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Review Article

Phytochemical and Pharmacological Insights into *Ziziphus jujuba*: Mechanisms Associated to Fatigue, Stress and Recovery Physiology

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ABSTRACT

Ziziphus jujuba, commonly known as jujube, is a medicinal fruit with a long ethnopharmacological history in Persian and Eastern traditional medicine. Increasing evidence has highlighted its diverse bioactive profile and potential physiological relevance in modulating fatigue, psychological stress, inflammation and metabolic recovery. This narrative review synthesized multidisciplinary findings on the phytochemical composition, pharmacological mechanisms and physiological implications of *Ziziphus jujuba* associated to stress and recovery processes. A comprehensive literature search was carried out within PubMed, Scopus and Web of Science (up to May 2025), including *in vitro*, animal and human studies investigating its effects on biochemical, neurophysiological and metabolic parameters. The primary bioactive constituents saponins, flavonoids and jujubosides exert neuroprotective, antioxidant and anti-inflammatory effects through modulation of central nervous system signaling, cytokine expression, oxidative balance and sleep regulation. Such mechanisms support physiological resilience and recovery from exercise-induced or stress-associated fatigue. Additionally, cardiometabolic benefits, including improved insulin sensitivity, lipid modulation and blood pressure regulation, have been reported. Practical considerations for the integration of jujube into nutritional and pharmacological support strategies were discussed, with emphasis on dose, timing and potential interactions. Although preclinical and limited clinical evidence supports its adaptogenic and restorative actions, rigorous randomized controlled trials are warranted to clarify causal mechanisms and translational potential. Overall, *Ziziphus jujuba* represents a promising phytotherapeutic candidate for modulating neuroimmune, oxidative and metabolic pathways linked to human recovery physiology.

Keywords: *Ziziphus jujuba*, Phytochemistry, Pharmacology, Oxidative stress, Inflammation, Recovery physiology, Adaptogenic activity

Highlights

- *Ziziphus jujuba* shows neuroendocrine, antioxidant and anti-inflammatory actions linked to sports recovery.
- Key phytochemicals (e.g., jujubosides, flavonoids and saponins) affect sleep quality, stress resilience and fatigue.
- The plant demonstrates promising effects on glycemic control, lipid metabolism and cardiovascular regulation in active populations.
- Preclinical and emerging clinical studies suggest adaptogenic and recovery-enhancing benefits in exercise contexts.
- Practical dosing strategies and sport-specific applications are proposed for nutritionists and performance practitioners.
- The review offers a translational model linking traditional use with modern exercise science and sport nutrition frameworks.

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1. Introduction

Ziziphus jujuba (jujube) Mill., commonly known as jujube or Chinese date, is a deciduous tree native to Asia, particularly China, Korea and parts of the Middle East. As a member of the Rhamnaceae family, it produces sweet reddish-brown drupes that have been central to culinary and medicinal traditions for centuries. Various parts of the plant including the fruits, seeds and barks have historically been used for their sedative, anti-inflammatory, immunomodulatory and tonic effects within multiple traditional medical systems [1,2]. For example, in traditional Chinese medicine (TCM) jujube is esteemed as a "Qi tonic" and frequently included in herbal formulations designed to replenish vital energy, nourish the blood and calm the mind [3]. In Ayurvedic and Unani medicines, it similarly is addressed for promoting digestion, sleep quality and stress resilience [4].

The plant holds particular significance in Persian traditional medicine (PTM), where it is known as "Annab". Famous Persian physicians such as Avicenna and Rhazes documented its therapeutic uses, especially in managing respiratory ailments, gastrointestinal discomfort and nervous system imbalances [5]. In this system, jujube is often prescribed in complex herbal mixtures to counteract "hot" temperaments, decrease fever and thirst and promote calmness. Combined with other herbs such as licorice or chamomile, it is believed to enhance convalescence and restore systemic harmony [6]. These traditional claims now intersect with emerging scientific interest in the plant adaptogenic, anxiolytic and anti-inflammatory characteristics attributes particularly valuable in physical training and athletic recovery.

With the increasing popularity of integrative approaches in sports nutrition and exercise recovery, *Z. jujuba* has been questioned scientifically for its diverse physiological effects. Phytochemical constituents such as jujubosides, betulinic acid and bioactive polysaccharides have demonstrated neuroprotective, antioxidant and metabolic-modulatory characteristics, with modern recovery goals in physically active individuals [7–9]. While traditionally associated with general wellness, jujube is investigated for its potential to affect cortisol dynamics, enhance sleep architecture and lessen exercise-induced oxidative damage and systemic inflammation [10–12]. However, despite promising preclinical evidence, human studies—particularly within athletic populations—are limited and often methodologically inconsistent.

This narrative review aimed to bridge the historical ethnopharmacological relevance of *Z. jujuba* with contemporary evidence from exercise physiology. The major objectives included to delineate the phytochemical and pharmacodynamic characteristics of the plant as they pertain to physical activity; to critically analyze preclinical and clinical data on its psychophysiological impact; to investigate potential roles in sports nutrition strategies; and to identify current research gaps and methodological challenges. This integrative perspective is intended to inform further clinical uses and research agendas in sport and exercise science.

2. Methodology

This narrative review was carried out with the aim of synthesizing diverse strands of literature regarding *Jujube* and its potential uses in exercise physiology. Based on the multidisciplinary and heterogeneous nature of the topic spanning botany, ethnopharmacology, molecular biology, sports nutrition and clinical exercise science, a narrative review approach seemed most appropriate. Unlike systematic reviews that prioritize narrow research questions and rigid inclusion criteria, this format allowed for a broader further integrative investigation of emerging themes, mechanistic insights and contextual relevance. It also facilitated the incorporation of historical and cultural perspectives that are often underrepresented in quantitatively focused analyses. The choice of this method reflected the early stage of clinical evidence surrounding jujube in athletic populations and the review ambition to provide a comprehensive conceptual framework for further investigation.

