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The effect of carbohydrate loading on physical performance and adaptations in amateur sports enthusiasts: A systematic review

Pengaruh carbohydrate loading terhadap performa dan adaptasi fisik pada atlet amatir: Suatu tinjauan sistematis

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Abstract

Background: Carbohydrate loading (CL) increases muscle glycogen reserves before intense physical activity. While CL has been shown to be beneficial for elite athletes, the metabolic capacity and activity duration of amateur and recreational athletes are variable. As sports nutrition guidelines for amateur athletes vary, especially regarding CL indications, duration, and dose, this variance has practical and therapeutic ramifications.
Objectives: This study aimed to systematically review the effects of carbohydrate loading on the physical performance and adaptation of amateur sports enthusiasts.
Methods: This systematic review was conducted following the PRISMA 2020 guidelines. We searched PubMed, ScienceDirect, ProQuest, and Google Scholar for publications from 2005 to 2025. Experimental or randomized controlled trials of high-carbohydrate diets in non-elite athletes were included in this review. Two reviewers independently selected the articles, and a third reviewer resolved any disagreements. VO2max, time to exhaustion, race results, and metabolic responses were all recorded. The risk of bias and study quality were assessed using the Cochrane Risk of Bias 2.0 and the NIH Quality Assessment Tools.
Results: Seven studies were included in the analysis. Five trials found that carbohydrate loading improved endurance and glucose stability and reduced fatigue. Events lasting > 90 min showed the greatest performance gains. Short-term and moderate-intensity activities had no meaningful impact on the two studies. These differences may have been caused by differences in training, glycogen storage, and diet.
Conclusion: Carbohydrate loading improves endurance performance and metabolic efficiency, particularly during long-duration exercise. However, inter-individual heterogeneity emphasizes the need for tailored carbohydrate regimens to maximize athletic performance in endurance sports.

Keywords:
Carbohydrate loading, amateur athletes, endurance, glycogen, performance

Abstrak

Latar belakang: Pemuatan karbohidrat (CL) meningkatkan cadangan glikogen otot sebelum aktivitas intensif. Atlet elit telah menunjukkan manfaatnya, namun kapasitas metabolik dan durasi aktivitas atlet amatir dan rekreasional bervariasi. Karena pedoman nutrisi olahraga atlet amatir bervariasi, terutama terkait indikasi, durasi, dan dosis CL, variasi ini memiliki implikasi praktis dan terapeutik.
Tujuan: Studi ini bertujuan untuk melakukan tinjauan sistematis terhadap efek pemuatan karbohidrat pada kinerja fisik dan adaptasi pada penggemar olahraga amatir.
Metode: Ulasan sistematis ini mengikuti pedoman PRISMA 2020. PubMed, ScienceDirect, ProQuest, dan Google Scholar dicari untuk publikasi tahun 2005–2025. Studi eksperimental atau uji coba terkontrol acak tentang diet tinggi

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karbohidrat pada atlet non-elit memenuhi syarat. Dua peninjau memilih artikel secara terpisah, dengan peninjau ketiga menyelesaikan perselisihan. VO_2max, waktu hingga kelelahan, hasil balapan, dan respons metabolik diekstraksi. Risiko bias dan kualitas studi dievaluasi menggunakan Cochrane Risk of Bias 2.0 dan NIH Quality Assessment Tools.
Hasil: Tujuh studi memenuhi syarat. Lima uji coba menemukan bahwa pemuatan karbohidrat meningkatkan daya tahan, stabilitas glukosa, dan penundaan kelelahan. Acara yang berlangsung lebih dari 90 menit menunjukkan peningkatan kinerja terbesar. Aktivitas jangka pendek dan intensitas sedang tidak memiliki dampak berarti dalam dua penelitian. Perbedaan ini mungkin disebabkan oleh latihan, penyimpanan glikogen, dan makanan.
Kesimpulan: Daya tahan dan efisiensi metabolik atlet amatir meningkat dengan pemuatan karbohidrat, terutama selama aktivitas berdurasi panjang. Namun, heterogenitas antarindividu menyoroti kebutuhan akan regimen karbohidrat yang disesuaikan untuk memaksimalkan kinerja atletik.

