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Relative Energy Deficiency in Sport (RED-S) in Female Athletes: Current Approaches and Evaluation Through Case Studies

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ABSTRACT
Relative Energy Deficiency in Sport (RED-S) has emerged as a critical multidimensional health concern among female athletes, affecting metabolic, endocrine, skeletal, psychological, and performance-related systems. This review aimed to synthesize current scientific evidence on RED-S and integrate recent real-world case reports to provide a comprehensive understanding of its clinical presentation, underlying mechanisms, and management strategies. A systematic literature search covering 2020–2025 was conducted across PubMed, Scopus, Web of Science, SPORTDiscus, and Google Scholar using keywords related to RED-S, low energy availability (LEA), female athletes, menstrual dysfunction, and bone health. Eligible studies included randomized controlled trials, observational studies, systematic reviews, consensus statements, and published case reports. Findings demonstrate that LEA (<30 kcal/kg FFM/day) is the primary driver of RED-S, leading to metabolic suppression, impaired thyroid and gonadal function, and disruptions in key anabolic pathways. Menstrual dysfunction ranging from luteal phase defects to functional hypothalamic amenorrhea emerged as a sensitive early indicator of RED-S. Literature and case reports consistently show that restoration of energy intake results in gradual endocrine recovery, with menstruation returning within approximately 2–12 months depending on severity. Bone health consequences were substantial, with reduced bone mineral density and elevated stress-fracture incidence particularly evident in endurance and aesthetic sports. Performance decrements were observed across VO_2max, lactate threshold, sprint capacity, and recovery metrics. Psychosocial determinants including perfectionism, body-image pressure, disordered eating tendencies, and coach–athlete communication were strongly associated with RED-S risk. Current evidence supports multidisciplinary management emphasizing nutritional rehabilitation, psychological support, training-load modification, and routine screening using updated IOC REDs CAT2 guidelines.

1. INTRODUCTION

Energy balance represents one of the fundamental determinants of health and performance in athletes. However, when training loads increase, the energy consumed may no longer meet the physiological demands of both exercise and essential bodily functions. This imbalance highlights the importance of the concept of energy availability (EA). A state of low energy availability defined as an insufficient amount of dietary energy remaining after exercise expenditure was formally conceptualized by the International Olympic Committee (IOC) in 2014 as Relative Energy Deficiency in Sport (RED-S). Since then, RED-S has been recognized as a complex, multisystem condition that can negatively affect the health and performance of both female and male athletes [1].

Historically, low EA in women was described primarily through the Female Athlete Triad, which encompassed three interrelated components: low EA, menstrual dysfunction, and decreased bone mineral density. However, the RED-S framework expanded this concept substantially by demonstrating that insufficient energy availability can disrupt multiple physiological systems, including endocrine metabolic, immune, cardiovascular, gastrointestinal, and neuromuscular pathways [2]. Recent systematic reviews indicate that the prevalence of low EA in athletes is remarkably

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high. A 2024 meta-analysis reported that approximately 44% of female athletes meet the criteria for low EA [3]. Such findings underscore the broader impact of RED-S, which extends beyond performance decrements to include serious health consequences such as bone stress injuries, chronic fatigue, impaired immune function, and hormonal disturbances [4].

Given these findings, the early identification, prevention, and management of RED-S in female athletes is of critical importance. Therefore, the present study aims to synthesize current literature on RED-S in female athletes, highlight key components such as energy availability, menstrual function, and bone health, and integrate insights derived from contemporary clinical and case-based observations.

2. CONCEPTUAL FRAMEWORK AND DEFINITIONS

2.1. History of RED-S

To understand the relationship between energy balance, health, and performance in female athletes, the concept of "energy availability" (EA) was first defined. Energy availability is calculated as the difference between the energy consumed through diet and the energy expended during exercise, normalized to the athlete's lean body mass (LBM). Seminal laboratory studies on energy availability have shown that values ≤30 kcal/kg FFM/day induce hormonal and metabolic changes resembling hypothalamic suppression, whereas higher availability (~45 kcal/kg FFM/day) supports normal physiological function [5].

As a result of this physiological suppression, not only the reproductive system but also thyroid function, bone turnover, immune function, and metabolic rate are negatively affected. Therefore, the first comprehensive clinical definition was established in the mid-1990s with the emergence of the Female Athlete Triad concept. First defined in 1992 by the American College of Sports Medicine (ACSM), the Triad consists of three components: low energy intake (or energy availability), menstrual dysfunction (oligomenorrhea/ amenorrhea), and low bone mineral density / osteopenia / osteoporosis [6].

However, this three-component model was found to be insufficient for explaining the clinical picture, as it became clear that multiple physiological systems are affected in female athletes experiencing low energy availability. Consequently, in 2007, the Triad model was revised with a stronger emphasis on "low energy availability," although its limitation to female athletes remained a major criticism.

In response to these limitations, the International Olympic Committee (IOC) introduced a more comprehensive model in 2014 and officially incorporated the term Relative Energy Deficiency in Sport (RED-S) into the literature. According to the 2014 IOC Consensus Statement, RED-S is a syndrome encompassing multi-system impairments including metabolic, hormonal, immune, hematological, gastrointestinal, cardiovascular, psychological, and bone-related dysfunctions arising from inadequate energy availability [1].

RED-S extends beyond the three components of the Female Athlete Triad, defining a broad multisystem impact and emphasizing that the condition occurs not only in women but also in male athletes. These systemic effects include:

- Decreased basal metabolic rate
- Suppression of thyroid hormone production
- Increased cortisol and altered stress response
- Suppression of the HPO axis
- Reduced bone metabolism (disrupted osteoclast/osteoblast balance)
- Impaired immune function
- Gastrointestinal disturbances
- Cognitive and psychological effects (anxiety, irritability, decreased attention) [1,7].