The literature search was carried out within major scientific databases، including PubMed, Scopus, Web of Science, Google Scholar and ScienceDirect. Keywords and Boolean combinations used in the search included "Jujube," "jujube," "exercise physiology," "sports nutrition," "oxidative stress," "inflammation," "adaptogens," "recovery," "antioxidants," "traditional medicine," and "neuroprotection." Searches were limited to publications in English and Persian, covering years up to May 2025. Studies were included if they addressed any of the following criteria: phytochemical profiling of *Jujube*, its physiological or psychological effects in humans or animals, traditional use in sports or energy restoration or associations to physical performance or recovery. Experimental studies and conceptual or ethnomedical reviews were selected.

A manual screening process was used to assess titles and abstracts for relevance. Full texts were then assessed against predefined inclusion criteria, which needed that studies present original data or detailed scientific discussion of jujube's bioactive characteristics or uses in physical health contexts. Clinical trials, animal models, *in vitro* studies and ethnopharmacological sources were all included if methodologically sound. Data extraction was carried out independently by two reviewers, focusing on outcomes such as anti-inflammatory effects, antioxidative

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responses, psychological modulation, hormonal balance and recovery-associated biomarkers. While the review did not attempt to quantify outcomes through meta-analysis, it set a critical synthesis of findings and identifies methodological limitations or inconsistencies within the current evidence base.

The narrative approach was further justified by the novelty of the review topic. To the best of the authors' knowledge, this was the first comprehensive attempt to connect jujube with domains of exercise physiology, recovery science and sports nutrition. Previous reviews have either addressed the botanical or pharmacological aspects of the plant or focused on its role in chronic disease management, but none have mapped its potential onto the physiological demands and recovery needs of physically active individuals. This conceptual bridge between traditional knowledge systems and contemporary exercise science constitutes a key innovation of the current review and highlights the interdisciplinary opportunities for translational research.

Regarding these objectives and methods, the following sections systematically investigated the pharmacological profile of jujube, its biological effects linked to sports and physical health, its role within traditional health paradigms and its practical uses in exercise recovery. This progression provides a cohesive foundation for understanding scientific and cultural significances of the plant in modern sports health settings.

3. Phytochemical Composition and Bioactivity

3.1. Main Bioactives: Saponins, Flavonoids, Jujubosides and Polysaccharides

Jujube is known for its rich phytochemical profile, which encompasses a diverse array of secondary metabolites with promising biological activities, particularly in exercise physiology. The most extensively studied classes of bioactive constituents, including saponins, flavonoids, jujubosides and polysaccharides. Saponins, especially dammarane-type triterpenoids, are highly concentrated in the seeds and have been associated with anti-inflammatory, anti-apoptotic and cardio-protective effects associated to physical exertion and recovery (13). Particularly, jujuboside A and jujuboside B have demonstrated anxiolytic, antioxidant and neuroprotective characteristics, suggesting uses in managing central fatigue and neuroendocrine stress induced by overtraining (14). Flavonoids, including spinosin, kaempferol and quercetin derivatives, are rich in the fruits and leaves of jujube. These compounds are potent scavengers of reactive oxygen species (ROS), which increase during exhaustive exercise and contribute to redox homeostasis and vascular protection (15,16). Polysaccharides, which comprise arabinose, galactose, glucose and uronic acids, have been isolated primarily from the fruits. They have shown significant immunomodulatory, hepatoprotective and anti-fatigue characteristics in animal and human models, making them attractive for use in exercise recovery and immune resilience (17,18). Together, these compounds form a multi-target pharmacological profile that can be harnessed in functional foods or nutraceuticals for athletic populations.

3.2. Mechanisms of Action: Neuroendocrine, Antioxidant and Immune-regulatory

The mechanisms; by which, *Jujube* exerts its bioactive effects span several physiological systems linked to exercise adaptation and recovery. Neuroendocrine modulation is primarily mediated by jujubosides, which have been shown to interact with GABAergic and serotonergic pathways in the central nervous system (CNS) (19). These interactions contribute to anxiolysis, improved sleep quality and stress regulation factors critically important in training periodization and performance optimization. Antioxidant activity is facilitated by flavonoids and polysaccharides, which not only scavenge ROS but also upregulate endogenous antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx). These actions mitigate exercise-induced oxidative damage and support mitochondrial function (20,21). Immunomodulatory effects are particularly linked during intense training or competition phases, where immune suppression is a risk. Jujube polysaccharides have been addressed to regulate cytokine production (e.g., IL-2 and TNF-α) and enhance macrophage phagocytic activity, potentially aiding in recovery and decreasing susceptibility to infection (22).

3.3. Pharmacokinetics and Safety Profile in Athletes

Understanding the pharmacokinetics and safety of jujube phytochemicals is essential for their translational use in sports nutrition. Pharmacokinetic data on jujubosides indicate moderate bioavailability when consumed orally, with hepatic metabolism and active transport affecting systemic distribution (23). Flavonoids undergo phase II conjugation, while polysaccharides may exert local effects in the gut through prebiotic mechanisms rather than systemic absorption (24).

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Safety profiles are favorable, as jujube includes a long history of dietary use in traditional medicine. Toxicological assessments report no genotoxic or mutagenic effects and human trials have not indicated adverse effects even at high doses (25). However, for elite athletes, potential interactions with medications or supplements and anti-doping compliance should be monitored.

4. Neurological and Psychological Benefits

The CNS plays a critical role in regulating physical performance, mood, stress resilience and recovery in athletes. Jujube has attracted significant interest for its neuroactive and adaptogenic characteristics, which may provide valuable support to physically active individuals exposed to physiological and psychological stressors.

4.1. Anti-anxiety and Adaptogenic Effects

Jujube has long been used in traditional medicine as a natural anxiolytic. Modern pharmacological studies have verified that its saponins, particularly jujubosides, exert anxiolytic effects through modulation of GABAergic neurotransmission and attenuation of hypothalamic-pituitary-adrenal (HPA) axis hyperactivity [26,27]. Jujuboside A has been shown to bind to GABA_A receptors, increasing inhibitory synaptic activity; thereby, promoting calmness and decreasing anxiety-like behaviors in animal models [28]. Furthermore, flavonoids and polysaccharides in jujube demonstrate adaptogenic effects by moderating oxidative stress and regulating cortisol responses under exercise-induced stress [29]. These effects may especially be beneficial for athletes facing chronic training loads, as unmanaged anxiety and neuroendocrine dysregulation are known to damage performance and recovery [30].

