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Review Article

Comparing the Effects of Glucose-Fructose versus Glucose on the Oxidation Rate: A Systematic Review and Meta-Analysis

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Abstract

Background: Numerous studies have aimed to compare the effects of glucose (Glu) consumption with those of glucose-fructose (Glu-Fru) consumption on oxidation rates during exercise. However, divergent outcomes have surfaced due to variations in exercise protocols and concurrent substance ingestion, leading to a lack of consensus. This systematic review and meta-analysis investigated the comparative effects of Glu and Glu-Fru on total carbohydrate oxidation, endogenous carbohydrate oxidation, exogenous carbohydrate oxidation, and total fat oxidation rates during exercise.

Methods: A systematic search of PubMed, Scopus, and Web of Science databases up to February 2023. The search yielded 14 randomized controlled trials involving 125 endurance athletes.

Results: The meta-analyses revealed that Glu supplementation significantly increased total carbohydrate oxidation (WMD: 0.21 g/min) compared to Glu-Fru. Endogenous carbohydrate oxidation significantly increased with Glu (WMD: -0.12), while Glu-Fru led to increased exogenous carbohydrate oxidation (WMD: 0.27 g/min). Total fat oxidation decreased with Glu-Fru (WMD: -0.06 g/min).

Conclusion: By investigating athletic nutrition complexities, our findings shed light on metabolic responses to Glu-Fru versus Glu supplementation. Tailoring hydration strategies, athletes should select an optimal Glu-Fru to Glu ratio for maximal oxidation and enhanced performance. Future research could explore dose-response relationships for optimal metabolic benefits during exercise.

Keywords: Carbohydrate; Endurance exercise; Oxidation rate; Performance

Introduction

Optimizing athletic performance involves numerous physiological and metabolic factors, with efficient energy substrate utilization being crucial. Substrate oxidation refers to the breakdown of carbohydrates and fats to fuel muscle activity during exercisehd (1-4). Higher rates of substrate utilization and metabolism correspond to increased rates of oxidation (5-7).

Glucose and fatty acids are the main energy sources during exercise, with their oxidation rates affected by exercise intensity, duration, and substrate availability. Consuming carbohydrates during extended moderate- to high-intensity exercise is known to boost performance (8-10). Ingestion of glucose typically results in a peak rate of external carbohydrate oxidation of approximately 1 gram/minute (11, 12).

Emerging research suggests that performance gains may be further augmented when carbohydrates are ingested in combination with fructose and glucose (13, 14). This blend facilitates multiple absorption pathways in the gastrointestinal tract, leading to enhanced gut comfort, increased rates of carbohydrate oxidation, and ultimately improved endurance performance compared to consuming single sugars (15, 16). The simultaneous transport of fructose and glucose may involve the recruitment of specific transporters, such as SGLT1 and GLUT5, to the intestinal membrane (17-19). The expedited absorption of these multiple-transportable carbohydrates may mitigate gut discomfort by facilitating carbohydrate clearance and increasing exogenous carbohydrate availability, both of which are critical factors contributing to enhanced endurance performance (20-23).

Despite many studies on the effects of fructose-glucose (Fru-Glu) and glucose (Glu) on oxidation rates during exercise, results remain inconclusive. This meta-analysis evaluated the literature to determine the impact of Fru-Glu versus Glu on oxidation rates in athletes, aiming to guide optimal carbohydrate supplementation strategies for improved performance.

Materials and Methods

This meta-analysis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (24).