The updated version of the RED-S model was published again in 2023 by the IOC, introducing the RED-S Clinical Assessment Tool 2 (RED-S CAT2) for early identification in athletes [1]. This tool categorizes athletes into green–yellow–red risk levels. Recognizing symptoms associated with low energy availability is crucial for planning appropriate treatment. Recent literature also demonstrates that the emergence of RED-S is influenced not only by physiological but also psychosocial factors. Particularly, body-image pressures, weight concerns, performance anxiety, social media influences, and the athlete–coach relationship increase the risk of low energy intake in young female athletes [8,9]. For this reason, RED-S is now regarded not merely as a biological syndrome but as a biopsychosocial health condition.

Table 1. Differences Between RED-S and the Female Athlete Triad [1]

Feature	Female Athlete Triad	RED-S
Sex	Female only	Female + Male
Systems involved	3 systems	12+ systems
Assessment focus	Health only	Health + Performance
Clinical approach	Amenorrhea and BMD focused	Includes energy, hormones, metabolism, psychology

2.2. Components of RED-S

2.2.1. The Concept of Energy Availability and the Physiological Basis of RED-S

At the core of the pathophysiology of RED-S lies low energy availability (LEA). Energy availability refers to the amount of energy remaining for essential physiological processes after subtracting the energy expended during exercise from the total dietary energy intake [5]. In female athletes, when energy availability falls below 30 kcal/kg of lean body mass, reproductive function becomes suppressed, thyroid hormone concentrations decrease, leptin levels drop, peripheral action of growth hormone becomes impaired, and multiple metabolic adaptations emerge [10]. When energy deficiency is sustained, the hypothalamic–pituitary–gonadal axis becomes suppressed, estrogen levels decline, and this results in both menstrual disturbances and reductions in bone mineral density. RED-S demonstrates that energy imbalance affects not only a few biological systems but also significantly influences neurocognitive performance, sleep, immune function, and psychological well-being [2]. Therefore, energy availability represents both the starting point and the primary determinant of clinical severity in RED-S.

Although an energy availability threshold of <30 kcal/kg fat-free mass/day is widely used to define low energy availability (LEA), emerging evidence suggests that this cut-off may not apply uniformly across all sport disciplines. Athletes participating in endurance, aesthetic, or weight-category sports may experience physiological suppression at higher energy availability levels due to prolonged training duration, cumulative energy expenditure, or restrictive eating behaviors. Conversely, athletes in power- or strength-based sports may tolerate lower short-term energy availability without immediate endocrine disruption. Therefore, low energy availability should be interpreted as a dynamic and context-dependent continuum rather than a fixed universal threshold, with sport-specific demands, training load, and individual susceptibility playing critical roles in RED-S development.

2.2.2. Menstrual Dysfunction

One of the most apparent clinical manifestations of RED-S in female athletes is menstrual dysfunction. Functional hypothalamic amenorrhea (FHA) emerges as a result of low energy availability suppressing the pulsatile secretion of gonadotropin-releasing hormone (GnRH), which leads to a significant reduction in estradiol concentrations [11]. Complete cessation of menstruation (amenorrhea), delayed or irregular menstrual cycles (oligomenorrhea), or luteal phase defects are directly associated with the severity of the energy imbalance. Menstrual dysfunction is considered an “early warning sign,” and if left untreated, it may produce long-lasting adverse consequences on bone health.

2.2.3. Bone Health and Stress Fractures

Estrogen deficiency and low energy availability negatively affect bone turnover in female athletes by increasing osteoclast activity and reducing bone formation. This situation increases susceptibility to stress fractures, particularly in high-impact sports. The literature indicates that the risk of stress fractures is 4- to 6-fold higher in female athletes diagnosed with RED-S [11]. Additionally, low bone mineral density (BMD) prevents optimal peak bone mass from developing during youth, thereby increasing long-term risk for osteoporosis.

2.3. Effects of RED-S on Performance and Health

Low energy availability associated with RED-S affects not only physiological health but also athletic performance. Reduced glycogen stores, fatigue, decreased training tolerance, impaired concentration and decision-making, and performance loss in sprint and endurance tests are among the performance-related consequences of RED-S [13]. Furthermore, weakened immune function increases the frequency of illness and injury and prolongs recovery times. In conclusion, RED-S is not a simple energy-deficiency state but a multidimensional clinical condition affecting all physiological systems. By offering a broader and more inclusive framework than the Triad model, applying to both female and male athletes, and necessitating a more holistic diagnostic approach, RED-S has become one of the central models in contemporary sports science. Recognizing RED-S in female athletes, evaluating energy availability, and monitoring menstrual and bone health in an integrated manner are critical for protecting performance and ensuring long-term health.

2.4. Epidemiology and Risk Factors

The prevalence of low energy availability and RED-S in female athletes is high and varies depending on sport type and training load. Recent systematic reviews report that approximately 30–50% of female athletes fall into the LEA risk category [3]. Aesthetic sports (gymnastics, dance, figure skating), endurance sports (running, triathlon), and weight-class sports (taekwondo, boxing) represent the highest-risk categories. In young athletes, energy requirements increase due to ongoing growth and development, making them particularly susceptible to RED-S [3]. Risk factors are multidimensional. Biological contributors include high training volume, inadequate dietary intake, low body fat, and hormonal sensitivity; psychosocial contributors include perfectionism, body-image pressure, aesthetic norms, and coach-athlete dynamics [14]. Social media influences and performance-related pressure are emerging modern-era risks that increase restrictive eating behaviors among female athletes. Additionally, insufficient nutrition education and misunderstanding of energy needs further contribute to the development of RED-S. Therefore, the epidemiology of RED-S should be understood as a complex interplay of physiological, environmental, and behavioral components.