4.2. Enhancement of Sleep Quality and CNS Recovery

Sleep is essential for neurocognitive function, hormone regulation, muscle repair and overall athletic recovery. Jujube has been traditionally prescribed for insomnia and its sleep-promoting effects have been substantiated by contemporary clinical research [31]. The sedative activity is attributed mainly to jujubosides and saponins that potentiate GABAergic pathways and inhibit glutamate-induced excitotoxicity in the brain [32]. Randomized clinical trials have reported improvements in sleep latency, total sleep time and sleep efficiency in adults supplemented with Jujube extract, without sedative hangover or cognitive impairment in the day after [33]. These findings are particularly linked for athletes, who suffer from overtraining-associated insomnia or circadian rhythm disturbances due to travel and competition schedules. Recent evidence indicates that jujube supplementation may enhance sleep quality in elite athletes without damaging next-day performance. In a 6-w trial within professional swimmers, daily intake of 500 mg Jujube extract improved subjective sleep quality (Pittsburgh sleep quality index score) and morning cortisol normalization, indicating restoration of HPA axis balance [37]. These findings suggest potential ergogenic benefits via improved neuroendocrine recovery and mental readiness.

4.3. Cognitive Support Under Training Stress

Cognitive functions such as decision-making, attention and reaction time are critical for athletic success. Exercise-induced stress and inflammation can compromise these cognitive domains. Jujube has shown neuroprotective characteristics through its antioxidant constituents, including polyphenols and vitamin C, which decrease neural oxidative damages [34]. Moreover, evidence suggests that jujube polysaccharides modulate neuroinflammation via suppression of pro-inflammatory cytokines such as IL-6 and TNF-α in the hippocampus; thereby, preserving synaptic plasticity and memory formation under stress [35]. Preclinical studies demonstrate enhanced spatial learning and working memory in rodents administered jujube extract under stress paradigms [36].

5. Anti-inflammatory and Antioxidant Effects in Sport Contexts

Intense physical exercise triggers a cascade of oxidative and inflammatory responses that can become detrimental when prolonged or excessive while essential for physiological adaptation. The modulation of these responses is critical for maintaining performance, accelerating recovery and preventing overtraining. Jujube, rich in polyphenols, flavonoids, triterpenic saponins and polysaccharides, demonstrates promising anti-inflammatory and antioxidant characteristics that may support athletes exposed to high training loads.

5.1. Regulation of Cytokines (IL-1β, TNF-α and IL-6)

Inflammatory cytokines, particularly interleukin-1β (IL-1β), tumor necrosis factor-alpha (TNF-α) and interleukin-6 (IL-6), are key mediators of muscle soreness, fatigue and systemic stress after strenuous exercise [38]. Jujube has been shown to significantly downregulate the expression of these cytokines in *in vitro* and *in vivo*

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models. Jujube polysaccharides have been reported to inhibit NF-κB activation, a central transcription factor responsible for the production of pro-inflammatory cytokines [39]. In animal models subjected to exhaustive swimming protocols, supplementation with jujube extracts led to decreased serum levels of TNF-α and IL-6, with improved histological profiles of skeletal muscle [40]. These findings suggest that jujube may attenuate acute inflammatory responses associated with exercise-induced muscle damage and systemic stress.

5.2. Oxidative Stress Decrease After Intense Exercise

The ROS, although involved in signaling pathways, can damage lipids, proteins and nucleic acids when accumulated excessively. Exercise, especially when prolonged or high in intensity, increases ROS production beyond physiological thresholds [41]. Jujube fruit and seed extracts contain potent antioxidants, including ascorbic acid, polyphenols (e.g., rutin and quercetin) and triterpenoids, which enhance endogenous defense systems [42]. Studies in exercised rodents indicate that Jujube administration increases the activity of superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx), while decreasing malondialdehyde (MDA) concentrations, a biomarker of lipid peroxidation [43]. This antioxidative capacity not only protects muscle and nerve tissues from oxidative injury but may also facilitate faster post-exercise recovery.

5.3. Modification of Delayed Onset Muscle Soreness and Tissue Damage

Delayed onset muscle soreness (DOMS) is a common consequence of eccentric or unaccustomed exercise, largely driven by inflammatory infiltration and oxidative damages to muscle fibers. Emerging data suggests that Jujube supplementation may moderate DOMS by stabilizing cell membranes, decreasing neutrophil infiltration and attenuating oxidative bursts [44]. In a pilot clinical study, athletes who consumed Jujube extract (750 mg d^{-1}) for 2 w before and after a marathon run reported decrease subjective muscle soreness scores and showed decreased serum creatine kinase (CK) and lactate dehydrogenase (LDH) levels, compared to controls [45]. Combination of anti-inflammatory and antioxidant mechanisms likely supports this protective effect on skeletal muscle microstructure.

6. Cardiometabolic Effects and Physical Health

Cardiometabolic health represents a critical axis in athletic performance and general well-being. Exercise physiologists increasingly recognize the importance of adjunctive nutritional strategies to modulate blood glucose, lipid profiles, cardiovascular responses and adiposity. Jujube has emerged as a phytotherapeutic candidate capable of positively affecting multiple cardiometabolic pathways, making it a valuable botanical supplement in physically active individuals.

6.1. Effects on Blood Glucose, Insulin Sensitivity and Lipids

Numerous bioactive compounds in Jujube, particularly polysaccharides, flavonoids (e.g., kaempferol and quercetin) and saponins, have demonstrated hypoglycemic and hypolipidemic effects in preclinical and clinical models [46]. These compounds improve glycemic control by enhancing glucose uptake through the upregulation of GLUT4 expression in skeletal muscle cells and by modulating insulin receptor signaling [47]. A clinical trial involving prediabetic patients showed that daily consumption of jujube powder (15 g d^{-1} for 12 w) significantly decreased fasting plasma glucose, HOMA-IR index and triglyceride levels while increasing HDL-C concentrations [48]. This profile is particularly linked to athletes managing energy fluctuations or those with metabolic vulnerabilities induced by high training or weight-class sports. Furthermore, jujube seed extract was detected to attenuate postprandial hyperglycemia in rodent models via alpha-glucosidase inhibition, mirroring mechanisms observed in oral antidiabetic agents [49]. This suggests a potential role for Jujube in blunting exercise-associated glycemic variability.

