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Fuellingthe aquatic athlete: A review of nutritional interventions for swim performance and recovery

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Abstract

Competitive swimming places extraordinary demands on athletes, who often train twice daily and must fuel both explosive anaerobic efforts and prolonged aerobic work within tightly compressed recovery windows. Nutrition has emerged as one of the few performance levers directly under an athlete's control, yet swim-specific guidance has historically lagged behind that developed for running and cycling. This narrative review synthesizes current evidence on nutritional interventions relevant to two interconnected outcomes in competitive swimmers: race performance and post-exercise muscular regeneration. Peer-reviewed studies, systematic reviews, meta-analyses, and position stands published between 2012 and 2025 were identified through PubMed, Scopus, and Google Scholar and synthesized narratively around macronutrient foundations (carbohydrate availability and nutrient-timed protein intake) and five well-evidenced ergogenic compoundscreatine monohydrate, beta-alanine, sodium bicarbonate, caffeine, and L-arginine/L-citrulline alongside two culturally accessible, food-based options of particular relevance to Indian swimmers, ashwagandha and beetroot. The evidence indicates that each intervention acts on a distinct physiological bottleneck, from phosphagen resynthesis and intramuscular buffering to central fatigue perception and vascular oxygen delivery, such that supplementation strategies are most effective when matched to event distance and training phase rather than applied uniformly. Important gaps remain, including small sample sizes, heterogeneous dosing protocols, and extrapolation from resistance-trained or mixed-endurance populations rather than swimmers themselves. Overall, the review supports a periodized, individualized approach to swim nutrition that layers macronutrient strategy with targeted, event-specific ergogenic support to optimize both performance and recovery across a demanding competitive season.

Keywords: Creatine, beta-alanine, sodium bicarbonate, caffeine, L-arginine, and L-citrulline

Introduction

Competitive swimming is a sport defined by margins of hundredths of a second, in which the difference between a podium finish and elimination often comes down to variables that athletes and coaches can directly control. Among these, nutrition occupies a uniquely influential position, shaping not only the energy available for a single race but also the swimmer's capacity to absorb weeks of high-volume, mixed aerobic-anaerobic training and to recover from its session after session (Huang *et al.*, 2025) [2]. Unlike land-based sports, swimming imposes a distinctive physiological and logistical profile: athletes frequently train twice daily, contend with substantial thermoregulatory and fluid-balance demands in the heated pool environment, and must fuel both explosive sprint efforts and prolonged aerobic sets within the same training block (Shaw *et al.*, 2014) [5]. This combination of high training load and narrow performance margins makes swimming an ideal, and arguably urgent, context in which to examine how targeted nutritional strategies can be used to enhance performance and accelerate muscular regeneration.

Historically, sports nutrition research directed at swimmers lagged behind that for running and cycling, in part because open-water buoyancy and reduced mechanical loading were assumed to blunt the muscle damage and glycogen depletion responses seen in weight-bearing sports. More recent work has challenged this assumption, demonstrating that swimmers experience meaningful glycogen depletion, exercise-induced muscle damage, and cumulative fatigue across a training week, particularly during in-season periods characterized by high yardage and frequent race-pace efforts (Burke &Mujika, 2014) [1]. Because swim training macrocycles vary considerably in volume and intensity across a season, from taper phases to high-volume aerobic blocks, nutrition requirements are not static; rather, they must be periodized alongside training load to support the shifting balance between fueling performance and promoting adaptation (Shaw *et al.*, 2014) [5]. This periodized view of nutrition has become a cornerstone of contemporary sports nutrition guidance and provides the conceptual backbone for the present review.

Two nutritional pillars dominate the literature on swim performance and recovery: carbohydrate availability and protein intake. Carbohydrate remains the primary fuel for the high-intensity efforts that characterize competitive swimming, and insufficient carbohydrate availability has been linked to impaired training quality, elevated perceived exertion, and blunted adaptive responses to training (Shaw *et al.*, 2014) [5]. At the same time, protein intake, particularly when strategically distributed throughout the day and around key training sessions, is now understood to be central to muscle protein synthesis, the repair of exercise-induced muscle damage, and the maintenance of lean mass throughout a demanding season (Jäger *et al.*, 2017). The International Society of Sports Nutrition has further emphasized that the timing and composition of nutrient intake, rather than total daily amounts alone, can meaningfully influence recovery, tissue repair, and mood state following high-volume or high-intensity training (Kerksick *et al.*, 2017) [3]. For swimmers, whose training schedules often compress recovery windows between morning and afternoon sessions, these nutrient-timing principles carry particular practical weight.