2.5. Current Approaches, Assessment, and Management

The management of Relative Energy Deficiency in Sport (RED-S), as emphasized in the 2023 update by the International Olympic Committee (IOC), requires a multidisciplinary and individualized approach. Since the syndrome cannot be diagnosed through a single test, the assessment process must encompass multiple components. The cornerstone of assessment is the measurement of Energy Availability (EA), which involves a detailed 3–7-day dietary record combined with an evaluation of exercise energy expenditure. A 10–15% suppression in Resting Metabolic Rate (RMR) is considered a strong indicator of low EA. Body composition analysis is also included in the assessment. For the evaluation of menstrual function, beyond cycle length, the IOC 2023 update states that oligomenorrhea, luteal phase defects, and ovulatory dysfunction must also be considered part of the RED-S spectrum. In the assessment of bone health, measuring Bone Mineral Density (BMD) via DEXA, screening for a history of stress fractures, and monitoring vitamin D and calcium levels are essential; notably, reduced lumbar BMD has been frequently reported in endurance athletes. Finally, Psychological and Behavioral Assessment plays a critical role and includes eating-related behavior questionnaires (EDE-Q, LEAF-Q) and the evaluation of psychosocial pressures. Studies from 2025 have demonstrated that psychosocial stressors are among the strongest predictors of low EA [15].

In line with this multidimensional assessment framework, the International Olympic Committee recommends the use of the updated Relative Energy Deficiency in Sport Clinical Assessment Tool 2 (IOC RED-S CAT2) to support both screening and clinical management. In practical application, CAT2 can be integrated into routine athlete health evaluations to stratify athletes into low-, moderate-, or high-risk categories based on medical history, menstrual function, injury patterns, and behavioral indicators. For athletes classified as moderate or high risk, the tool assists clinicians in guiding training modification, medical referral, and return-to-play decisions. Repeated use of CAT2 during follow-up evaluations also enables monitoring of recovery progression and facilitates communication within multidisciplinary teams.

2.6. Treatment Strategies and Controversial Approaches

The primary goal in the treatment of RED-S is to increase Energy Availability (EA) to levels above 45 kcal/kg FFM/day. The main component of treatment is a Nutritional Intervention, which includes increasing daily caloric intake by 300–600 kcal and adjusting carbohydrate intake to match training intensity. Ensuring a protein intake of 1.6–2.2 g/kg/day and avoiding excessively low-fat diets is also important for female athletes. The FUEL Intervention developed by Fahrenholtz et al. [15] is recognized as an effective model for significantly improving EA levels. Alongside nutritional adjustments, Training Modifications, such as reducing weekly training load by 10–20% and limiting high-intensity intervals, are crucial to achieve rapid recovery in athletes experiencing acute energy deficiency. Additionally, addressing issues related to body image disturbance and perfectionism requires Psychological Support, which is often neglected but represents one of the most critical elements of RED-S management.

Traditional pharmacological approaches have become increasingly controversial. Combined oral contraceptives (COCs) are generally not recommended, as they do not resolve the underlying energy deficiency and may “mask” menstrual status. Studies by Mountjoy et al. [1] have shown that COC use does not improve BMD. The IOC does not recommend COCs as the sole treatment for RED-S and supports their use only in specific endocrine disorders. Hormone replacement therapy (HRT) may be considered only in select cases of hypothalamic amenorrhea; however, the fundamental treatment must still focus on increasing energy intake. Monitoring treatment progress involves evaluations every two weeks during the first three months, followed by monthly assessments. These follow-ups include reassessment of RMR, menstrual status, and BMD.

2.7. Prevention and Awareness Model

Modern approaches conceptualize the management of RED-S within a “preventive health” framework rather than a treatment-centered model. This framework incorporates Education Programs aimed at athletes, coaches, and families, focusing on energy–cost balance, recognition of at-risk behaviors, and promoting healthy training and nutrition habits. Regular Screening is a central component of prevention, with tools such as the LEAF-Q and short-form RED-S screening questionnaires widely recommended for routine use. A contemporary example is the 2025 initiative of the Women Cyclists Alliance, which advocates for mandatory RED-S screening within the UCI system [16]. Within Nutrition and Training Planning, periodic assessments of energy availability and competition-specific fueling strategies are essential to prevent acute and chronic energy deficits. Finally, at the level of clubs and sport federations, Policy Interventions—including shifting away from weight-focused training cultures, discouraging harmful dietary practices, and establishing psychological support mechanisms—play a vital role in preventing the emergence of RED-S. These psychosocial support measures are particularly important for young female athletes, who may be more vulnerable to performance pressure and body-image–related stressors.

3. MATERIALS AND METHODS

This study is a review article conducted to systematically examine the current scientific evidence related to Relative Energy Deficiency in Sport (RED-S) in female athletes. A two-component methodological framework was adopted: (1) a systematic evaluation of recent literature, and (2) a qualitative analysis of real case reports and clinical observations published in international literature. Therefore, the study does not involve the collection of any individual data and does not require ethical committee approval.

3.1. Literature Search Strategy and Study Selection

The literature search and study selection process followed a structured and transparent approach to enhance methodological clarity. Electronic searches were conducted independently across PubMed, Scopus, Web of Science. The search strategy combined Medical Subject Headings (MeSH) and free-text terms related to Relative Energy Deficiency in Sport, including “RED-S”, “low energy availability”, “female athlete triad”, “menstrual dysfunction”, and “bone health”. Records identified through database searching were screened in two stages. First, titles and abstracts were reviewed to exclude clearly irrelevant studies. Subsequently, full-text articles were assessed for eligibility based on predefined inclusion and exclusion criteria. Only peer-reviewed articles published in English and focusing on female athletes were considered. Discrepancies in study relevance were resolved through consensus.