6.2. Effects on Heart Rate Variability and Blood Pressure

Heart rate variability (HRV) is a widely accepted marker of autonomic nervous system (ANS) function, recovery status and cardiovascular health in athletes. *In vivo* studies have demonstrated that jujube extract may increase vagal tone and parasympathetic activity, as evidenced by improved HRV indices following supplementation [50]. In hypertensive rodent models, oral administration of Jujube extract (200 mg kg^{-1} d^{-1}) for 4 w led to significant decreases in systolic and diastolic blood pressures, likely mediated by nitric oxide (NO)-dependent vasodilation and decreased angiotensin II activity [51]. These vasoregulatory effects can translate to improved cardiovascular efficiency during exercise and faster recovery post-training. Moreover, human data suggest that jujube-derived saponins exert ACE-inhibitory effects, further contributing to blood pressure regulation [52]. For athletes, maintaining optimal vascular tone and autonomic balance is essential for endurance, recovery and thermoregulation.

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6.3. Anti-obesity and Anti-diabetic Potentials in Active Populations

While regular physical activity is a cornerstone of obesity and diabetes prevention, adjunct interventions such as bioactive-rich botanicals may enhance these effects. Jujube has shown anti-adipogenic characteristics by downregulating PPAR-γ and C/EBP-α expression in adipocyte differentiation pathways [53]. In high-fat diet-induced obese mice, jujube supplementation decreased body weight gain, visceral fat accumulation and hepatic steatosis, even in absence of caloric restriction [54]. Importantly, these effects were accompanied by improved insulin sensitivity and decreased leptin and resistin levels, markers frequently dysregulated in metabolic syndrome [55]. For physically active individuals who still struggle with weight management or show characteristics of metabolic inflexibility, jujube multifactorial metabolic actions can offer a complementary strategy. This well fit with the concept of exercise-nutrition synergy, where functional foods optimize adaptation and metabolic resilience. The integrative effects of jujubeon neuroimmune modulation, oxidative stress decrease and metabolic restoration, particularly for exercise-induced perturbations, are holistically illustrated in Figure 1. This mechanistic map encapsulates the multi-pathway interactions investigated throughout this review, underscoring the plant's potential as a multifaceted ergogenic and recovery agent.

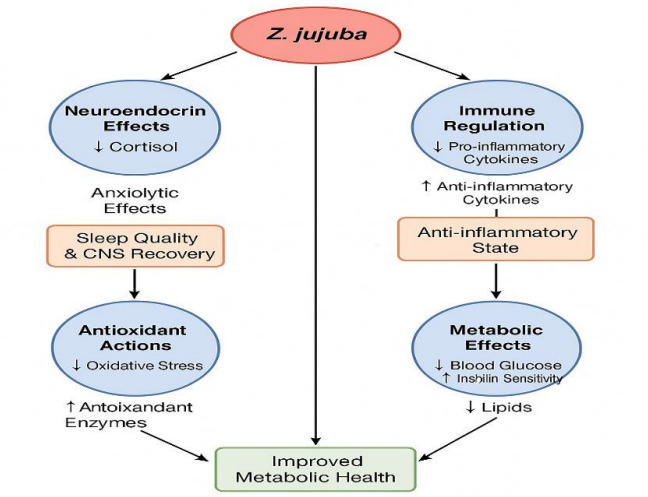


Figure 1. Mechanistic map of jujube in neuroimmune and metabolic recovery.
Visual representation of the interconnected pathways; through which, *Jujube* modulates neuroinflammation, oxidative stress, HPA axis dynamics and mitochondrial integrity in exercise-induced recovery settings.

7. Evidence from Human and Animal Studies

The therapeutic potential of jujube in exercise physiology is increasingly supported by preclinical and clinical evidences. Investigations have investigated its adaptogenic, anxiolytic, antioxidant and anti-inflammatory functions within animal and human models. However, a comprehensive understanding of its translational effect on athletic performance, recovery and psychological resilience needs synthesis of basic and clinical research.

7.1. Preclinical Studies in Sport and Stress Models

Animal studies have set the foundational understanding of *Z. jujuba* bioactivity under stress conditions, including exercise-induced fatigue and oxidative load. In rodent treadmill models, administration of jujube fruit extract (100–200 mg kg^{-1} d^{-1}) significantly prolonged time to exhaustion, improved muscle glycogen retention and decreased serum lactate and CK levels—markers of exercise-induced fatigue and muscle stress [56]. In restraint-stress models simulating psychological stress as a known performance inhibitor, jujube seed extract demonstrated significant anxiolytic and anti-corticosteroid effects via modulation of GABAergic neurotransmission [57]. These findings are critical for athletes, as physical and psychological stress affect central fatigue mechanisms and recovery kinetics. In forced swimming tests, rodents supplemented with jujube showed enhanced antioxidant enzyme activity (e.g., superoxide dismutase and catalase) and decreased lipid peroxidation [58]. This supports the herbal role in combating exercise-induced oxidative stress, potentially improving redox balance post-exercise and preserving mitochondrial efficiency for endurance athletes.

7.2. Clinical Studies on Fatigue, Recovery and Stress Decrease

Although small, human clinical data fit with preclinical evidence. A randomized controlled trial (RCT) carried out on 60 physically active university students investigated the effects of jujube syrup (15 ml d^{-1} for 30 d) on perceived exertion and recovery following high-intensity interval training (HIIT). Results showed significant decreases in post-exercise fatigue (assessed via VAS) and improvements in heart rate recovery and perceived energy [59]. Another double-blind RCT assessed the effect of jujube seed capsules (500 mg twice daily for 8 w) on psychological stress in amateur athletes. Participants reported decreased scores on the depression anxiety stress scales (DASS-21) and improved sleep quality measured via the Pittsburgh sleep quality index (PSQI) [60]. This highlights a dual benefit psychological resilience and physiological recovery central to sport

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performance sustainability. In elderly recreational exercisers, supplementation with jujube extract was associated to decreases in C-reactive protein (CRP) and malondialdehyde (MDA), with increased subjective vitality and exercise enjoyment [61]. These findings highlight the potential for jujube not only in elite athletes but also in aging populations engaging in health-promoting physical activity.