Beyond these macronutrient foundations, a substantial and growing body of research has examined ergogenic aids and dietary supplements as adjuncts to swim-specific training. Compounds such as creatine, beta-alanine, sodium bicarbonate, caffeine, L-arginine, and L-citrulline have each been investigated for their potential to enhance sprint performance, buffer metabolic acidosis, or support post-exercise recovery (Wang *et al*., 2023) [6]. A recent systematic review and network meta-analysis synthesizing data from 58 randomized trials found that L-arginine produced the largest improvement in 100 m swimming time relative to placebo, that beta-alanine was most effective for reducing blood lactate accumulation, and that creatine combined with sodium bicarbonate produced the greatest increase in blood pH, a marker of enhanced buffering capacity during high-intensity efforts (Huang *et al*., 2025) [2]. These findings illustrate both the promise and the specificity of nutritional ergogenic aids: different supplements appear to target distinct physiological bottlenecks, meaning that a one-size-fits-all supplementation strategy is unlikely to be optimal for every swimmer or every event distance.

Despite this expanding evidence base, important gaps and inconsistencies remain. Many of the trials underpinning current recommendations involve small sample sizes, heterogeneous dosing protocols, and short supplementation windows, limiting the strength of conclusions that can be drawn for elite, event-specific populations (Huang *et al*., 2025) [2]. Furthermore, much of the foundational nutrient-timing and protein literature has been generalized from resistance-trained or mixed-endurance populations rather than derived specifically from swimmers, raising questions about the direct applicability of these guidelines to the unique demands of aquatic training environments (Jäger *et al*., 2017). Questions also persist regarding how best to sequence carbohydrate and protein intake around two-a-day training sessions, how to individualize supplementation strategies by event distance and training phase, and how nutrition interacts with other recovery modalities such as sleep, hydrotherapy, and active recovery.Given these considerations, this review aims to synthesize the current evidence on nutritional interventions for competitive swimmers, with particular attention to two interconnected outcomes: swim performance and muscle regeneration.

Methodology

This paper adopts a narrative review design, appropriate for synthesizing a heterogeneous evidence base spanning macronutrient physiology, ergogenic aids, and food-based adaptogens, rather than for generating a single pooled effect estimate. A narrative approach was selected because the relevant literature spans multiple methodological traditions, including mechanistic physiology, randomized controlled trials, systematic reviews, network meta-analyses, and professional position stands that do not lend themselves to formal meta-analytic pooling within a single manuscript (Huang *et al*., 2025) [2].

A structured literature search was conducted across PubMed, Scopus, Web of Science, and Google Scholar for publications from January 2012 to mid-2025. Search terms combined swimming-specific keywords (“swim*”, “aquatic athlete”, “competitive swimmer”) with nutrition- and recovery-related terms (“nutrition”, “ergogenic aid”, “dietary supplement”, “protein timing”, “carbohydrate availability”, “muscle damage”, “recovery”) and the names of individual compounds of interest, including creatine, beta-alanine, sodium bicarbonate, caffeine, L-arginine, L-citrulline, ashwagandha, and beetroot/nitrate. Reference lists of retrieved systematic reviews and meta-analyses, particularly the 58-trial network meta-analysis by Huang *et al*. (2025) [2], were hand-searched to identify additional primary studies and position stands not captured by the initial search.

Results

Beyond whole-food and culturally rooted strategies, a smaller set of isolated dietary supplements has accumulated the strongest and most consistent evidence base in competitive swimming and closely related high-intensity sports. Each of the following five compounds acts on a distinct physiological pathway relevant to the repeated high-intensity efforts, metabolic acidosis, and recovery demands that define swim training and competition.