Search Strategy and Selection of Studies

We conducted a thorough search of Scopus, PubMed (MEDLINE), and Web of Sciences (including the Korean Citation Index-Korean Journal Database, MEDLINE, the Russian Science Citation Index, and the SciELO Citation Index) from inception to January 2023. The search strategy, in summary, utilized keywords such as "carbohydrate" OR "glucose" OR "fructose" OR "glucose-fructose" OR "beverage*" OR "hydrogel" AND "oxidation" AND "athlete*" OR "cyclist*" OR "runner*" OR "train*" OR "endurance*" NOT "Animal" NOT "disorder" NOT "pregnant" NOT "children" NOT "maternal" AND "Clinical trials" OR "RCT" OR "intervention" OR "trial" OR " OR "controlled trial" OR "randomized" OR "placebo" OR "crossover" OR "Intervention Study" OR "double-blind" OR "Cross-Over Study" OR "parallel trial" OR "parallel" OR "random". We focused on clinical trials, RCTs, interventions, placebo-controlled trials, crossover studies, double-blind trials, and parallel trials without language or time restrictions.

Two independent researches, Z-GD and M-HR, conducted a systematic selection process using EndNote 20. After removing duplicates, we screened abstracts and then full texts to identify eligible studies, ensuring high-quality inclusion.

Inclusion criteria for trials were: 1) Comparing oral glucose or maltodextrin beverages with glucose-fructose beverages during steady-state exercise; 2) Use of glucose and fructose in their monosaccharide forms only, as the digestion process of disaccharides like sucrose could influence oxidation rates(12); 3) Athletes aged 18-40 with >2 years training and no diabetes or dysglycemic conditions; 4) Crossover design with at least 7-day separation; 5) Trials that involved consistent endurance-based exercise protocols, where exercise intensity was maintained at or below 70% VO_2 max to ensure uniform metabolic demands across studies. 6) Participants required to abstain from alcohol for 24 hours and caffeine for 12 hours prior to the experimental trials. Exclusion criteria were: 1) Use of other carbohydrates; 2) Combination with protein; 3) Conducted in extreme temperatures (>28°C or <5°C); (4) Involving children; 5) Participants with medical conditions or obesity; 6) Variable exercise intensity; 7) Nonrandomized or observational studies.

Data Extraction

The data were extracted following the PRISMA methodology (25), with a focus on collecting information pertaining to participants, interventions, comparisons, outcomes, and study design (PICOS). Specifically, information related to training time, total volume of drink, amount of beginning drink, dose and ratio of intervention products, time intervals between each drinking session, and subjects' characteristics such as age, body mass index, study features such as washout periods and the country where the study was conducted were independently collected by two authors (Z.G.D. and M.H.R.). In cases where data were presented graphically, images were magnified to enhance data precision, and an online application (26) was utilized for data extraction. For investigations reporting multiple time points, the average of all measurements for each oxidation rate obtained during the bout was used for analysis.

Quality Assessment

We assessed RCT quality using the Risk of Bias tool version 2 (27) which evaluates 5 domains: randomization process, intervention deviation, missing outcome data, outcome measurement, and selection bias. For crossover RCTs, we also considered bias from period and carryover effects. Each domain was rated low, high, or somewhat concerned about bias, and scores were totaled for each trial. Table 1 presents the quality assessment of the included trials.

We used the GRADE tool to assess evidence certainty for each outcome (28). Certainty levels were categorized as high, moderate, low, or very low based on criteria including risk of bias, inconsistency, indirectness, imprecision, and publication bias.

Statistical analysis

A comprehensive analysis compared the effects of Glu and Glu-Fru on oxidation rates during endurance exercise. Subanalyses included age, VO2 max, training time, G/F ratio, and amount. STAT version 17 was used for statistical analyses, pooling results with random-effect models for heterogeneity ($I^2 > 50\%$). Heterogeneity levels were minor (25%-50%), moderate (50%-75%), and substantial (>75%). Meta-regression analyzed the dose-dependent relationship between Glu-Fru rates and changes in carbohydrate and fat oxidation. Egger's and Begg's tests, along with funnel plots, assessed publication bias. Sensitivity analysis evaluated each trial's effect on pooled results (43).

Results

General characteristics of included studies

As shown in Fig. 1, by utilizing the best keywords, we found 3771 articles by searching 3 databases (PubMed, Scopus, and Web of Science).