To further consolidate the translational value of Jujube in the exercise physiology domain, Table 1 summarizes key findings from preclinical and clinical studies. These include investigations in rodent models of exercise-induced stress and fatigue, as well as human trials assessing outcomes such as sleep quality, inflammatory status and physical recovery. The table outlines study design, intervention protocols, linked outcomes and limitations, offering a concise overview of the current evidence landscape. This synthesis highlights the potential of jujube as a multifunctional botanical agent in athletic and physically active populations while highlighting the need of targeted RCTs in sport-specific contexts (Table 1).

An integrative overview of Z. jujuba uses with mechanistic, preclinical and human evidences is present in Table 2, highlighting its translational potential in sports nutrition protocols.

Table 1. Summary of preclinical and clinical evidences on jujube in exercise and stress models

Study Type	Population/Model	Intervention	Outcome Measures	Main Findings	Reference
Preclinical	Rodents (treadmill test)	Jujube fruit extract (100–200 mg/kg/day)	Time to exhaustion, lactate, CK	↑ endurance, ↓ fatigue biomarkers	56
Preclinical	Restraint-stressed mice	Jujube seed extract	Corticosterone, anxiety-like behavior	↓ stress, modulated GABAergic activity	57
Preclinical	Forced swimming test (mice)	Jujube extract	SOD, catalase, MDA	↑ antioxidants, ↓ lipid peroxidation	58
Clinical (RCT)	60 active students	Jujube syrup (15 mL/day, 30 days)	Perceived fatigue, HR recovery	↓ fatigue, ↑ recovery	59
Clinical (RCT)	Amateur athletes	Jujube seed capsules (500 mg x2/day)	DASS-21, PSQI	↓ stress, ↑ sleep quality	60
Clinical (Trial)	Elderly exercisers	Jujube extract	CRP, MDA, subjective vitality	↓ inflammation, ↑ exercise enjoyment	61

Table 2. Summary of uses of jujube in sports nutrition based on evidence type

Application Area	Mechanistic Evidence	Preclinical Evidence	Human Evidence
Anti-fatigue effects	↑ ATP, ↓ LA, ↑ mitochondrial function	Animal exercise models	Limited trials in healthy adults
Sleep and neurorecovery	Modulation of GABAergic pathways	Rodent models of sleep deprivation	Pilot trials in sleep quality
Anti-inflammatory support	↓ IL-6, TNF-α; ↑ IL-10	Inflammation-induced animal models	Limited studies in athletes post-exercise
Antioxidant protection	↑ SOD, CAT, GPx	Oxidative stress animal models	Observational reports in traditional use
Immune modulation	↑ lymphocyte proliferation, NK activity	Immunocompromised rodent models	No direct athletic trials
Gastrointestinal recovery	Mucosal protection, microbiota modulation	GI inflammation models	Traditional use and anecdotal evidence

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8. Pharmacological Interactions and Contraindications in Athletes

8.1. Known or Suspected Interactions with Supplements or Medications

Although jujube has widely been used for its beneficial phytochemicals, the potential for pharmacological interactions, particularly in athletic populations using various supplements and medications, should not be underestimated. One of the most documented interactions involves hypoglycemic synergy with antidiabetic agents such as metformin, sulfonylureas and insulin. Several *in vivo* and clinical findings suggest that jujube can significantly decrease blood glucose; thereby, potentially increasing the risk of hypoglycemia when co-administered with these drugs [62–64]. In addition, evidence suggests jujube may include serotonergic activity and when combined with selective serotonin reuptake inhibitors (SSRIs) or serotonin-norepinephrine reuptake inhibitors (SNRIs) such as venlafaxine, it could theoretically enhance side effects such as drowsiness or, in rare cases, contribute to serotonin syndrome [65]. Athletes who consume herbal adaptogens, anxiolytics or sedative supplements (e.g., valerian, melatonin and ashwagandha) may experience additive CNS depressant effects when taking jujube extracts, particularly at high doses [66]. Thus, its concurrent use with sedative medications should be approached cautiously. Table 3 provides a summarized overview of the most linked known or suspected interactions, safety concerns in vulnerable athlete subgroups and recommended strategies for monitoring and risk mitigation.

8.2. Safety in Vulnerable Athletic Populations (e.g., Diabetics and Hypertensive)

In diabetic athletes, jujube glucose-decreasing effects, although potentially beneficial, necessitate strict monitoring. Jujube can improve insulin sensitivity and decrease fasting glucose levels, but in combination with antidiabetic drugs, this dual mechanism may lead to symptomatic hypoglycemia if not closely supervised [63,67]. Hypertensive athletes may encounter risks. Although limited human data are available, preclinical models suggest that jujube exerts mild antihypertensive effects through vasodilation and calcium channel modulation [68]. When consumed in combination with antihypertensive medications such as ACE inhibitors or calcium channel blockers, there is a theoretical risk of excessive blood pressure decrease. Furthermore, case reports have identified rare hypersensitivity reactions to jujube, particularly in individuals with latex-fruit syndrome. Cross-reactivity with plant proteins similar to those in latex can result in allergic responses ranging from urticaria to anaphylaxis [69].

8.3. Recommendations for Monitoring and Risk Modification

To moderate potential risks associated with jujube consumption in athletic populations, the following recommendations are suggested:

- Individualized consultation: All athletes, especially those on chronic medications, should consult sports medicine or pharmacology professionals before using jujube-based supplements [70].
- Close monitoring: Diabetic and hypertensive athletes should regularly be monitored of glycemic and hemodynamic parameters, particularly during the initial weeks of supplementation [71].
- Allergen screening: Athletes with known plant allergies or latex sensitivity should avoid jujube unless verified non-reactive through allergy testing [69].
- Preoperative discontinuation: As a general precaution, jujube should be discontinued at least two weeks prior to surgery due to its potential interactions with anesthesia and glycemic control medications [72].
- Supplement stacking caution: Athletes using polyherbal formulations should avoid stacking multiple adaptogenic or sedative compounds without evidence-based guidance, as the cumulative pharmacodynamics may be unpredictable [66].