The literature search covered the period between January 2018 and December 2025, prioritizing high-quality and up-to-date studies published within the last five to seven years. Searches were conducted across PubMed, Scopus, Web of Science, SPORTDiscus, ScienceDirect, and Google Scholar databases. The following keywords and their combinations using Boolean operators (“AND”, “OR”) were applied: “Relative Energy Deficiency in Sport”, “RED-S”, “Female Athlete Triad”, “energy availability”, “menstrual dysfunction”, “bone health”, “female athlete”, “low energy availability”, and “endurance female athlete”. The search was limited to peer-reviewed journal articles, official consensus statements, and published case reports.

Inclusion criteria were defined as follows: (a) studies involving female athletes, (b) articles examining physiological, hormonal, metabolic, bone-health-related or performance-related variables associated with RED-S, low energy availability, or the Female Athlete Triad, and (c) case reports, clinical studies, randomized controlled trials, systematic reviews, and consensus documents. Exclusion criteria consisted of studies involving non-athlete populations, research focusing solely on male athletes, dietary studies not evaluating energy availability, and non-peer-reviewed publications.

The evaluation of the literature was carried out in two phases. In the first phase, titles and abstracts were screened for relevance, and eligible studies were retrieved for full-text review. In the second phase, methodological quality, sample characteristics, assessment tools, RED-S diagnostic criteria, and reported physiological or clinical outcomes were analyzed thematically. The thematic analysis primarily focused on three major components: energy availability, menstrual function, and bone health. Hormonal regulation, metabolic responses, psychosocial factors, and performance outcomes were also examined as secondary themes.

The second methodological component, the case analysis, was conducted through a systematic review of real clinical case reports published in the literature. Selected cases included those in which female athletes were diagnosed with RED-S or presented with clinical findings suggestive of low energy availability. Each case was analyzed in terms of clinical presentation, energy intake level, training load, hormonal and metabolic findings, bone health outcomes, interventions applied, and final results. These case reports were used to support and contextualize the findings extracted from the literature.

Through this two-stage methodological approach, the study aimed to provide both a theoretical (literature-based) and clinical (case-based) perspective on RED-S. This structure enabled a comprehensive evaluation of the multidimensional physiological, hormonal, and performance-related characteristics of RED-S in female athletes.

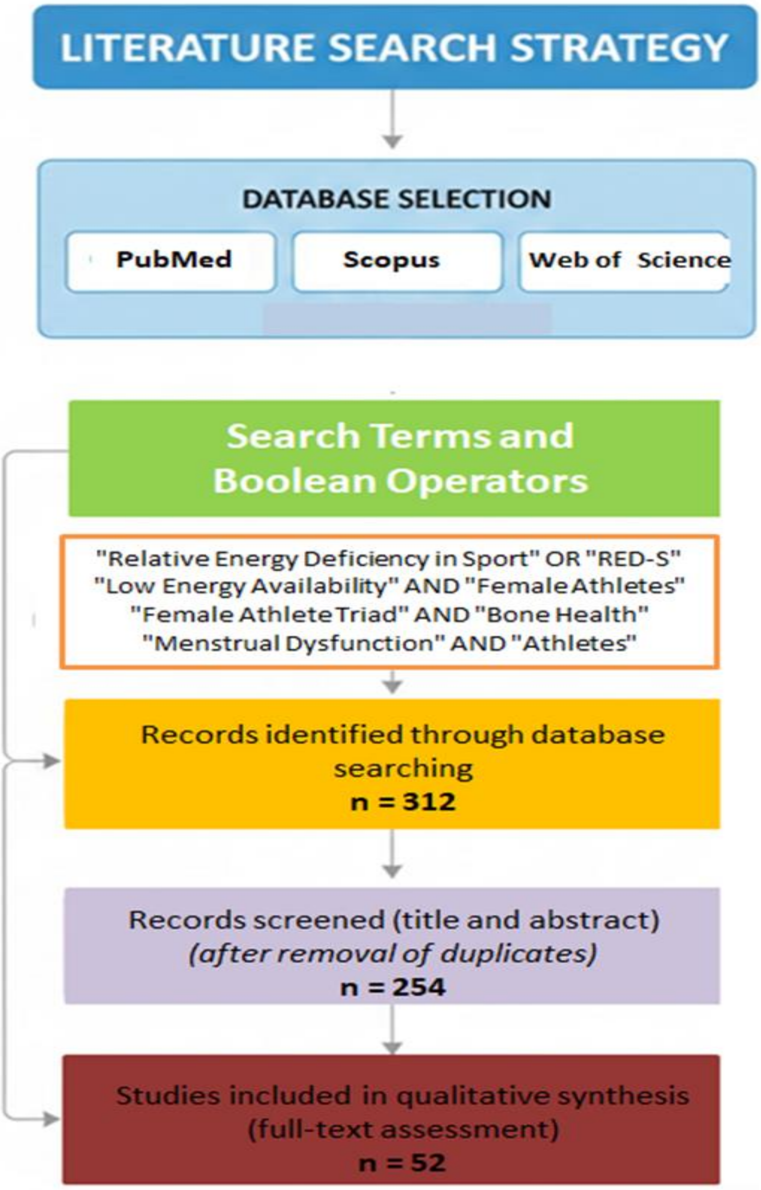

Figure 1. Flow diagram of literature search and study selection process.

4. RESULTS

This section synthesizes current findings related to Relative Energy Deficiency in Sport (RED-S) among female athletes, focusing on energy availability, menstrual function, bone health, performance outcomes, and psychosocial dimensions. The results are structured based on clinical studies, randomized controlled trials, case reports, and systematic reviews published between 2020 and 2025.