Table 1: Quality assessment of the included trials

Study, year	Bias arising from the randomization process	Bias due arising from the randomization process	Bias due to deviations from intended intervention	Bias due to missing outcome data	Bias in measurement of the outcome	Bias in selection of the reported result	Overall quality
Trommelen 2017 (29)	Low	Low	Some concern	Low	Low	Some concern	Some Concern
Wilson, 2016 (30)	Low	Low	Low	Low	Low	Low	Low
Baur, 2014 (31)	Low	Low	Low	Low	Low	Low	Low
Roberts JD, 2014 (32)	Low	Low	Some concern	Low	Low	Low	Low
Tarpey MD, 2013 (33)	Low	Low	Low	Low	Low	Low	Low
Virgile, 2010 (34)	Low	Low	Some concern	Low	Low	Low	Low
Rowlands, 2008 (35)	Low	Low	Low	Low	Low	Low	Low
Currell K, 2008(36)	Low	Low	Low	Low	Low	Low	Low
Jeukendrup AE, 2006 (37)	Some	Low	Low	Low	Low	Low	Low
Jentjens RL, 2006(38)	Low	Low	Some	Low	low	Low	Low
Jentjens RL, 2005(39)	Low	Low	Low	Low	Low	Low	Low
Wallis GA, 2005(40)	Low	low	Some Concerns	Low	Low	Low	Low
Jentjens RL, 2004(41)	Some concern	Low	Some concern	Low	Some concern	Some concern	High
Carl J.Hulston(42)	Low	Low	Some concern	Low	Low	Low	Low

Domain 1 addresses bias from randomization, Domain S focuses on bias from period and carryover effects, Domain 2 addresses bias from deviations in the intended intervention, Domain 3 considers bias due to missing outcome data, Domain 4 examines bias in measuring the outcome, and Domain 5 explores bias in selecting the reported result.