Kata Kunci:
Pemuatan karbohidrat, atlet amatir, daya tahan, glikogen, kinerja

Introduction

Endurance exercise requires a sustained energy supply, and carbohydrate loading remains a widely used nutritional strategy to enhance performance by increasing glycogen availability in the skeletal muscle and liver prior to competition (Jeukendrup, 2017). Glycogen plays a central role in supporting high-rate energy production during prolonged exercise, delaying fatigue, and improving the capacity to maintain exercise intensity, particularly in events lasting longer than 90 min (Thomas et al., 2016). Consequently, carbohydrate loading has been incorporated into endurance sports as an evidence-based approach to optimize performance.

Nevertheless, physiological responses to carbohydrate loading are not uniform and may differ considerably between trained athletes and individuals who are unaccustomed to endurance training (Pesta et al., 2025). These differences are likely influenced by variability in glucose handling, baseline glycogen reserves, and metabolic capacity, which may affect the magnitude of performance benefits after carbohydrate loading (Zierath et al., 2025; Phielix et al., 2019).

In addition, the effectiveness of carbohydrate loading may depend on the training load and recovery status (Zanini et al., 2021). Excessive training without adequate recovery has been associated with impaired glucose tolerance and reduced metabolic adaptation, which may limit the expected performance benefits, even in endurance-trained individuals (Flockhart et al., 2021). These maladaptive responses have also been linked to functional overreaching and overtraining syndrome, both of which may adversely affect performance and metabolic health (Ostojic et al., 2021).

Despite the widespread implementation of carbohydrate loading, evidence remains insufficient to determine the conditions under which this strategy consistently produces performance benefits in amateur athletes, particularly across varying metabolic profiles and exercise durations.

The novelty of this review lies in its exclusive focus on amateur athletes, considering their metabolic status and the duration of their activities. This study aimed to systematically review the effects of carbohydrate loading on the physical performance and adaptation of amateur sports enthusiasts

Methods

Study Design

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines (2020). This protocol aims to identify, appraise, and synthesize existing evidence regarding the effects of carbohydrate loading and high-carbohydrate dietary interventions on exercise performance in amateur and recreational athletes.

Search Strategy

A comprehensive literature search was conducted across PubMed, ProQuest, ScienceDirect, and Google Scholar without restrictions on the publication year (all years). The final search was performed on October 3, 2025. The search terms were developed using relevant keywords and Boolean operators related to the population, intervention, and outcomes of interest. The search strategies were as follows: PubMed and ProQuest: (recreational athletes or amateur athletes) AND "Carbohydrate loading" AND (exercise performance or endurance or exercise capacity or time to exhaustion); ScienceDirect: ((carbohydrate) AND (sport) AND (endurance) AND (amateur) AND (glucose)); and Google Scholar: (" amateur athlete" or "endurance sports" or "sports enthusiasts" or "amateur runners" or "long duration sports") AND ("Carbohydrate loading " or "high carbohydrate supplementation") AND (" normal diet " or "normal carb") AND ("energy reserves" or "exercise duration" or speed or intensity or glucose or performance or "continuous glucose monitoring" or "finish time" or endurance). All retrieved records underwent identical eligibility screening and full-text assessment.

Eligibility Criteria

The eligibility criteria for this review were established using the PICOS framework to ensure a structured and transparent selection process. The population of interest comprised adults aged ≥ 18 years who were classified as amateur or recreational athletes, physically active individuals, or non-elite sports participants. Studies on elite or professional athletes were excluded to maintain focus on populations with limited or inconsistent training adaptation, which was central to our research question.

Literature Search

The PRISMA flow diagram illustrates the study selection process of this systematic review. A total of 451 records were identified through database searches (ScienceDirect, n=131; PubMed, n=70; ProQuest, n=150; and Google Scholar, n=100), of which 321 duplicates were removed, leaving 130 records for further screening. After title and abstract screening, 71 records were excluded and 59 full-text reports were retrieved. All retrieved records, including eligible preprints, were subjected to the same predefined eligibility criteria, full-text screening, and risk-of-bias assessment as peer-reviewed studies. Of the 29 reports assessed for eligibility, 22 were excluded due to a lack of relevant intervention (n=10) or an ineligible population (n=12), including studies conducted in populations other than athletes or physically active individuals, such as amateur or recreational participants. Ultimately, seven studies met the inclusion criteria and were included in this review (Figure 1).

