preseason/peak periods in team sports [67]. Although mechanistic insights remain limited, emerging data indicate that high training loads may reduce hunger [68]. The future scope of research in this area includes longitudinal Randomized Controlled Trials (RCTs) evaluating phase-specific EI-EEE synchronization, including carbohydrate periodisation during matches, training, and rest days, which is crucial to avert catabolic conditions, while practice tips include energy-dense food consumption during such periods.

Concerns regarding body image, in conjunction with other psychosocial factors such as gender norms, cultural pressures, media exposure, and stress, are significant drivers of low EI. Reduced caloric intake among athletes may be inadvertently promoted by coaches and the media, and female athletes may be more prone to adopt restrictive eating practices [16, 54]. This finding aligns with the current evidence of 2025, which identifies body image dissatisfaction (the pursuit of muscularity/thinness) as a significant pathway to RED-S [69]. Our findings reveal the scope of future population-stratified studies on Eating Disorders (ED) and Disordered Eating (DE) with RCTs focused on gender-specific nutritional counselling, emphasising body image acceptance and coping strategies through comprehensive psychological evaluation.

Inadequate dietary practices directly reduce EI due to macronutrient deficits, restricted diets (such as low-carbohydrate), prevalent myths and beliefs, and time constraints. These diminish energy density and satiety [13]. Currently, educational programmes that improve macro-awareness and efficacy have been reported as a solution [70]. Our data support the need for prospective evaluation of culture-specific attitudes and intake motivators and consistent athlete counselling, supported by various institutional policies and programmes to improve EI.

Lack of nutritional literacy and socioeconomic status are critical factors of LEA, intensified by environmental obstacles including insufficient team support, unfamiliarity with food, and challenges related to availability and pricing [55, 57]. Data from recent publications demonstrate a significant correlation between poor socioeconomic status and limited access to facilities and diminished motivation [71]. Contextual heterogeneity highlights nation-specific processes. Future scope includes country-specific environmental studies underpinning strategic dietary guidelines, emphasising policy-driven access to nourishment for vulnerable populations.

Physiological adaptations resulting from training disrupt appetite regulation and hormonal equilibrium (such as elevated ghrelin levels and dysregulation of PYY/CCK), a domain that remains insufficiently explored, as indicated by neural profiling of postprandial suppression in 2025 [53, 72]. This necessitates, in the future, thorough hormonal phenotyping, particularly in fasting and training conditions, essential for establishing precision nutrition frameworks that improve performance and metabolic health.

Methodological limitations decrease the integrity of LEA data, with insufficient incorporation of Indian biomarkers (*e.g.*, T3, ferritin) for cutoff validation, as critiqued in recent reviews of tool heterogeneity [36, 73]. Standardized, strong designs that use population-specific biomarkers are needed to obtain accurate prevalence metrics.Heterogeneous evaluation modalities for EA produce varying estimates due to the lack of standardised protocols, a shortcoming highlighted by recent studies that call for cohesive multi-method frameworks [74]. Establishing global and population-adjusted standards using gold-standard methods and biomarkers can improve study comparability and clinical applicability.

In summation, the review reveals that LEA is widespread globally and is primarily influenced by factors including training, psychosocial, dietary, socioeconomic, physiological, and methodological aspects. It therefore advocates for RCT-based interventions that are culturally appropriate, biomarker-informed, and standardized.

5. LIMITATIONS

Due to a scarcity of literature, the review included all study designs, using single-reviewer database searches and no quality exclusions to capture all reported determining factors.

CONCLUSION

The high prevalence of LEA among competitive athletes globally suggests the need to conduct causal research to build a deeper understanding of the various factors leading to inadequate dietary intake among athletes, especially phase-specific, population-specific factors across cultures. This needs to be in conjunction with concomitant investigation of biomarkers and standardized RCTs to examine interventions for the identified factors influencing LEA. This will enable the development of strategic eating plans, counselling, and motivators for effective LEA prevention.