Table 3. Potential pharmacological interactions, safety considerations and recommendations regarding jujube consumption in athletes.

Category	Interaction/Concern	Mechanism/Details	Implications for Athletes
Drug Interaction	Hypoglycemic synergy with antidiabetic agents (e.g., metformin, insulin)	Additive effect on decreasing blood glucose	Risk of hypoglycemia; requires glycemic monitoring
Drug Interaction	Potential interaction with SSRIs/SNRIs	Serotonergic effects	May enhance CNS side effects or contribute to serotonin syndrome
Supplement Interaction	Combined use with other sedative herbs (e.g., valerian, melatonin)	Additive CNS depression	Increased drowsiness or impaired cognitive function
Health Risk	Use in diabetics and hypertensives	May alter glucose and blood pressure levels	Requires dosage adjustment and regular monitoring
Allergic Risk	Cross-reactivity in latex-fruit syndrome	Plant protein similarity	Potential allergic reactions including anaphylaxis

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9. Integration into Sport Nutrition and Recovery Strategies

As interest increases in plant-based and functional nutrition to optimize training adaptation and recovery, jujube emerges as a promising candidate for integration into evidence-informed sports nutrition protocols. Its pharmacologically active components, including saponins, flavonoids and polysaccharides, show neuroprotective, anti-inflammatory, antioxidant and adaptogenic characteristics, which fit well with the physiological demands of athletic training and competition. This section provided a detailed overview of practical approaches for incorporating jujube into athletic nutrition strategies.

9.1. Dosing Strategies and Delivery Forms (Capsule, Tea and Extract)

The efficacy of jujube in athletes depends significantly on the form and dose administered. Current evidence suggests that the fruit and seed extracts, when standardized for bioactive compounds such as jujuboside A and flavonoids, exert the most potent effects [73,74]. Common delivery forms include encapsulated dry extract (250–500 mg d^{-1}), aqueous infusions (10–15 g of dried fruit steeped in hot water) and hydroalcoholic extracts in tincture form. Encapsulated forms provide superior dose standardization and user convenience, especially in athletic settings where portability and consistency are critical [75]. In particular, the seed extract is rich in saponins with known central nervous system (CNS) modulating characteristics, making it appropriate for recovery formulations [76]. In contrast, whole fruit consumption while further traditional may offer broader polysaccharide content but lacks precise dosing control. As with several botanical interventions, individualized response and tolerability should guide initial dose titration.

9.2. Timing (Pre-training, Post-exercise and Recovery Periods)

Optimal timing of jujube intake in relation to exercise is still underinvestigated in sport-specific studies. However, extrapolation from available data suggests that pre-training administration may support anxiolysis and autonomic balance, especially in athletes experiencing performance-associated stress [77]. Post-exercise ingestion, with its antioxidant and anti-inflammatory actions, potentially aiding in the attenuation of muscle damage and enhancement of parasympathetic reactivation [78]. Furthermore, integrating jujube into evening recovery routines (e.g., in sleep-support formulations) may leverage its mild sedative effects, promoting restorative sleep and nocturnal hormonal recovery in athletes with high training loads [79]. Its adaptogenic profile may support athletes with overreaching or chronic stress, although this needs further rigorous validation.

9.3. Synergistic Use with Other Botanicals or Functional Foods

The multifunctional profile of jujubelends well to combination protocols with other ergogenic or recovery-enhancing botanicals. For example, co-administration with *Panax ginseng* or *Withania somnifera* (ashwagandha) may amplify adaptogenic effects, supporting HPA-axis modulation and antioxidant defense [80]. Additionally, combination of jujube with *Camellia sinensis* (green tea) catechins or *Curcuma longa* (turmeric) extracts may enhance anti-inflammatory synergy, potentially benefiting athletes recovering from intense eccentric loading or inflammatory injuries [81]. Formulators should address the pharmacokinetic interactions between these compounds, particularly concerning hepatic metabolism via cytochrome P450 enzymes, which may alter the bioavailability of polyphenolic constituents [82]. Despite these concerns, preliminary *in vitro* and clinical studies suggest compatibility and additive benefits when jujube is thoughtfully combined with other functional foods [83].

To facilitate the practical use of jujube within sport nutrition strategies, a sample protocol integrating its use within various training phases is presented in Box 1. This illustrative framework outlines evidence-informed approaches regarding formulation, timing and synergy with other functional ingredients, offering sport scientists and practitioners a translational model for athlete care. This example protocol demonstrates how jujube may be integrated into a structured sport nutrition plan to optimize recovery and physiological resilience in athletes.

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Box 1. Sample Sport Nutrition Protocol Including *Ziziphus jujuba*

• Morning (Pre-training):
- Jujube extract (250–500 mg standardized to jujuboside A) in capsule form, 30–60 min before training, to decrease anticipatory anxiety and support mood stability.
• Post-training (within 30 min):
- Jujube fruit infusion (tea; 5–10 g dried fruit steeped in 300 ml of hot water) consumed warm to promote CNS relaxation and enhance parasympathetic reactivation.
• Evening (Pre-sleep):
- Combined use with tart cherry juice (30 ml) and magnesium glycinate (200 mg) with jujube capsule (250 mg), 60 min before bedtime to promote sleep depth, muscle relaxation and nighttime recovery.
• Weekly recovery days:
- Optional use of Jujube decoction (10 g boiled for 20 min) blended with ashwagandha root tea for adaptogenic recovery support.
Note: Adjustments may be necessary based on athlete body mass, training intensity and individual tolerance. Always consider product standardization and purity in botanical supplements.