4.1. Energy Availability and Metabolic Responses

Recent studies demonstrate that low energy availability (EA < 30 kcal/kg FFM/day) is strongly associated with metabolic adaptations in female athletes. Melin et al. [17] reported that individualized nutritional interventions in professional female handball players were able to modulate physiological alterations linked to low EA, particularly improving resting metabolic rate (RMR) and thyroid hormone levels. Similarly, Fahrenholtz et al. [15] showed that low EA in endurance athletes was associated with significant reductions in leptin, IGF-1, and T3 concentrations, highlighting the biological underpinnings of RED-S.

Metabolic suppression of RMR is considered a critical biomarker of RED-S. In a randomized controlled trial published in 2025, five weeks of energy restriction in female athletes resulted in an average 12% reduction in RMR, which paralleled the observed decline in performance [18]. This study specifically demonstrated that metabolic adaptations can emerge rapidly in weight-category sports involving “weight cycling.”

4.2. Menstrual Function and Endocrine Responses

One of the most prominent clinical manifestations of RED-S in female athletes is menstrual dysfunction. De Souza et al. have demonstrated that low energy availability leads to suppression of follicle-stimulating hormone (FSH), luteinizing hormone (LH), and estrogen levels through disruption of the hypothalamic–pituitary–ovarian axis. Evidence indicates that menstrual disturbances associated with low energy availability are potentially reversible following nutritional rehabilitation and increased energy intake; however, the recovery process is often prolonged and highly variable, frequently requiring several months or longer depending on the severity and duration of energy deficiency [19].

The 2024 IOC consensus update emphasized that menstrual dysfunction is not limited to classical amenorrhea; shortened luteal phase, ovulatory dysfunction, and irregular cycles should also be considered components of the RED-S spectrum [1].

4.3. Bone Health and Stress Fractures

One of the most serious consequences of RED-S in female athletes is reduced bone mineral density (BMD) and the increased risk of stress fractures. Turner & Ackerman [4] reported significantly lower BMD in female athletes with RED-S, particularly in the lumbar spine and femoral neck regions. A case report involving a 42-year-old female endurance athlete with multiple pelvic stress fractures [20] showed that chronic low energy availability combined with sustained high training loads resulted in severe skeletal injury. This finding highlights that bone-related complications of RED-S can become more pronounced with advancing age. Furthermore, a large clinical study demonstrated that the risk of RED-S–related stress fractures is particularly elevated in endurance and aesthetic sports (running, dance, gymnastics), and that a substantial proportion of female athletes exhibit low bone mineral density [21].

4.4. Effects on Performance

The performance-related consequences of RED-S are multifaceted: endurance, strength, speed, coordination, and perceived fatigue are all directly influenced by low energy availability. Burke et al. [22] reported performance impairments associated with low energy availability, including reduced endurance capacity, impaired training adaptations, and decreased exercise tolerance in athletes. In an elite Muaythai athlete, Bulínová et al. [18] documented notable decreases in anaerobic power, resting metabolic rate (RMR), and muscular strength during a 5-week period of energy restriction. This demonstrates that RED-S effects can emerge even during short-term weight management phases. Conversely, interventions involving nutrition education and structured energy monitoring have been shown to restore performance parameters [23].

4.5. Psychosocial Factors and Behavioral Components

RED-S is associated not only with biological processes but also with psychosocial determinants. A study conducted in 2025 [15] demonstrated that among ultra-endurance athletes, perfectionism, body image pressure, and performance anxiety significantly predict low-energy-intake behaviors. Another study reported that coach–athlete communication is a critical variable in determining RED-S risk; low awareness and inappropriate nutritional guidance were shown to increase restrictive eating behaviors in athletes [24]. Psychosocial pressures are particularly prominent in aesthetic sports such as gymnastics, dance, and figure skating, with younger athletes being at even greater risk.

4.6. Current Intervention Approaches

The FUEL program (nutrition + education + monitoring), developed by Fahrenholtz et al. [15], has been shown to increase energy intake, reduce hormonal dysfunction, and improve overall well-being in female athletes. International consensus statements emphasize that the management of RED-S requires a multidisciplinary approach—integrating medical, nutritional, psychological, and coaching support—and that single-intervention strategies are insufficient. Accordingly, RED-S management should involve comprehensive and continuous monitoring within a coordinated multidisciplinary team [23]. Collectively, these findings indicate that RED-S cannot be managed through a single intervention; instead, it requires a comprehensive and continuous monitoring strategy.

4.7. Case Evaluations

Below are real case reports published in the international literature involving female athletes diagnosed with RED-S or exhibiting clinical manifestations related to low energy availability. The case data correspond directly to the thematic areas discussed in the Results section—energy availability, menstrual function, bone health, performance outcomes, and psychosocial determinants.

The clinical cases included in this review represent female athletes from a wide range of age groups, sport disciplines, and training backgrounds. Reported cases primarily involved endurance sports (e.g., long-distance running, cycling), aesthetic sports (e.g., ballet, dance), and weight-category or combat sports. The age of athletes ranged from adolescence to middle adulthood, with training volumes typically described as moderate to high, often exceeding 6–10 hours per week.

Across cases, common characteristics included sustained high training loads combined with insufficient energy intake, recurrent injuries or fatigue, menstrual disturbances, and impaired bone health. Although the level of detail varied between reports, the available demographic and sport-specific information was sufficient to contextualize RED-S presentation and recovery patterns across different athletic populations.