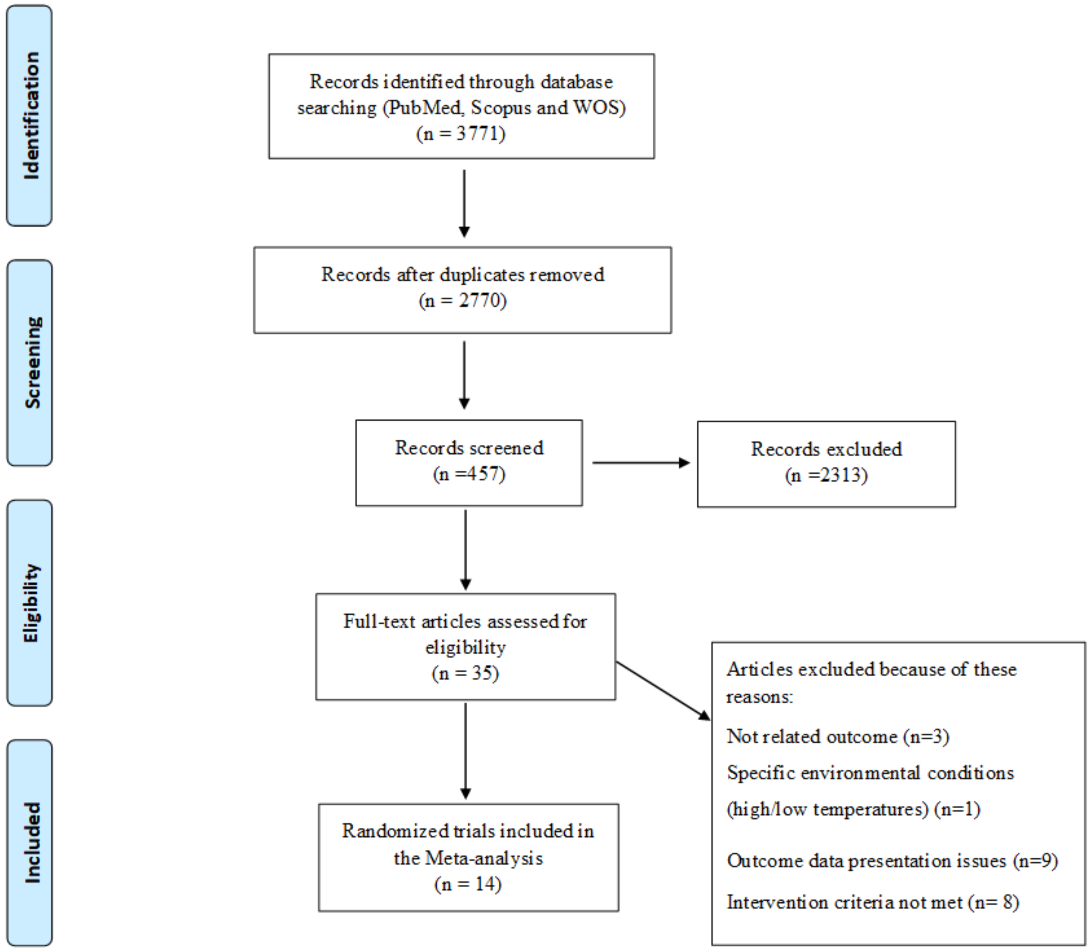

Fig. 1: Flowchart of study selection in the systematic review

Table 2 shows the main characteristics of the included studies. All trials were published between 2003 and 2017 and were crossover in design. All of the participants were at least cyclists, but 2 articles were conducted on runners and endurance trainers. In addition, among the 154 participants who were men, the maximum power was confined to 319-411.4%, the maximum VO2 was 56.8-73.4 ml/kg/min, and the age and body mass ranged from 25-35.8 years and 69.5-84.4 kg, respectively. Most trials were conducted in the UK, and the others were conducted in the Netherlands, Switzerland, the US, or New Zealand. The administered doses of glucose and glucose-fructose beverages ranged from 0.6-2 and 0.9-2.4 g/min, respectively, as the duration of training increased from 120 to 300 min. Additionally, the most repeated G/F ratio was 2:1. In the selected studies, carbohydrate and fat oxidation were measured using a combination of indirect calorimetry and stable isotope techniques. Oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) were utilized to calculate total carbohydrate and fat oxidation rates based on the stoichiometric equations of Frayn. Furthermore, exogenous carbohydrate oxidation was determined by administering isotopically labeled carbohydrates (e.g., ^{13}C-glucose and ^{13}C-fructose) and measuring the $^{13}C/^{12}C$ ratio in expired air samples via gas chromatography-combustion-isotope ratio mass spectrometry (GC-C-IRMS). This approach allowed researchers to differentiate between exogenous and endogenous substrate oxidation during exercise.

Table 2: Summary design and participants

Author, year	Sport field	Body mass (kg)	G dose (gr/min)	G/F	Training duration (min)	W max (%)	VO2 max (ml/gamin)
Trommelen, 2017 (29)	Cyclists/Triathletes	74.8	1.8	2:1	180	411.4	65
Wilson, 2016 (30)	Runner	72	1.3	1.2:1	120	360	56.8
Baur, 2014 (31)	Cyclists	77	1.03 1.55	2:1	120	360	62
Roberts JD, 2014 (32)	Cyclist	73.69	1.7	2:1	150	352.64	60.38
Tarpey MD, 2013(33)	Cyclists/Triathletes	76.1	1.7	2:1	150	319	59.2
Virgile, 2010 (34)	Cyclist	69.5	2	3:2	120	365	73.4
Currell K, 2008 (36)	Cyclist	84.4	1.8	2:1	120	364	64.7
Rowlands, 2008 (35)	Cyclists/Triathletes	77	0.6	2:1 1.2:1 1:0.85	120	360	61
Jeukendrup AE, 2006 (37)	Endurance-trained	75.3	1.5	2:1	300	367	62.7
Jentjens RL, 2006 (38)	Cyclists/Triathletes	74.5	1.5	2:1	120	361	64
Jentjens RL, 2005 (39)	Cyclists/Triathletes	74.3	1.2	1:1	150	376	68.1
Wallis GA, 2005 (40)	Cyclists/Triathletes	78.8	1.8	2:1	150	360	64.1
Jentjens RL, 2004 (41)	Cyclists/Triathletes	75.1	1.2	2:1	120	360	62
Carl J.Hulston (42)	Cyclists	71.4	0.8	2:1	150	333	62