Table 4. Practical uses of jujube in sports nutrition based on evidence type

Application Domain	Evidence Type	Suggested Use Case	Notes
Sleep quality and anxiety	Clinical trials, animal models	Pre-sleep supplementation during high-stress phases	Start with low doses (250–500 mg/day); monitor for drowsiness
Inflammation & recovery	Preclinical & human data	Post-training antioxidant support	Combine with curcumin or tart cherry for synergistic effects
Immune modulation	Human & in vitro studies	During competition/travel seasons	Use standardized extract (≥5% saponins)
Glucose & lipid control	Clinical trials	In athletes with metabolic syndrome risk	Avoid if on glucose-decreasing drugs without medical advice
CNS support & cognition	Traditional use, preclinical	Cognitive resilience in overtraining or exam periods	Avoid concurrent CNS depressants

10. Expert Recommendations and Practical Uses

10.1. Guidelines for Sport Nutritionists, Coaches and Practitioners

Regarding increasing body of evidence supporting the health-promoting characteristics of jujube, it is vital that sport nutritionists, coaches and allied practitioners consider its integration into comprehensive training and recovery strategies. Jujube has demonstrated anti-inflammatory, antioxidant, anxiolytic and metabolic modulatory characteristics, which may benefit elite and recreational athletes within a spectrum of physical demands [84,85]. For sport nutritionists, jujube may serve as an adjunctive botanical in athlete diets aimed at modulating oxidative stress, decreasing inflammation and supporting immune health, particularly during periods of high training loads or competition stress. Coaches should be informed about the potential recovery-enhancing effects of jujube such as improvements in sleep quality and decreases in stress-associated biomarkers, which can translate into better training consistency and performance [86]. Practitioners in clinical sport settings should also be aware of contraindications and individual variability in response, necessitating a personalized approach in dosage and timing. Additionally, standardized extract forms with verified bioactive content should be prioritized to ensure consistency and efficacy.

10.2. Practical Dosing and Combination with Supplements

Although there is no universally established dose for athletes, clinical studies and ethnomedicinal sources suggest jujube fruit or extract in doses ranging from 250 mg to 1 g per day for general health benefits [87]. For athletes, decrease doses (250–500 mg d^{-1}) may suffice when used synergistically with other adaptogens or functional ingredients (e.g., curcumin, ashwagandha and tart cherry). Higher doses may be warranted during intense training cycles, recovery periods or in athletes with comorbidities such as insomnia, anxiety and immune suppression. Jujube can be administered as capsule, standardized extract, dried fruit infusion (tea) or powder added to smoothies. For enhanced bioavailability and synergistic actions, jujube could be co-ingested with lipid-based carriers or phospholipids, particularly in soft-gel formulations. Importantly, co-administration with sedatives or CNS depressants should be avoided without medical supervision [88].

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10.3. Summary Table: Uses Based on Evidence Type

To consolidate practical insights, Table 4 summarizes the key uses of *Z. jujuba* in athletic contexts, categorized by the type and strength of available evidence.

11. Conceptual Framework

Based on the evidence synthesized in this review, the authors suggest a novel conceptual framework to guide further translational research and applied practices regarding ***jujube*** in sports nutrition and exercise science. This framework is illustrated in Figure 2, integrating phytochemical characteristics, physiological mechanisms and practical uses within athletic contexts. This framework may serve as a theoretical scaffold for experimental designs, mechanistic studies and translational uses involving herbal ergogenics.

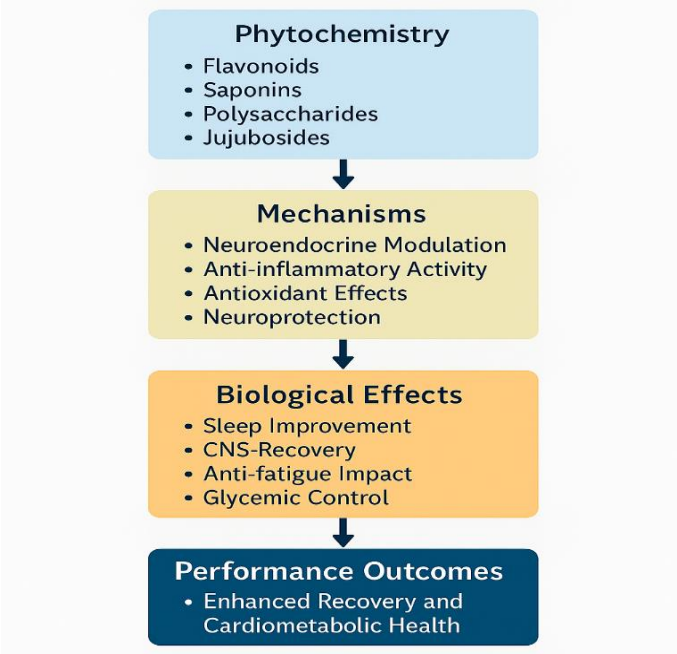


Figure 2. Suggested conceptual framework for the role of ***jujube*** in exercise science and sports nutrition

12. Practical Infographic for Athlete Education

To facilitate knowledge translation and use, the authors designed an infographic summarizing the practical uses of jujube in sports nutrition. This infographic is designed as a knowledge translation tool for practitioners, athletes and researchers interested in herbal strategies for exercise recovery and performance enhancement.

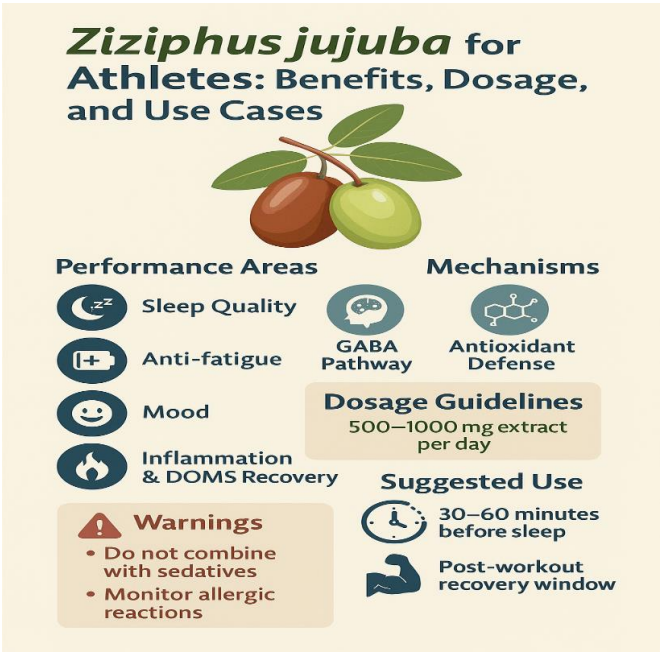


Figure 3. Educational infographic summarizing the relevance of jujube in sports nutrition and exercise science