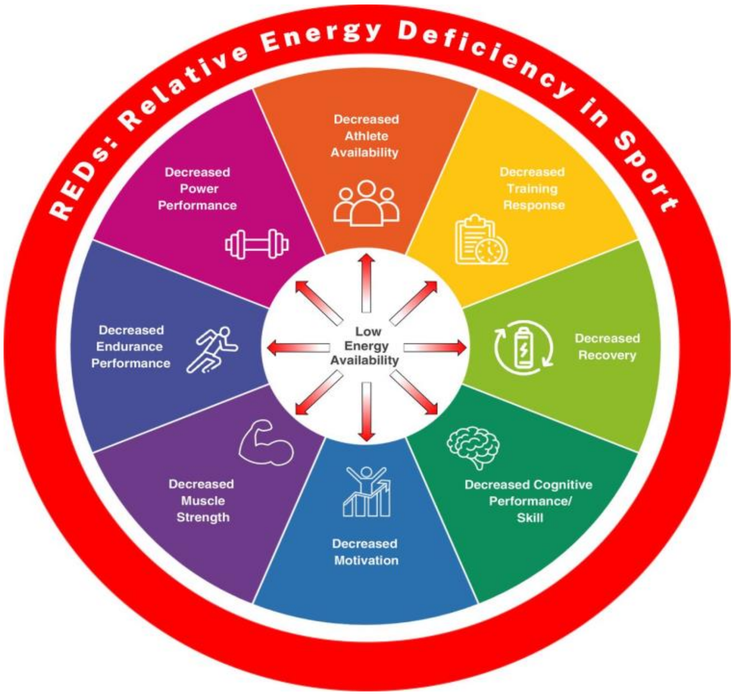

Figure 2. REDs Performance Conceptual Model. The effects of LEA exist on a continuum. While some exposure to LEA is mild and transient, termed adaptable LEA (arrow depicted in white), problematic LEA is associated with a variety of adverse REDs performance outcomes (arrow depicted in red). LEA, low energy availability; REDs, Relative Energy Deficiency in Sport [1].

Table 2. Case Reports of RED-S in Female Athletes (2020-2025)

Case No.	Athlete Profile	Key Findings	Source	Integration with Main Findings
1	Young adult female tennis player, elite level	Long-standing weight loss, amenorrhoea, low BMD; co-existing RED-S and anorexia nervosa. After 3 years of multidisciplinary treatment (nutrition + psychotherapy + training modification), gradual improvements in body mass, menstrual function and bone health	[25]	Demonstrates that LEA-related hormonal suppression, amenorrhoea and bone loss can be at least partially reversible with combined nutritional and psychosocial interventions plus training adjustments.
2	15-year-old high school distance runner	Recurrent metatarsal stress fractures, >12 months amenorrhoea, low BMD; diagnosed with Female Athlete Triad / RED-S; clinical improvement after increased energy intake and reduced training load	[26]	Shows that in adolescents, low EA combined with high running volume is a strong risk factor for stress fractures and amenorrhoea, and that early recognition can limit long-term bone loss.
3	Young female recreational athlete	Rapid weight loss, functional hypothalamic amenorrhoea, low energy intake; initially suspected anorexia nervosa; detailed evaluation revealed RED-S as primary diagnosis; menstrual function recovered following nutritional rehabilitation	[27]	Highlights that RED-S may occur without full-threshold eating disorders, and that mislabelling such cases as purely psychiatric can delay appropriate sport-specific management.
4	Adult female long-distance runner	Long-term amenorrhoea, low BMD, fatigue and performance decline; multi-year follow-up showed gradual recovery of menses and bone parameters within ~6–24 months after increased energy intake and training modification	[19]	Supports the notion that recovery of menstrual function may take many months or years, and that delayed intervention prolongs recovery (in line with section 4.2 on menstrual function).
5	42-year-old female endurance runner	Multiple pelvic stress fractures, chronic low energy intake, high training volume; discussed as a RED-S case in the context of the "Goldman's dilemma"; management included increasing energy intake and reducing training load	[20]	Underlines that RED-S is not limited to young athletes; in middle-aged women, chronic LEA plus high impact loading can lead to severe pelvic fractures (supporting section 4.3 on bone health).
6	Elite female Muaythai athlete	Five-week weight-cutting phase with marked energy restriction; ~12% reduction in RMR, hormonal changes and performance decline; rapid onset of metabolic adaptations resembling RED-S	[18]	Demonstrates that "weight cycling" in combat sports can quickly induce RED-S-like metabolic suppression and performance decrements (linked to sections 4.1 and 4.4).
7	Typical female athlete from a multidisciplinary RED-S outpatient clinic cohort (Nutrients study)	Among 58 athletes with suspected RED-S, a typical female case presented with LEA, menstrual disturbances, fatigue and performance impairment; after multidisciplinary treatment (nutrition, psychological support, medical and training supervision), improvements were observed in body mass, energy levels and performance indicators	[28]	Represents a "real-world" clinical RED-S case managed in a multidisciplinary setting, supporting the effectiveness of comprehensive, long-term treatment and follow-up (ties directly to section 4.6 and treatment strategies).