1. **Creatine Monohydrate:** Creatine is among the most extensively researched ergogenic aids in sports nutrition and works by increasing intramuscular concentrations of phosphocreatine, the substrate used to rapidly regenerate adenosine triphosphate (ATP) during short, high-intensity efforts via the creatine kinase/phosphocreatine energy shuttle (Kreider *et al*., 2017) [17]. Because swim races and race-pace training sets rely heavily on this phosphagen system, particularly starts, turns, and sprint finishes, an expanded phosphocreatine pool allows swimmers to sustain higher power output across repeated efforts before fatigue sets in. The International Society of Sports Nutrition's position stand concludes that creatine supplementation reliably improves high-intensity exercise capacity and training adaptations, while also noting benefits for post-exercise recovery through enhanced glycogen resynthesis and reduced markers of muscle damage (Kreider *et al*., 2017) [17]. Within swimming specifically, network meta-analytic data have identified creatine, particularly when combined with sodium bicarbonate, as producing the largest improvements in blood pH following high-intensity swimming efforts, reflecting its role in supporting anaerobic energy provision during interval-based training (Huang *et al*., 2025) [2].

2. **Beta-Alanine:** Beta-alanine is a non-essential amino acid that serves as the rate-limiting substrate for the synthesis of carnosine, an intramuscular dipeptide that buffers hydrogen ions produced during anaerobic glycolysis (Saunders *et al*., 2017) [23]. During high-intensity swimming efforts lasting roughly 30 seconds to ten minutes, a range that captures most competitive swim events, glycolytic metabolism generates hydrogen ions that lower muscle pH and impair the contractile machinery, contributing to fatigue. By elevating muscle carnosine content, chronic beta-alanine supplementation (typically 4-6 g/day over several weeks) extends the muscle's buffering capacity, delaying the onset of acidosis-related fatigue (Saunders *et al*., 2017) [23]. A comprehensive meta-analysis spanning 40 studies confirmed that beta-alanine's ergogenic effect is greatest for exercise in this

intermediate duration range, directly overlapping with swim race distances from 100 m to 400 m (Saunders *et al*., 2017) [23]. Consistent with this mechanism, a recent network meta-analysis in competitive swimmers identified beta-alanine as the most effective intervention for reducing post-exercise blood lactate accumulation, reinforcing its buffering role during repeated high-intensity swim sets (Huang *et al*., 2025) [2].

3. **Sodium Bicarbonate:** Whereas beta-alanine buffers hydrogen ions inside the muscle cell, sodium bicarbonate works extracellularly by increasing blood bicarbonate concentration and pH, which widens the pH gradient across the muscle membrane and facilitates greater efflux of hydrogen ions and lactate out of working muscle during high-intensity exercise (Huang *et al*., 2025) [2]. This enhanced buffering capacity is particularly relevant to swimming's characteristic combination of high-intensity intervals and closely spaced repeated efforts, where incomplete recovery between bouts causes progressive acidosis. Meta-analytic evidence indicates that sodium bicarbonate supplementation confers ergogenic benefits for middle-distance swimming efforts, though effects are less consistent for very short sprints where anaerobic alactic (phosphagen) metabolism dominates rather than glycolysis (Grgic&Mikulic, 2022) [11]. Notably, the combination of creatine and sodium bicarbonate has been shown to produce synergistic effects, with creatine supporting rapid ATP resynthesis through the phosphagen system while sodium bicarbonate mitigates the resulting metabolic acidosis, together producing the largest observed increase in post-exercise blood pH among all nutritional interventions tested in competitive swimmers (Huang *et al*., 2025) [2].

4. **Caffeine:** Caffeine is a central nervous system stimulant that acts primarily as a non-selective antagonist of adenosine receptors in the brain, reducing the perception of effort and fatigue while also enhancing motor unit recruitment and excitation-contraction coupling within skeletal muscle (Guest *et al*., 2021) [12]. These combined central and peripheral mechanisms translate into improvements in both endurance capacity and short-duration, high-intensity performance, making caffeine one of the few supplements with evidence supporting benefit across the full spectrum of competitive swim distances. The International Society of Sports Nutrition position stand recommends doses of approximately 3-6 mg/kg body mass, typically ingested 60 minutes before exercise, noting that alternative delivery methods such as caffeinated gum or mouth rinses can also enhance performance, which may be practical for swimmers seeking to avoid gastrointestinal discomfort before racing (Guest *et al*., 2021) [12]. A meta-analysis specific to swimming performance further confirmed that caffeine ingestion improves swim time trial performance, with effects observed across sprint and middle-distance events (Grgic, 2022) [10].