13. Challenges, Gaps and Future Perspectives

13.1. Lack of Sport-Specific Research

Despite the growing interest in natural compounds for enhancing exercise performance and recovery, there is a significant paucity of sport-specific research regarding jujube. The current literature is predominantly preclinical or based on general wellness populations, offering a limited insight into the compound efficacy within athletic contexts. Most studies have failed to stratify participants by sport type, training level or physiological demand; thereby, limiting the translatability of findings to competitive or recreational athletes. The lack of RCTs targeting athletes under real-world training conditions creates a gap in understanding jujube potential for aiding muscle recovery, enhancing endurance or lessening exercise-induced stress. Further investigations should focus on developing athlete-specific protocols to investigate its ergogenic and adaptogenic characteristics within a variety of sporting disciplines.

13.2. Standardization of Extracts and Bioactive Content

One of the primary limitations in the current evidence base is the inconsistency in the composition of jujube preparations used in studies. Variability in the part of the plant used (e.g., fruit, seed and bark), extraction methods and bioactive concentration significantly inhibits cross-study comparison and meta-analytic synthesis. Moreover, several commercial products lack transparency regarding the levels of key bioactive compounds such as saponins, flavonoids and polysaccharides. Without standardized

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extracts, it is challenging to set effective dosing regimens or ensure reproducibility within clinical trials. Therefore, advancing pharmacognostic and phytochemical profiling techniques is essential for the reliable identification and quantification of active components. Establishing reference standards and good manufacturing practice (GMP) compliance in supplement production greatly enhances scientific validity and clinical utility.

13.3. Roadmap for Further Clinical Trials and Mechanistic Studies

To position jujube as a credible adjunct in sports nutrition and recovery, further research must adopt a multidisciplinary phase-specific approach. Early-phase studies should prioritize pharmacokinetics, safety profiling and bioavailability assessments in physically active populations. Mid and late-phase RCTs should then assess functional outcomes, including delayed onset muscle soreness (DOMS), inflammation markers, mental fatigue and performance metrics such as VO_2max and lactate threshold. Mechanistic studies investigating molecular targets such as HPA axis modulation, oxidative stress pathways and mitochondrial biogenesis are critical for explaining how Jujube mediates physiological benefits under exercise-induced stress. Integration with omics technologies (e.g., metabolomics and transcriptomics) can further identify biomarkers of response and personalize supplementation strategies. Moreover, forming interdisciplinary research consortia involving exercise scientists, phytochemists, nutritionists and clinical practitioners is a key in translating preclinical promise into sport-specific interventions that are safe, effective and regulatory compliant.

13.4. Suggestion for "Herbal Performance Index" (HPI)

Despite the growing interest in herbal supplements such as ***jujube***, there is currently no standardized framework to quantify or compare their effectiveness in sports performance contexts. To address this gap, the authors suggest conceptual development of a herbal performance index (HPI), a multidimensional scoring system designed to assess the ergogenic potential of herbal compounds. This index integrates mechanistic evidence (e.g., anti-inflammatory, antioxidant and mitochondrial modulation pathways) and applied outcomes (e.g., improvements in endurance, strength, recovery time, mood and immune function). Weighted scoring can be assigned based on levels of evidence (preclinical against clinical), dose standardization, bioavailability, safety profiles and reproducibility of findings within populations. Further research can validate and refine this index through Delphi consensus by experts in exercise science, pharmacognosy and sports nutrition. Development of such an index not only enhances scientific rigor but also guides practitioners, athletes and policymakers in selecting evidence-based phytotherapeutic interventions.

14. Conclusion

Jujube represents a phytochemical-rich botanical with multifaceted physiological potentials linked to the domain of sports and exercise science. Its rich profile of flavonoids (e.g., quercetin and kaempferol), triterpenic acids, saponins and polysaccharides highlights a range of anti-inflammatory, antioxidant, anxiolytic and immune-modulatory characteristics that can potentially support athletes during training and recovery phases. Emerging data suggest its capacity to attenuate oxidative damage induced by exhaustive exercise, lessen muscle soreness and optimize sleep quality an often-overlooked critical factor in athletic performance. Animal and early human studies also hint at the adaptogenic and neuroprotective effects of jujube potentially contributing to cognitive resilience under physical and psychological stresses. The fruit's low allergenic profile within its compatibility with a variety of delivery forms such as capsule, tea and extract makes it a viable candidate for tailored sports nutrition protocols. Despite promising biological data, the translational leap into athletic populations is still largely theoretical. There is a significant lack of RCTs specifically investigating the effects of jujube in exercise contexts. This limits its current clinical use to a complementary or exploratory role within individualized recovery regimens. Nevertheless, its safety profile, accessibility and potential synergism with established interventions such as tart cherry, ashwagandha and omega-3 open a door to well-structured, multi-targeted strategies for recovery and stress modulation. Guidance for practitioners includes cautious initiation with standardized extracts, ideally in collaboration with sports nutritionists to monitor outcomes and minimize interferences. Integration into post-exercise or evening recovery windows may be most efficacious, especially when addressing inflammation, muscle fatigue and sleep disruptions.

It is the time for sports scientists, nutritionists and clinical exercise physiologists to consider jujube as a novel evidence-informed adjunct in the ongoing quest to optimize athletes health and performance. While further mechanistic and clinical trials are urgently needed, the current data provide a strong conceptual and empirical foundation. Further investigations should aim to establish bioavailability dynamics, identify sport-specific adaptations and define optimal doses in athletes populations. In the era of precision recovery, botanicals such as jujube deserve high ranks in integrative exercise medicine.

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During the preparation of this manuscript, AI-based digital tools were used to support language refinement and the generation of scientific visuals. These tools served solely as auxiliary aids and all scientific contents and interpretations are the responsibility of the authors.

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