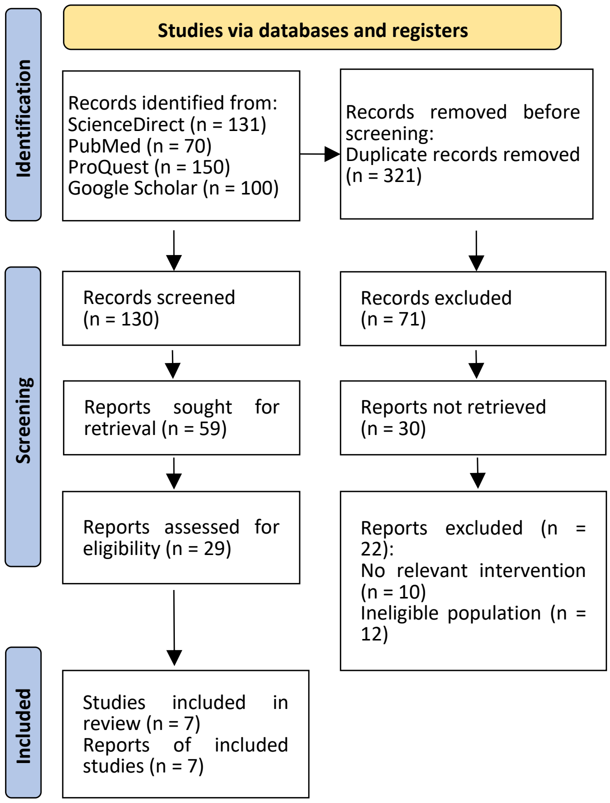

Figure 1. PRISMA Flowchart

The interventions of interest included any protocol involving carbohydrate loading, a carbohydrate-rich dietary regimen, or carbohydrate supplementation, specifically designed to augment exercise performance. The comparator groups comprised individuals receiving their usual or habitual diet, a low-carbohydrate regimen, or alternative macronutrient-based interventions such as high-protein or high-fat diets.

The primary outcomes were performance-related physiological parameters, including maximal oxygen uptake (VO_2max), time to exhaustion, race or time trial performance, power output, and overall endurance capacity. Secondary outcomes included biomarkers relevant to metabolic and physiological adaptation, such as blood glucose concentration, lactate level, muscle glycogen content, and anthropometric indices of body composition.

Eligible study designs included randomized controlled trials, crossover trials, and quasi-experimental studies published in English language. Observational studies and qualitative research were included only if they provided quantifiable data on carbohydrate-loading practices and their measurable physiological consequences. Studies involving pediatric or clinical populations, animal experiments, review articles, or those lacking accessible full-text manuscripts were excluded from the analysis.

Results

Study Characteristics

This systematic review included seven studies that investigated the effects of carbohydrate diet interventions on physical performance, primarily focusing on athletes and physically active individuals. The included studies were conducted in diverse regions, including the United States, China and Brazil. They comprised different methodological approaches, such as randomized crossover trials, randomized controlled intervention trials, and comparative observational studies.

The assessed interventions varied considerably and included high-carbohydrate (high-CHO), low-carbohydrate (low-CHO), and diets with different protein and fat compositions. Control or comparator groups typically followed diets with different macronutrient proportions or baseline/normal diets. The sample sizes ranged from six to 30 participants, including recreational swimmers, amateur runners, healthy and physically active men, and competitive bodybuilders. Most participants were men, with mean ages ranging from 22 to 73. Physical performance outcomes included VO2 max, race or exercise performance (running, jump squat, and cycling), and anthropometric measurements such as weight, height, and body mass index (BMI). Some studies have utilized pretest–posttest designs to assess changes in physical performance and metabolic biomarkers following dietary interventions. Intervention durations varied from single-day phases to 7 weeks, including washout periods and dietary manipulations lasting several days. Table 1 provides a detailed overview of the characteristics of the included study.