Abbreviations: G, glucose; F, fructose; G/F, glucose–fructose ratio; M, male

Meta regression

A random-effects meta-regression analysis evaluated the dose-dependent relationship between Glu-Fru rate (g/min) and oxidation outcomes. Fig. S1–S4 in the Supplementary file (Not showed here) display the meta-regression correlations. An inverse relationship was found between Glu-Fru rate and endogenous carbohydrate oxidation (1.061 g/min; $P = 0.042$), with no significant correlation for other oxidation outcomes.

Quality assessment

Using the ROB 2 tool, most trials showed a low risk of bias, except for two. One had potential issues with intervention deviation and reporting bias, while the other had unclear randomization and outcome measurement bias. All studies had no missing outcomes, reflecting low risk in that domain. The main concern was deviation from the intended intervention. The GRADE tool was also used to assess the evidence certainty in the included studies. As Table 3 shows, all outcomes had low scores in this assessment. The reasons for downgrading were >50% heterogeneity and the small number of study participants (fewer than 300 persons).

Table 3: Effect of the GRADE profile of Glu vs Glu-Fru on the oxidation rate

Quality assessment							
Outcomes	Risk of bias	Inconsistency	Indirectness	Imprecision	Publication Bias	Sample sizes	Quality of evidence
Total Carbohydrate Oxidation Rate	Not serious	Serious[a]	Not serious	Serious[b]	None	154	⊕⊕◯◯ Low
Endogenous Carbohydrate Oxidation Rate	Not serious	Serious[a]	Not serious	Serious[b]	None	101	⊕⊕◯◯ Low
Exogenous Carbohydrate Oxidation Rate	Not serious	Serious[a]	Not serious	Serious[b]	None	85	⊕⊕◯◯ Low
Total Fat Oxidation Rate	Not serious	Serious[a]	Not serious	Serious[b]	None	108	⊕⊕◯◯ Low

Effect of Glu vs. Glu-Fru on total CHO oxidation

Selected trials comparing Glu-Fru to Glu supplementation on total carbohydrate oxidation demonstrated a significant increase in Glu-Fru consumption (WMD: 0.21 g/min; 95% CI: 0.13, 0.30; I2: 66.1%; $P < 0.05$, GRADE: low) (Fig. 2).