AUTHORS’ CONTRIBUTIONS

The authors confirm contribution to the paper as follows: S.G., P.R.L.: Study conception and design; S.G.: Data collection; S.G., P.R.L.: Analysis and interpretation of results; S.G.: Draft manuscript. All authors reviewed the results and approved the final version of the manuscript.

LIST OF ABBREVIATIONS

FAT	=	Female Athlete Triad
REDs	=	Relative Energy Deficiency in Sports
EA	=	Energy Availability
EI	=	Energy Intake
EEE	=	Exercise Energy Expenditure
LBM	=	Lean Body Mass
LEA	=	Low Energy Availability
RCTs	=	Controlled Trials
ED	=	Eating Disorders
DE	=	Disordered Eating

CONSENT FOR PUBLICATION

Not applicable.

STANDARDS OF REPORTING

PRISMA guidelines were followed.

AVAILABILITY OF DATA AND MATERIALS

All the data and supporting information are provided within the article.

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None.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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Declared none.

SUPPLEMENTARY MATERIAL

PRISMA checklist is available as supplementary material on the publisher's website along with the published article.

Appendix 1. Search strategy.

DATABASE/DATE	FILTERS	COMMAND LINE
WOS (14-07-2023)	Search fields: WOS Core Collection All editions, All fields Date: 01-01-2003 to 14-07-2023	"Energy Availability" AND Athlet* AND "Energy Intake"
		"Energy Availability" AND Athlet* AND ("Die* Intake*" OR "Die* Choic*" OR "Die* Habi*" OR "Die* Practic*")
		"Energy Availability" AND Athlet* AND ("Food Intake*" OR "Food Choic*" OR "Food Habi*" OR "Food Practic*")
		1 OR 2 OR 3
SCOPUS (14-07-2023)	Search fields: Article Title, Abstract, Keywords Year: 2003-2023	{Energy Availability} AND Athlet* AND "Energy Intake"
		("Die* Intake*" OR "Die* Choic*" OR "Die* Habi*" OR "Die* Practic*") AND {Energy Availability} AND Athlet*
		("Food Intake*" OR "Food Choic*" OR "Food Habi*" OR "Food Practic*") AND {Energy Availability} AND Athlet*
		1 OR 2 OR 3
PUBMED (14-07-2023)	Search fields: All fields Date: 01-01-2003 to 14-07-2023	"Energy Availability" AND Athlet* AND "Energy Intake"
		"Energy Availability" AND Athlet* AND ("Dietary Intake*" OR "Dietary Choic*" OR "Dietary Habi*" OR "Dietary Practic*")
		"Energy Availability" AND Athlet* AND ("Food Intake*" OR "Food Choic*" OR "Food Habi*" OR "Food Practic*")
		1 OR 2 OR 3
PROQUEST (14-07-2023)	Search fields: Full Text(Document Text) Year: 2003-2023	"Energy Availability" AND Athlet* AND "Energy Intake"
		"Energy Availability" AND Athlet* AND ("Die* Intake*" OR "Die* Choic*" OR "Die* Habi*" OR "Die* Practic*")
		"Energy Availability" AND Athlet* AND ("Food Intake*" OR "Food Choic*" OR "Food Habi*" OR "Food Practic*")
		1 OR 2 OR 3
GOOGLE SCHOLAR (16-07-2023)	Year: 2003-2023 Sort by Relevance	"Energy Availability" Athlete "Energy Intake"
		"Energy Availability" AND Athlet* AND ("Diet Intake" OR "Diet Choice" OR "Diet Habit" OR "Diet Practice")
		"Energy Availability" AND Athlet* AND ("Dietary Intake" OR "Dietary Choice" OR "Dietary Habit" OR "Dietary Practice")
		"Energy Availability" AND Athlete AND ("Food Intake" OR "Food Choice" OR "Food Habit" OR "Food Practice")
		1 + 2 + 3 + 4

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