Study Outcomes

The included studies evaluated the effects of carbohydrate diet interventions on the physical performance of athletes and physically active individuals. The primary outcomes included the energetic cost of swimming (Cs), VO_2, marathon finishing time, average speed, power output, time to exhaustion (TTE), 5 km running performance, total work performed, rowing time, and muscle thickness. Secondary outcomes included heart rate, oxygen pulse, blood lactate, glucose, and insulin levels, K^+, body mass and circumferences, macronutrient intake adherence, pacing strategy, mood states, gastrointestinal symptoms, and skeletal muscle biopsies (fiber type, oxidative enzyme activity, and hypertrophy) (Table 2).

Bestard et al. (2020) investigated the short-term effects of a high-carbohydrate low-fat (HCLF) diet versus a low-carbohydrate high-fat (LCHF) diet in recreational swimmers. HCLF increased CHO utilization but did not improve swimming economy at 50–70% VO_2 max. LCHF may be beneficial for ultra-distance swimming because of its reliance on fat oxidation. Dai et al. (2024) evaluated high-CHO supplementation in amateur marathon runners, demonstrating improved finishing performance, stabilized blood glucose, and delayed speed decline, with glucose stability moderately correlated with performance. Hatfield et al. (2006) assessed CHO diets in healthy men performing jump squats, showing both diets supported higher mean power than baseline, indicating that elevated carbohydrate intake is not required to optimize acute repetitive power-endurance at the start of a workout. Lima-Silva et al. (2013) compared low-CHO and high-CHO diets in physically active men, finding that low-CHO impaired aerobic contribution while high-CHO offered no additional ergogenic benefit. Rosa et al. (2022) examined 30%, 60%, and 80% CHO diets in amateur runners and found no significant differences, although 80% CHO slightly improved pacing by 2.3%. Toma (2009) evaluated high-CHO versus high-protein low-CHO diets combined with rowing training, showing that the HC diet yielded superior gains in performance, muscle hypertrophy, and lipid profile, whereas HP improved cardiovascular health but limited exercise intensity and total work, with some participants exhibiting urinary ketosis. Moraes et al. (2019) investigated carbohydrate loading in competitive bodybuilders, demonstrating increased body mass, muscle thickness, circumference, and silhouette scores, while mood states were unaffected, and gastrointestinal symptoms were frequent in the CL group.

Overall, the findings indicate that although carbohydrate intake strategies do not consistently confer ergogenic benefits across all exercise modalities, higher carbohydrate availability, particularly through strategic carbohydrate loading, tends to support more consistent improvements in prolonged or repeated exercise outcomes, muscle adaptation, and exercise capacity than low-carbohydrate approaches. In contrast, the effects on short-duration or high-intensity strength–power outcomes remain unclear.

Table 1. Characteristic of the included studies

Authors Year	Total Sample	Intervention	Category of Intervention	Comparator	BMI (kg/m^2)	VO2	Follow-up Duration
Bestard et al. (2020) USA	8 (Recreational swimmers/ Endurance)	High-carbohydrate, low-fat (HCLF): 69% CHO (~5.7 g/kg/day), 15.5% fat, 16% protein for 3 days	High-CHO diet short-term	Low-carbohydrate, high-fat (LCHF): 16% CHO (~1.3 g/kg/day), 66.7% fat, 17.6% protein for 3 days	23.8 ± 2.6	VO2 max: 70%	4 days
Dai et al. (2024) China	30 (Amateur runners/ Endurance)	The high-carb and normal-carb groups received 80 g/h and 50 g/h, respectively.	CHO intake during exercise	The normal CHO intake group was supplemented with 50 g/h, defined as group NHigh, and the high CHO intake group was supplemented with 80 g/houp with 80g/h, defined as group H.	Group H 22.3 ± 1.9 Group N 22.1 ± 1.4	N.A	1 marathon race (Nanjing Marathon 2023)
Hatfield et al. (2006) USA	8 (Healthy men/ Non-endurance)	High-CHO diet (80% CHO; 6.5 g/kg/day)	High-CHO diet short-term	Baseline habitual diet (~55% CHO) and moderate-CHO diet (50%)	N.R	N.A	Each diet phase lasted 4 days, separated by 1-week washout
Lima-Silva et al. (2013) Brazil	6 (Healthy physically active men/ Endurance)	High-CHO diet: 70% CHO, 10% protein, 20% fat, 48 hours Low-CHO diet: 25% CHO, 30% protein, 45% fat, 48 hours	High-CHO diet short-term	Control diet (~50% CHO) for 48 h	N.R	VO2max 46.7 ± 10.9 mL·kg −1·min −1)	48 h dietary manipulation + supramaximal test to exhaustion
Rosa et al. (2022) Brazil	10 (Amateur male runners/ Endurance)	7-day carbohydrate diets with 30%, 60%, and 80% CHO (2.2 g/kg, 4.2 g/kg, 5.6 g/kg)	High-CHO diet short-term	Pretest baseline diet (≈55% CHO, 4.2 g/kg)	N.R	Vpeak: 17.51 ± 1.52 km/h (approximately 89% Vpeak maintained during 5 km)	5 weeks (1 pretest + 3 × 7-day diet interventions with running tests)
Toma (2009) USA	17 (HP 8, HC 9) Healthy	High-CHO Low-Fat (HC): 57.5% CHO, 25.4% fat, 14.2% protein;	High-CHO diet short-term	HC vs HP diet, 7 weeks	N.R	HC 61.33 ± 8.43 HP	7 weeks (diet + progressive rowing