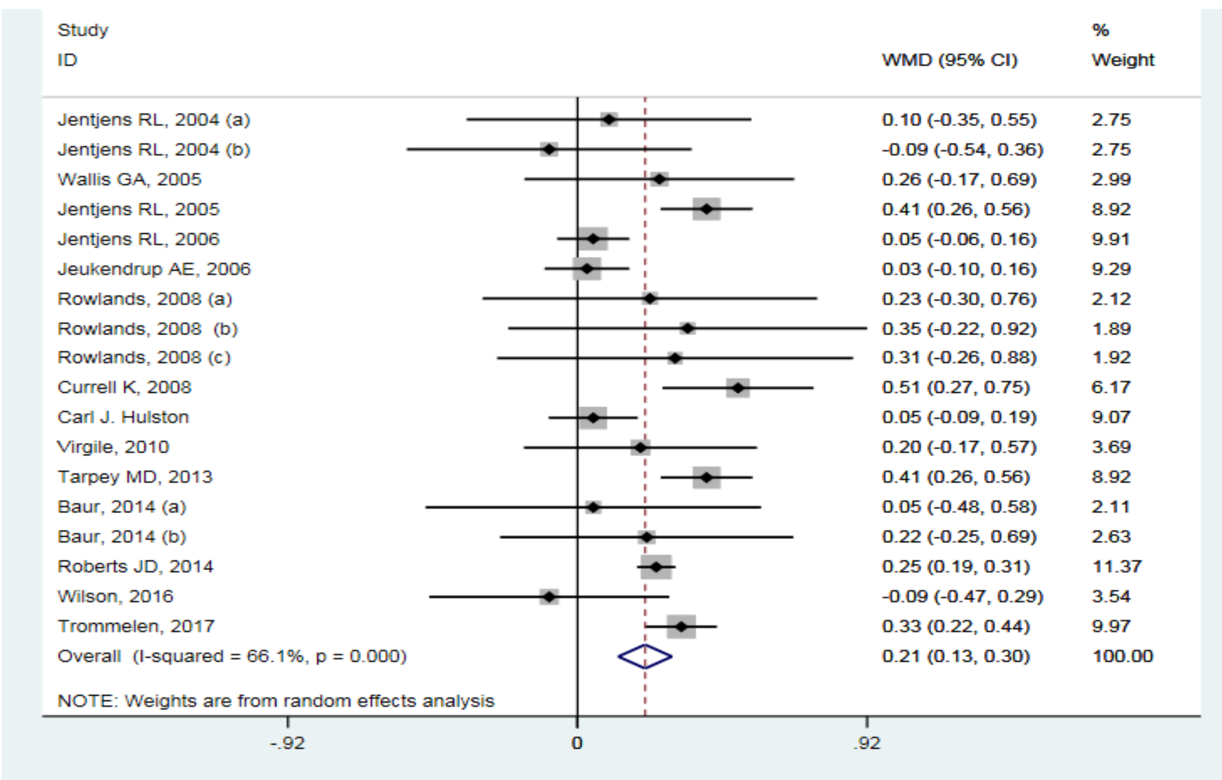

Fig. 2: Effect of Glu-Fru vs. Glu on total carbohydrate oxidation during exercise. The forest plot shows standardized mean differences with 95% confidence intervals (CIs) for 14 studies that included a measurement of the total carbohydrate oxidation rate

Subgroup analyses were conducted based on participant characteristics, training parameters, and beverage consumption intervals, revealing heterogeneity attributed to differing intervals between beverage consumption (Supplementary Table 1). Notably, consuming beverages every 20 minutes appeared to influence Glu's overall effect on total carbohydrate oxidation. Sensitivity analysis confirmed the stability of the overall effect size. Evaluation of publication bias via Egger's test, Begg's test, and funnel plot analysis yielded non-significant results (P = 0.70) (Fig. 3).