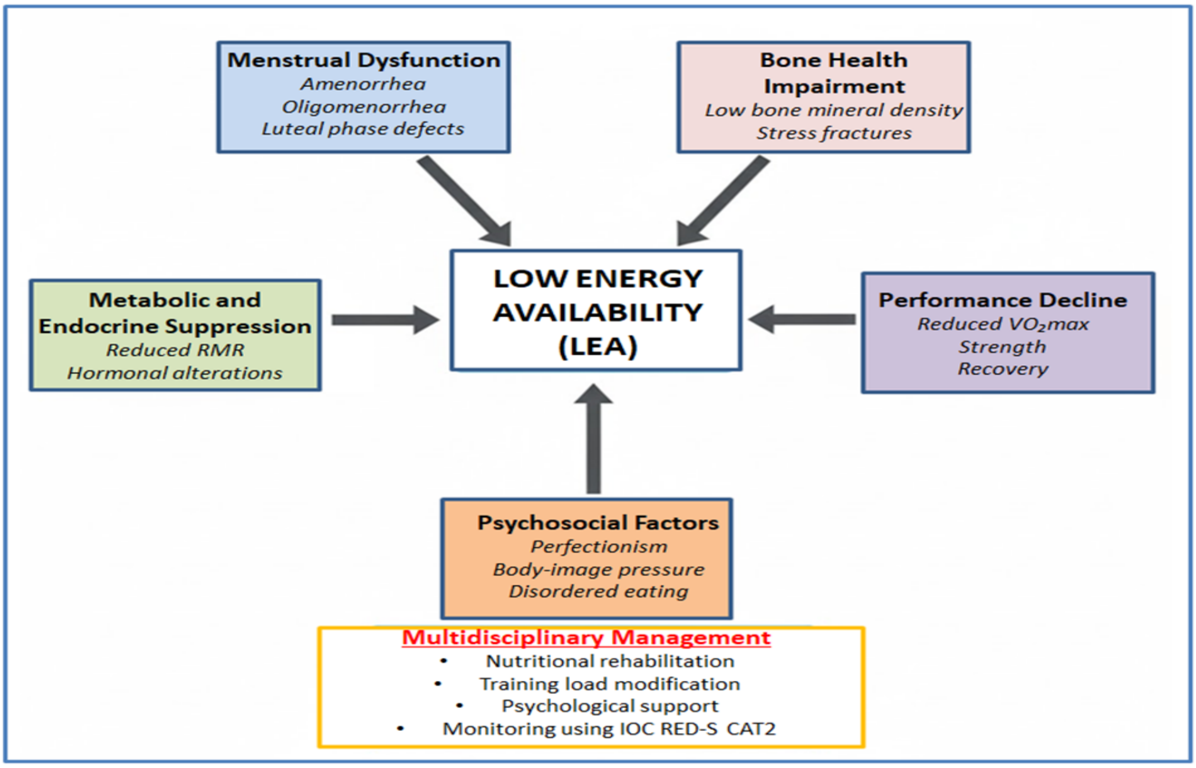

Figure 3. Conceptual summary of key findings related to Relative Energy Deficiency in Sport (RED-S) in female athletes.

5. DISCUSSION

In this review, the core components of Relative Energy Deficiency in Sport (RED-S) in female athletes—namely low energy availability, menstrual dysfunction, impaired bone health, performance outcomes, and psychosocial factors—were examined through a multidimensional perspective, drawing on clinical studies, systematic reviews, and case reports published over the last five years. The findings indicate that RED-S should no longer be conceptualized as a "triad-based clinical condition" but as a multisystemic syndrome that holds a central role in athlete management from both health and performance standpoints. This conclusion aligns with the 2023 IOC. Consensus Statement, which defines RED-S as a broad physiological model affecting metabolic, endocrine, immune, hematologic, gastrointestinal, psychological, and growth-related systems [1].

Our findings parallel studies demonstrating that low energy availability (EA < 30 kcal/kg FFM/day) is a key driver of metabolic adaptations, most notably through resting metabolic rate (RMR) suppression and down-regulation of thyroid and anabolic axes. Evidence from a 2022 study reporting improvements in RMR and thyroid parameters in professional handball players following individualized nutritional intervention supports the notion that low EA is a dynamic and reversible condition [2]. Similarly, within the FUEL intervention program, Fahrenholtz et al. [15] reported that female endurance athletes exhibiting RED-S symptoms demonstrated improvements in sports nutrition knowledge and positive trends in energy intake behavior following nutrition education and digital monitoring. These findings reinforce that metabolic suppression is not merely an "inevitable adaptation," but a targeted area for intervention.

From a metabolic perspective, evidence from combat sports and small-scale experimental studies demonstrates that even short-term but intensive energy restriction can significantly impair RMR and performance. In the case study of an elite female Muaythai athlete reported by Bulínová et al. [18], a five-week training camp resulted in notable decreases in RMR and anaerobic power, highlighting how "weight-cycling" strategies represent a critical risk factor for RED-S. These findings are consistent with the systematic review by Gallant et al. [3], which reported higher-than-expected rates of low energy availability and RED-S risk among both female and male athletes, alongside consistent associations with reduced performance and increased injury incidence.

Regarding menstrual function and endocrine responses, the findings strongly align with existing literature. The IOC consensus emphasizes that menstrual dysfunction should not be limited to classical amenorrhea but should also include shortened luteal phase, anovulatory cycles, and irregular menses within the RED-S spectrum [1]. In female athletes with exercise-induced menstrual dysfunction, it has been reported that adding approximately 360 kcal/day can restore menses within an average of 2–3 months, with multiple cycles observed during follow-up [29]. This suggests that menstrual disturbances are reversible in the early stages; however, prolonged dysfunction may lead to more persistent suppression of the endocrine axis. These results align with the comprehensive review by Angelidi et al. [4], which highlighted the suppressive effects of low EA on the hypothalamic pituitary gonadal axis, thyroid function, and stress hormone regulation. Case series reporting menstrual recovery within 6–12 months in long-distance runners further demonstrate that endocrine restoration occurs progressively following increased energy intake [19].

With respect to bone health and stress fractures, the compiled cases and studies indicate that RED-S significantly reduces bone mineral density particularly in weight-bearing skeletal regions such as the lumbar spine, femoral neck, and pelvis and markedly increases the risk of stress fractures. The RED-S case involving a 42-year-old female endurance athlete with multiple pelvic stress fractures reported by İs & Aydoğ [20] demonstrates that skeletal complications may progress more severely with advancing age. Review studies reporting elevated stress fracture incidence in endurance and aesthetic sports likewise confirm that low EA and RED-S are major determinants of fracture risk in disciplines such as running, gymnastics, and dance [29, 30].