	young men/ Endurance	High-Protein Low-CHO (HP): 30.6% CHO, 38.5% fat, 29.9% protein				61.91 ± 8.08	training: 2x/week first 3 weeks, 3x/week last 4 weeks)
Moraes et al. (2019) Brazil	24 (bodybuilders for amateur/ Non-endurance)	Loading phase (24h post-weigh-in until competition): 8–12 g/kg/day CHO (mean 9.0 ± 0.7 g/kg/day)	CHO loading pre-event	No carbohydrate loading (NC group: <5 g/kg/day CHO)	26.7 ± 2.5 in CL group, 27.1 ± 1.8 in NC group	N.A	4 days

CL (Carbohydrate Loading); CHO (Carbohydrate); HC (High-Carbohydrate, Low-Fat); HCLF (High-Carbohydrate, Low-Fat); HP (High-Protein, Low-Carbohydrate); LCHF (Low-Carbohydrate, High-Fat); N.A (Not Available); N.R (Not Reported); NC (No Carbohydrate Loading); Vpeak (Peak Velocity); VO2 (Maximal Oxygen Uptake)

Table 2. Outcomes of the included studies

Authors, Year	Primary Outcomes	Secondary Outcomes	Main Findings	Risk of Bias/ Quality of the study
Bestard et al. (2020)	Energetic cost of swimming (Cs), VO_2, Respiratory exchange ratio (RER)	Heart rate, oxygen pulse (stroke volume estimate)	A short-term HCLF diet increased CHO use but did not improve swimming economy at 50–70% VO_2max. LCHF may be beneficial for ultra-distance swimming because of its reliance on fat oxidation.	Low risk
Dai et al. (2024)	Marathon finishing time, average speed per 10 km, blood glucose (CGM)	High-CHO supplementation improved final performance and stabilized glucose; delayed speed decline in sub-elite; glucose stability moderately correlated with performance	This study demonstrated that high-carbohydrate supplementation (80 g/h) significantly improved marathon finishing time compared with normal intake (50 g/h) in amateur runners, primarily by stabilizing blood glucose and attenuating late-race pace decline, with glucose stability moderately correlated with performance.	Low risk
Hatfield et al. (2006)	Power output during 4 sets of 12 maximal jump squats at 30% 1RM	Blood lactate, serum glucose concentrations	Both CHO diets supported a higher mean power output than the baseline diet did. Elevated carbohydrate intake is not required to optimize acute repetitive power endurance when exercise is performed at the beginning of the workout.	Low risk
Lima-Silva et al. (2013)	Time to exhaustion (TTE), aerobic and anaerobic contribution	Blood lactate, glucose, insulin, K+	A low-CHO diet impaired performance and aerobic contribution, whereas the anaerobic contribution remained unchanged. Plasma K+ levels increased earlier with a low-CHO diet, possibly accelerating fatigue, and a high-CHO diet showed no additional ergogenic benefit.	Low risk
Rosa et	5 km running	Body mass	No significant performance differences	Moderate