5. **L-Arginine and L-Citrulline:** These amino acids serve as substrates for nitric oxide (NO) synthesis, a signaling molecule that promotes vasodilation, increases blood flow and oxygen delivery to working muscle, and enhances mitochondrial efficiency during exercise (Huang *et al*., 2025) [2]. Because citrulline is converted to arginine in the kidneys and bypasses the extensive hepatic first-pass metabolism that limits oral arginine's bioavailability, citrulline supplementation often produces more consistent elevations in circulating NO precursors. In a network meta-analysis of competitive swimmers, arginine supplementation produced the largest reduction in 100 m swimming time relative to placebo among all nutritional interventions studied, with citrulline showing the second-largest benefit, both attributed to enhanced oxygen delivery and delayed fatigue during high-intensity efforts (Huang *et al*., 2025) [2]. Beyond acute performance, arginine supplementation has also been linked to favorable hormonal responses during recovery, including increased growth hormone and reduced cortisol, suggesting a secondary role in supporting post-exercise regeneration (Moosakhani *et al*., 2018) [18].

Ashwagandha (Withaniasomnifera): Ashwagandha is a foundational herb in Ayurvedic medicine, classified as an adaptogen for its capacity to modulate the body's physiological response to stress. Its bioactive constituents, primarily steroidal lactones known as withanolides, are believed to act on the hypothalamic-pituitary-adrenal axis, helping to regulate cortisol output while also exerting direct antioxidant and anti-inflammatory effects at the muscular level (Choudhary *et al*., 2015) [8]. In a randomized, double-blind, placebo-controlled trial in healthy athletic adults, eight weeks of ashwagandha root extract supplementation produced a statistically significant increase in VO2max relative to placebo, alongside improved recovery-stress questionnaire scores and elevated antioxidant status (Choudhary *et al*., 2015) [8]. A subsequent systematic review and meta-analysis confirmed these findings across multiple trials, reporting a pooled VO2max improvement of approximately 4.09 mL/kg/min in athletes supplementing with ashwagandha compared to placebo (Jayawardena *et al*., 2025) [14]. For swimmers, whose performance is heavily dependent on aerobic capacity and whose training load imposes chronic physiological stress, ashwagandha's dual action on cardiorespiratory fitness and stress-recovery balance is particularly relevant.

Beetroot: Beetroot, consumed widely in Indian households as a vegetable, juice, or salad component, is one of the richest dietary sources of inorganic nitrate. Once ingested, nitrate is converted via the enterosalivary circulation into nitrite and subsequently into nitric oxide (NO), a potent vasodilator that improves blood flow and oxygen delivery to working muscle while also enhancing mitochondrial efficiency and reducing the oxygen cost of submaximal exercise (Huang *et al*., 2025) [2]. This mechanism is directly relevant to swimming, where efficient oxygen utilization during repeated high-intensity efforts can meaningfully affect race outcomes. In a controlled trial involving competitive swimmers, beetroot juice supplementation improved the aerobic response during a standardized swimming protocol, supporting its role as a practical, food-based ergogenic aid (Pinna *et al*., 2014) [20]. Beetroot's SUCRA-ranked benefit for reducing heart rate observed in recent network meta-analytic work further reinforces its relevance as a low-cost, culturally familiar nitrate source for Indian swimmers seeking to optimize aerobic efficiency (Huang *et al*., 2025) [2].

Table 1: Supplementsand their Mechanism on Performance and Recovery

Supplement	Main mechanism	↑ Increase	↓ Decrease
Creatine	ATP-PCrresynthesis	Power, strength, repeated-sprint ability	CK, some muscle-damage markers
Beta-Alanine	Muscle buffering	High-intensity capacity, exercise tolerance	Fatigue/acidosis-related fatigue
Sodium Bicarbonate	Extracellular buffering	Blood bicarbonate, high-intensity performance	H^+ accumulation
Caffeine	Adenosine receptor antagonism	Alertness, endurance, power	RPE/fatigue
L-Citrulline + Arginine	Nitric oxide production	NO availability, blood flow	Fatigue/RPE*
Ashwagandha	Adaptogenic/antioxidant effects	Strength, endurance capacity*	Stress/fatigue*
Beetroot	Dietary nitrate → NO	Exercise efficiency, endurance	O_2 cost/RPE*