In terms of performance outcomes, the findings also align with studies demonstrating that RED-S negatively impacts VO_2max, lactate threshold, sprint performance, and recovery. Gallant et al. [3] further showed that higher LEA risk scores are associated with increased injury incidence and performance decline. Notably, nutritional education and digital monitoring interventions aimed at improving energy balance appear capable of restoring performance parameters over time; the short- and long-term results of the FUEL program are promising in this respect [15]. These findings, together with the endurance athlete presenting with multiple pelvic stress fractures [20], underscore the clinical relevance of the link between energy deficiency and severe skeletal complications.

Psychosocial findings indicate that RED-S is not solely a biological syndrome but also a "context-dependent athlete experience" shaped by behavioral and sociocultural factors. The review by Colangelo et al. [14] in ultra-endurance athletes highlighted that perfectionism, discipline norms, the culture of "tolerating pain," and body-image pressure are closely linked to low energy intake and disordered eating behaviors. Similarly, the study by Scheid et al. [31], which associated low EA risk with anxiety levels and eating disorder symptoms in collegiate female athletes, suggests that psychological indicators may function both as risk factors and clinical manifestations of RED-S. Turkey based reviews further emphasize that body image pressure, coach/peer comments, and diet culture in aesthetic and weight-class sports reinforce low-energy-intake behaviors among female athletes [32]. Combined with the clinical case examples discussed in this article, these findings highlight the need for interventions that target not only the athlete but also the coach, family, and organizational culture.

Contemporary intervention approaches suggest that educational and behavioral programs are promising yet may not be sufficient as standalone strategies. The FUEL program developed by Fahrenholtz et al. demonstrated increased nutrition knowledge and modest but positive behavioral changes among female endurance athletes [15]. A systematic review conducted in 2025 examining LEA and nutrition education interventions highlighted that educational programs are effective in improving knowledge but require long-term follow-up and systemic support to ensure sustainable behavioral change [33]. The IOC's RED-S Clinical Assessment Tool (REDs CAT2) provides clinicians with a structured algorithm for early diagnosis and risk stratification, thereby reinforcing this multidisciplinary model; however, its routine implementation in field settings remains limited [9].

At the policy and organizational levels, calls for mandatory annual RED-S screening and bone mineral density assessments among professional female cyclists indicate a shift toward recognizing RED-S as a structural rather than solely individual athlete issue. The initiative led by The Cyclists Alliance advocating for UCI regulations mandating RED-S screening in female athletes is a recent example of this movement [16]. Such regulations should be viewed not only as medical monitoring but also as part of a broader cultural shift that prioritizes athlete health above performance.

A key strength of this review is its comprehensive integration of current literature published between 2020 and 2025 including randomized controlled trials, case reports, systematic reviews, and consensus statements while contextualizing findings through real clinical case examples. Nonetheless, certain limitations must be acknowledged. As a narrative review, methodological heterogeneity across included studies (e.g., differing RED-S diagnostic criteria, screening tools, athletic populations, and age groups) constrains the generalizability of some conclusions. Furthermore, the scarcity of epidemiological and interventional studies from Türkiye limits the ability to determine local RED-S prevalence and associated risk factors.

Future research should aim to evaluate RED-S prevalence across different sports and athlete levels (youth licensed athletes, elite competitors, collegiate athletes), assess long-term health and career implications, and examine the effectiveness of hybrid models combining education, policy interventions, and digital monitoring. Current evidence clearly indicates that RED-S is common among female athletes, often presenting silently and receiving delayed diagnosis, yet remains a reversible condition with early awareness and multidisciplinary intervention. Accordingly, expanding practices that center athlete health, routinely monitor energy availability, and address psychosocial dimensions should be prioritized in both clinical and sports policy settings.

Limitations of the Study

Despite its strengths, this study has several limitations:

- Data Collection Method: This article is a narrative review; no primary data were collected.
- Case Diversity: Case reports are limited to those available in the literature and do not cover all sport disciplines.
- Study Heterogeneity: Included studies vary methodologically (RCTs, reviews, case studies), which may influence interpretation.

Variability in Hormonal Assessments: Differences in hormonal measurement techniques and diagnostic criteria across studies reduce consistency in comparative evaluation.

6. CONCLUSION

Relative Energy Deficiency in Sport (RED-S) in female athletes is a complex clinical condition that exerts multidimensional effects on energy availability, hormonal balance, bone health, and performance. Literature from 2020–2025 demonstrates that RED-S is strongly associated not only with physiological mechanisms but also with psychosocial risk factors. Early recognition of low EA, monitoring of menstrual function, assessing stress fracture history, and tracking changes in metabolic markers are critical components of RED-S management. This study brings together current literature and clinical case examples to comprehensively illustrate the contemporary presentation of RED-S and highlights the central role of maintaining energy balance in safeguarding the health of female athletes.

Recommendations:

- Menstrual function should be monitored as the "fifth vital sign" of athlete health. Amenorrhea or irregular cycles must be treated as a health issue, not a performance concern.
- A multidisciplinary team approach must be implemented. Collaboration among sports physicians, dietitians, physiotherapists, psychologists, and coaches is the most effective model for RED-S management.
- Nutrition education and behavioral interventions should start at an early age. Energy management and body image education should be mandatory particularly for athletes aged 13–18.
- Training load–recovery balance should be monitored regularly. Periods of overreaching must be evaluated in conjunction with EA.
- Sports federations should establish RED-S awareness programs. RED-S modules should be integrated into coach education and certification programs.

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