al. (2022)	time (total and per km pacing)	before/after runs, macronutrient intake adherence, pacing strategy	were observed among the 30%, 60%, and 80% CHO diets; however, the 80% CHO diet showed a slight improvement in performance, with faster pacing, approximately 2.3% better than the 30% diet. Runners' habitual CHO intake (~4.2 g/kg) was below the ACSM recommendation of ≥5 g/kg/day, and overall, CHO manipulation did not significantly enhance performance in short-term amateur 5 km trials.	risk
Toma (2009)	Total work performed, post-exercise heart rate, rowing time, cardiovascular function	Blood lipids, anthropometry, skeletal muscle biopsies (fiber type, oxidative enzyme activity, hypertrophy)	Both diets combined with training improved fitness; however, the high-carbohydrate (HC) diet yielded superior gains in performance, muscle hypertrophy, and lipid profiles, whereas the high-protein (HP) diet enhanced cardiovascular health but limited exercise intensity and total work, with some participants exhibiting urinary ketosis. Overall, these findings suggest that a high-CHO low-fat diet is more effective in sustaining high-intensity aerobic performance than a high-protein low-CHO diet.	Low risk
Moraes et al. (2019)	Muscle thickness, Body circumferences, Subjective silhouette evaluation by bodybuilding judges	Mood states, Gastrointestinal symptoms	Carbohydrate loading increased body mass (~+2.8%), muscle thickness, circumference, and silhouette scores. Mood states did not significantly improve during the study period. Gastrointestinal symptoms were common in the CL group.	Good

CL (Carbohydrate Loading); CGM (Continuous Glucose Monitoring); Cs (Energetic Cost of Swimming); HC (High-Carbohydrate); HCLF (High-Carbohydrate, Low-Fat); HP (High-Protein, Low-Carbohydrate); LCHF (Low-Carbohydrate, High-Fat); RER (Respiratory Exchange Ratio); TTE (Time to Exhaustion); VO2 (Maximal Oxygen Uptake)

Risk of Bias

Figures 2 and 3 show the results of the risk of bias assessment using RoB 2.0, which was conducted on six of the seven included studies according to their research designs. Most domains were assessed as low risk, including the selection of reported results, measurement of outcomes, missing outcome data, and deviations from the intended interventions. However, there were some concerns in the randomization process domain and bias arising from period and carryover effects, indicating limitations in reporting the randomization method and the potential for period or carryover effects in crossover design. These limitations did not substantially alter the overall interpretation. Overall, the graph shows that the risk of bias of the assessed studies was relatively low, with only minor concerns in certain aspects; therefore, the methodological quality was considered good.

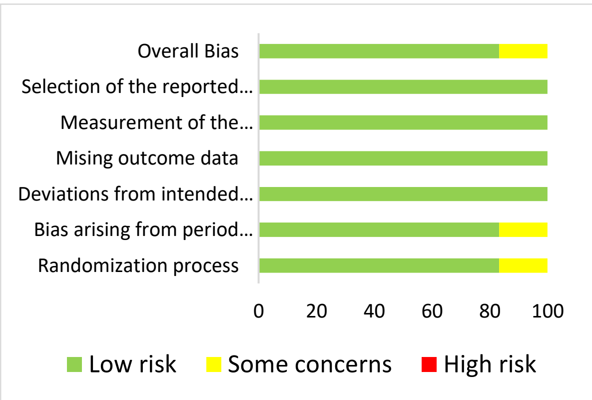

Figure 2. Risk of bias graph (%)

Figure 2 presents the results of the risk of bias assessment for six of the seven included studies based on their crossover or interventional designs. Most studies (Bestard et al., 2020; Dai et al., 2024; Hatfield et al., 2006; Lima-Silva et al., 2013; Toma, 2009) were assessed as having a low risk of bias across all domains, including the randomization process, bias arising from period and carryover effects, deviations from intended interventions, missing outcome data, outcome measurement, and selection bias. Only the study by Rosa et al. (2022) showed some concerns in the randomization process and bias arising from the period and carryover effect domains, primarily due to limited detailed randomization information and the absence of a washout period between the intervention phases. Therefore, the overall assessment fell into the category of some concerns. In general, most studies had good methodological quality with a low risk of bias, whereas only one study showed moderate concerns regarding certain aspects (Figures 2 and 3).