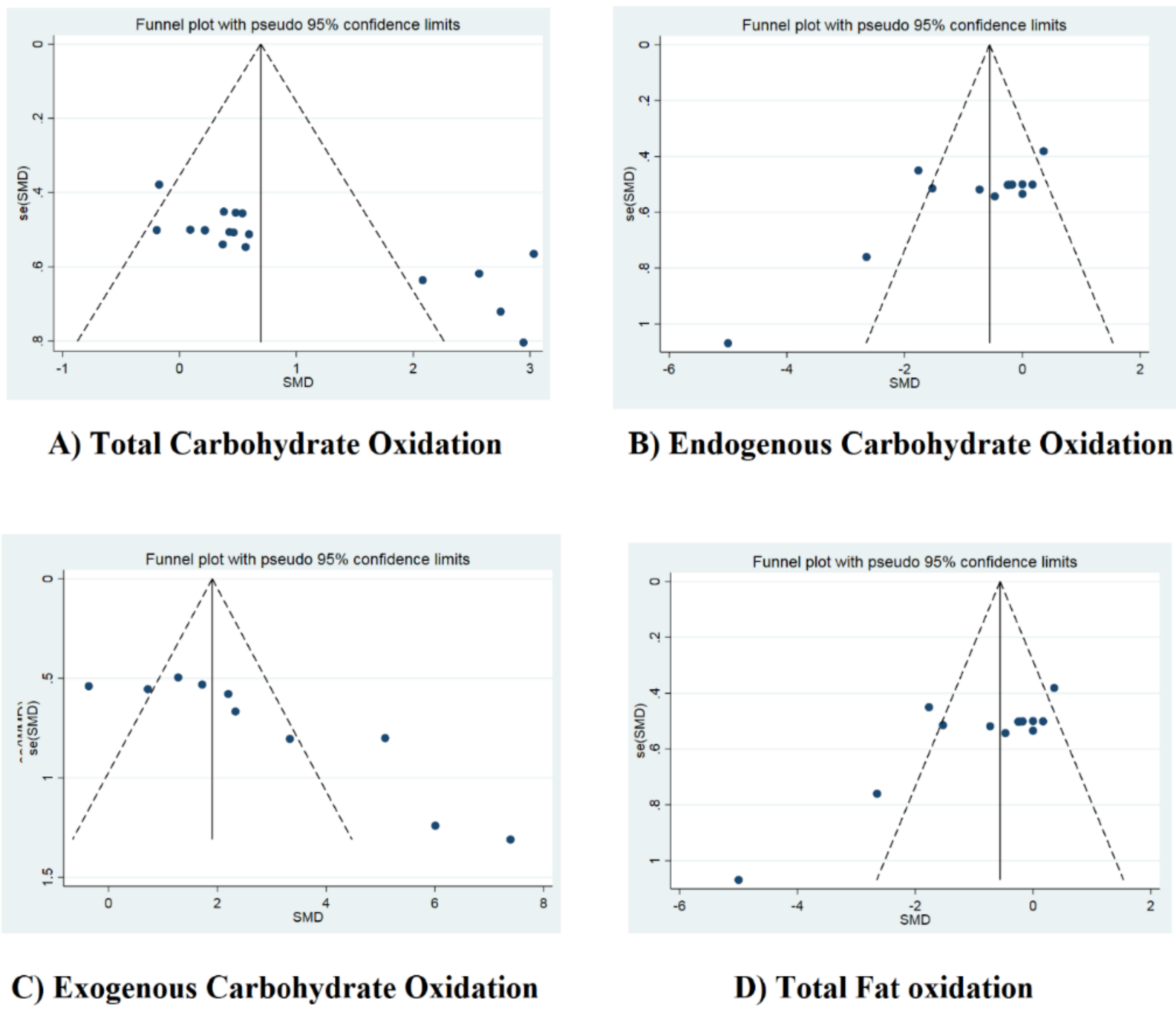

Fig. 3. Funnel plot for the comparison of Glu and Glu-Fru on oxidation rate during exercise

Effect of Glu vs. Glu-Fru on Endogenous CHO oxidation

The pooled effect of 9 trials (12 arms) comparing the influence of beverages used by athletes on endogenous carbohydrate oxidation revealed a significant decrease (WMD: -0.12; 95% CI: -0.21, -0.02; I2: 66.3%; *P* value< 0.05, GRADE: low) in the effect of drinking the Glu-Fru product (Fig. 4).