Collectively, these supplements target complementary physiological bottlenecks that constrain swim performance: phosphagen energy provision (creatine), intramuscular pH buffering (beta-alanine), extracellular pH buffering (sodium bicarbonate), central and peripheral fatigue perception (caffeine), and vascular oxygen delivery (arginine/citrulline). Because their mechanisms are largely independent rather than redundant, evidence suggests that swimmers and coaches may derive the greatest benefit by matching specific supplements to the metabolic demands of the events and training blocks being targeted, rather than adopting a single universal supplementation strategy.

Discussion

Taken together, the findings summarized above indicate that no single nutritional intervention addresses the full spectrum of demands imposed by competitive swimming. Creatine and sodium bicarbonate act synergistically on the phosphagen and extracellular buffering systems that underlie starts, turns, and sprint finishes, producing the largest observed gains in post-exercise blood pH among the compounds studied (Huang *et al*., 2025) [2]. Beta-alanine, by contrast, exerts its greatest benefit through intramuscular carnosine buffering across the 100–400 m range, where sustained glycolytic flux rather than phosphagen depletion is the dominant limiter (Saunders *et al*., 2017) [23]. Caffeine's combined central and peripheral mechanisms make it the most broadly applicable single compound, with demonstrated benefit across sprint and middle-distance events alike (Guest *et al*., 2021; Grgic, 2022) [10, 12], while L-arginine and L-citrulline appear most relevant where oxygen delivery and repeated-effort tolerance, rather than acid–base buffering, constrain performance (Huang *et al*., 2025) [2]. This pattern of largely non-overlapping mechanisms — phosphagen resynthesis, intramuscular buffering, extracellular buffering, central fatigue perception, and vascular oxygen delivery — is the central practical insight of the present review: rather than adopting a blanket supplementation protocol, coaches and swimmers are better served by mapping specific compounds onto the metabolic profile of the event and training phase being targeted.

Beyond isolated compounds, food-based and adaptogenic strategies offer a complementary, lower-cost route to some of the same physiological endpoints. Beetroot's nitrate-driven improvement in aerobic efficiency (Pinna *et al*., 2014) [20] and ashwagandha's dual action on cardiorespiratory capacity and stress-recovery balance (Choudhary *et al*., 2015; Jayawardena *et al*., 2025) [8, 14] are particularly relevant in the Indian context, where both are inexpensive, culturally familiar, and readily incorporated into an athlete's regular diet rather than requiring a discrete supplementation protocol. Other whole-food and nutraceutical adjuncts reported in the broader sports nutrition literature — including curcumin and turmeric for attenuating exercise-induced muscle damage (Clayton *et al*., 2023; Popescu-Radu *et al*., 2024) [9, 21], probiotic supplementation for recovery and gastrointestinal tolerance during heavy training (Salarkia *et al*., 2013; Shirkoohi *et al*., 2025) [22, 25], and carbohydrate-dense whole foods such as bananas as a practical alternative to engineered sports drinks (Nieman *et al*., 2012) [19] — point toward a broader ecosystem of accessible, food-first recovery strategies that merit direct investigation in swimmers specifically, given that most of this evidence currently derives from other sports.

From a practical standpoint, the periodized view of nutrition articulated in the introduction (Shaw *et al*., 2014) [5] extends naturally to supplementation: creatine loading and beta-alanine's saturation-dependent benefit (typically requiring several weeks of 4–6 g/day dosing) make both compounds better suited to base and pre-competition phases than to acute race-week use, whereas caffeine and sodium bicarbonate can be deployed acutely on race day itself (Kreider *et al*., 2017; Saunders *et al*., 2017; Guest *et al*., 2021) [12, 17, 23]. Protein distribution across the compressed recovery windows between morning and afternoon sessions, and around the two-a-day training structure typical of competitive swimming, remains an area where nutrient-timing principles developed largely in resistance-trained populations (Jäger *et al*., 2017; Kerksick *et al*., 2017) [3] require swim-specific validation rather than direct extrapolation.