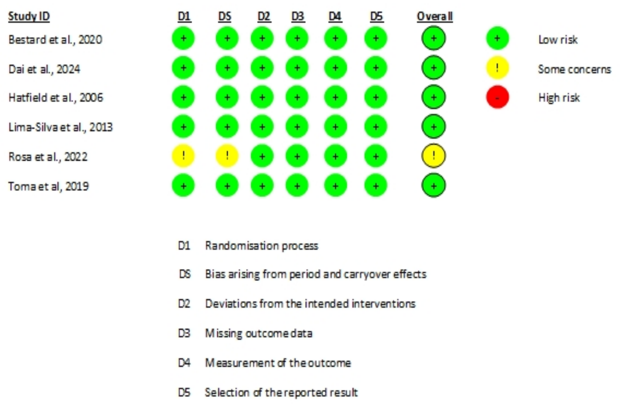

Figure 3. Risk of bias summary

Discussion

The present systematic review synthesized the findings of seven studies that evaluated the effects of carbohydrate loading and dietary carbohydrate manipulation on the physical performance of amateur and recreational athletes. Carbohydrate loading consistently increases carbohydrate availability and utilization; however, its ergogenic effect appears to be conditional rather than universally reproducible.

Consistent with classical models of glycogen supercompensation, several studies have demonstrated that increasing carbohydrate availability enhances performance during prolonged and high-intensity exercise. Dai et al. (2024) reported that amateur marathon runners consuming 80 g/h of carbohydrate achieved faster finishing times and more stable blood glucose profiles than those consuming 50 g/h, confirming the metabolic advantage of an adequate carbohydrate supply during endurance events. Similarly, Toma (2009) observed superior gains in total work and rowing performance among participants following a high-carbohydrate diet compared to those following a high-protein, low-carbohydrate regimen, highlighting the critical role of glycogen availability in sustaining high-intensity aerobic exercise. These findings align with the physiological rationale that carbohydrate loading increases muscle glycogen stores, delays fatigue, and supports a higher rate of carbohydrate oxidation during endurance exercises.

However, several studies have demonstrated inconsistent or minimal benefits, particularly in short-duration or submaximal exercise. Rosa et al. (2022) found no significant improvement in 5 km running performance among amateur athletes consuming 30%, 60%, or 80% carbohydrate diets, despite a modest (≈2.3%) pacing advantage with higher carbohydrate intake. Similarly, Bestard et al. (2020) reported that a high-carbohydrate low-fat diet increased carbohydrate utilization in recreational swimmers but did not improve swimming economy at 50–70% VO_2 max. These results suggest that the ergogenic threshold for carbohydrate loading may depend on exercise duration exceeding 90 min, as shorter bouts may not fully deplete glycogen stores or rely primarily on aerobic glycolysis.

Physiological disparities between trained and untrained individuals also contribute to this heterogeneity. Amateur athletes generally exhibit lower insulin sensitivity, reduced mitochondrial density, and limited glycogen storage capacity compared to elite endurance athletes. As described in the introduction, untrained muscle demonstrates lower GLUT4 expression, impaired glucose-6-phosphate synthesis, and reduced oxidative phosphorylation efficiency, which may attenuate the glycogen-loading response and limit subsequent energy availability. Consequently, carbohydrate loading protocols optimized for trained endurance athletes may not be effective in amateur populations without concurrent metabolic conditioning.