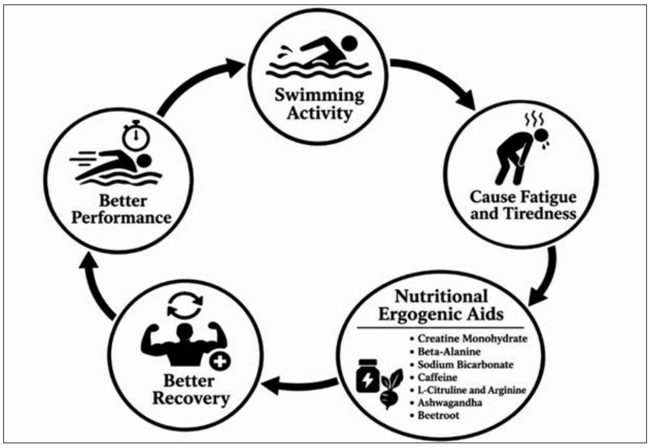

Fig 1: Illustration of the Study

Several limitations qualify these conclusions. Much of the strongest evidence for individual ergogenic aids derives from small trials with heterogeneous dosing protocols and short supplementation windows, limiting confidence in effect sizes for elite, event-specific populations (Huang *et al.*, 2025) [2]. Foundational protein and nutrient-timing guidance is frequently generalized from resistance-trained or mixed-endurance athletes rather than swimmers, whose thermoregulatory, fluid-balance, and two-a-day training demands differ meaningfully from land-based sports (Jäger *et al.*, 2017; Shaw *et al.*, 2014) [3, 5]. Finally, few studies have examined how nutritional strategies interact with other recovery modalities — sleep, hydrotherapy, and active recoverythat swimmers commonly use alongside dietary interventions, leaving an important gap in understanding the combined, rather than isolated, effect of recovery practices on adaptation across a training season.

Implications

The findings of this review indicate that nutrition should be integrated into the overall training and recovery plan of competitive swimmers. Adequate carbohydrate availability and strategically distributed protein intake should form the nutritional foundation, while supplementation should be individualized according to event distance, training phase, and specific performance demands. Creatine, beta-alanine, sodium bicarbonate, caffeine, and L-arginine/L-citrulline may provide targeted benefits through different physiological mechanisms, whereas beetroot and ashwagandha offer potentially accessible food-based and traditional options. However, these interventions should complement rather than replace a balanced diet and appropriate recovery practices.

Recommendations

Future nutritional planning for competitive swimmers should adopt an individualized and periodized approach, with carbohydrate, protein, and supplementation strategies adjusted according to training load, event characteristics, and competition phase. Athletes should evaluate the tolerance and effectiveness of supplements during training before their use in competition. Coaches and sports nutrition professionals should also consider nutrition alongside hydration, sleep, and other recovery strategies. Further research should prioritize adequately powered, swimmer-specific trials using standardized supplementation protocols and realistic training conditions, with particular attention to nutrient timing around twice-daily training sessions and the combined effects of nutrition and other recovery modalities.

Conclusion

Competitive swimming’s combination of high training volume, compressed recovery windows, and narrow performance margins makes nutrition one of the most actionable levers available to athletes and coaches. The evidence reviewed here indicates that carbohydrate availability and strategically timed protein intake remain the foundation of swim nutrition, while a small set of ergogenic compounds — creatine, beta-alanine, sodium bicarbonate, caffeine, and L-arginine/L-citrulline — offer targeted, mechanistically distinct benefits for specific event distances and training phases. Food-based and adaptogenic options such as beetroot and ashwagandha extend these benefits through accessible, culturally familiar means, particularly relevant for Indian swimmers. Because no single intervention addresses every physiological bottleneck swimmers encounter, the most effective approach is likely to be individualized and periodized, matching specific nutritional strategies to event distance, training phase, and the swimmer’s own recovery needs rather than applying a uniform protocol. Future research should prioritize swim-specific trials with adequate sample sizes and realistic training loads, closer examination of nutrient sequencing around two-a-day sessions, and investigation of how nutrition interacts with other recovery modalities, to translate the current evidence base into more precise, event-specific guidance for competitive swimmers.

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