Nevertheless, Moraes et al. (2019) confirmed that carbohydrate loading can induce measurable physiological changes, even outside endurance contexts. Competitive amateur bodybuilders exhibit increased body mass, muscle thickness, and visual muscle definition after short-term loading (8–12 g/kg/day), reflecting enhanced glycogen and intramuscular water storage. Although not directly related to endurance performance, this illustrates the consistent anabolic and volumizing effects of carbohydrate supercompensation across different exercise modalities. Variability in outcomes may also reflect methodological differences, including intervention duration, dietary composition, and performance metrics of the studies. Short loading phases (≤48 h) may be insufficient for full glycogen resynthesis, whereas high-fat comparators or habitual low-carbohydrate diets can influence substrate utilization during exercise testing. Moreover, amateur athletes' inconsistent adherence to dietary prescriptions and lack of professional nutrition guidance, as highlighted in previous surveys, further reduce the reproducibility of carbohydrate-loading benefits. This underscores the need for individualized nutrition education that emphasizes carbohydrate periodization based on exercise intensity, duration, and prior training status of the individual.

Operational recommendations should be tailored to exercise duration and intensity, consistent with contemporary sports nutrition guidelines (Thomas et al., 2016; Jeukendrup, 2017): exercise lasting <60 min: additional carbohydrate loading is generally unnecessary if habitual intake is adequate; exercise lasting 60–90 min: approximately 30 g of carbohydrate per hour may support performance; exercise lasting 90–150 min: 30–60 g of carbohydrate per hour is recommended; exercise lasting >150 min: up to 60–90 g of carbohydrate per hour, preferably using multiple transportable carbohydrates (e.g., glucose–fructose combinations) to enhance intestinal absorption and oxidation rates.

For pre-event preparation in prolonged endurance competitions, a carbohydrate intake of 7–10 g/kg/day for 2–3 days is appropriate, provided that athletes have practiced such strategies during training to optimize tolerance and metabolic adaptation (Burke et al., 2017; Thomas et al., 2016).

Overall, the synthesized evidence supports that carbohydrate loading remains an effective and evidence-based strategy to enhance endurance performance when applied appropriately, even in amateur athletes. However, the degree of benefit is moderated by the training level, event duration, and metabolic adaptability. For short-duration activities (< 60 min), moderate carbohydrate availability may suffice, whereas prolonged or repeated high-intensity events clearly benefit from structured carbohydrate loading protocols (7–10 g/kg/day for 2–3 days before competition). This systematic review has several limitations, including the absence of prior protocol registration, the inclusion of a preprint study that has not undergone formal peer review, and the relatively small sample sizes of the included studies, despite the detailed reporting of study characteristics and outcomes, which may limit its statistical power and generalizability.

In addition, heterogeneity in study populations and intervention definitions should be acknowledged, as carbohydrate loading was broadly operationalized to include classical pre-event loading protocols, short-term high-carbohydrate diets, and carbohydrate supplementation during exercise, potentially limiting the direct comparability between studies. However, most of the included studies demonstrated good methodological quality with a low-to-moderate risk of bias and a consistent direction of effects, indicating that the synthesized evidence remains adequate and clinically relevant to support the conclusions of this review and inform future research. Future research should prioritize well-controlled randomized trials in amateur cohorts, integrating muscle glycogen quantification, mitochondrial function markers, and continuous glucose monitoring to clarify the dose-response relationship and metabolic limits of carbohydrate loading in this population.

Conclusion

The findings of this systematic review demonstrate that carbohydrate loading is an effective and evidence-based nutritional strategy for improving endurance performance, particularly in amateur and recreational athletes performing prolonged or high-intensity exercise. Its benefits include delayed fatigue and improved energy availability; however, the magnitude of the effect varies according to the training status, protocol adherence, and exercise duration. For sports nutrition practitioners and coaches, carbohydrate loading should be prioritized for endurance sessions or competitions exceeding 90 min, with structured planning of carbohydrate intake in the days preceding the event and close monitoring of gastrointestinal tolerance and body mass changes. In amateur athletes, individualized protocols based on training load, habitual dietary patterns, and competition demands are recommended to optimize performance while minimizing unnecessary carbohydrate exposure during shorter- or moderate-intensity exercise. Further well-designed randomized trials are needed to refine the dosing, timing, and protocol duration for non-elite populations.

Declaration of Conflict of Interest

The authors declare that there are no financial, personal, or professional relationships that may be perceived to influence the content or outcomes of this manuscript. This study was conducted independently, with no external funding, sponsorship, or commercial interests involved in the design, data collection, analysis, interpretation or publication of the results.

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