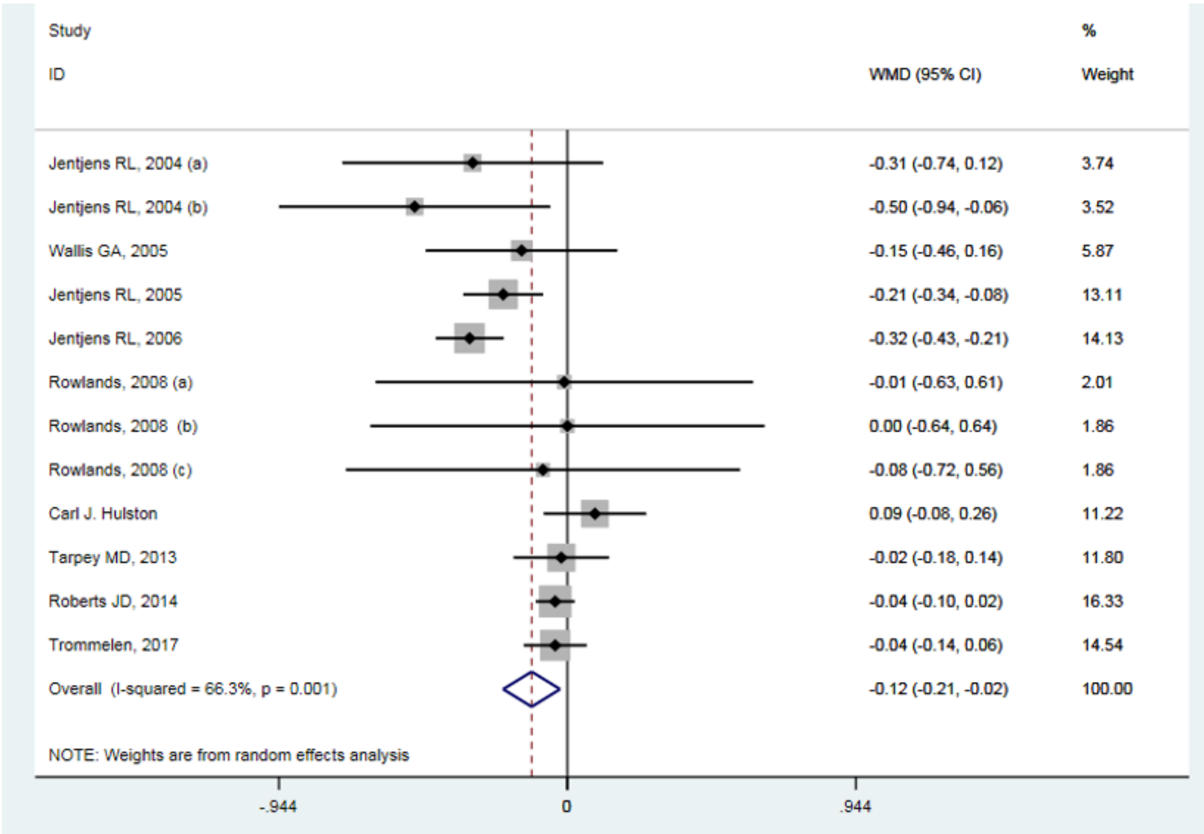

Fig. 4: Effect of Glu-Fru vs. Glu on endogenous carbohydrate oxidation during exercise. The forest plot shows standardized mean differences with 95% confidence intervals (CIs) for 9 studies that included a measurement of the endogenous carbohydrate oxidation rate

Additionally, we conducted subgroup analysis for endogenous CHO oxidation according to the participants' age, VO2 max, duration of training, G/F ratio, and beginning volume of consumed beverages. Therefore, we identified age and VO2 max as sources of heterogeneity (shown in Supplementary Table 1). Thus, heterogeneous pooled results were obtained for participants who were >=30 years old and who had a VO2 max of 61 or more. Sensitivity analysis verified that the overall effect size is stable. Furthermore, there was no publication bias for this result, based on the data from Egger's test, Begg's test, and the associated funnel plot (*P* value = 0.88).

Effect of Glu vs. Glu-Fru on Exogenous CHO oxidation

To investigate the effect of consumed beverages on carbohydrate oxidation in the exogenous state, 8 trials (10 arms) were analyzed and showed a meaningful increase (WMD: 0.27 g/min; 95% CI: 0.18, 0.37; I2: 93.9%; *P* value < 0.05, GRADE: low) when Glu-Fru beverages were consumed in comparison with Glu beverages (Fig. 5).

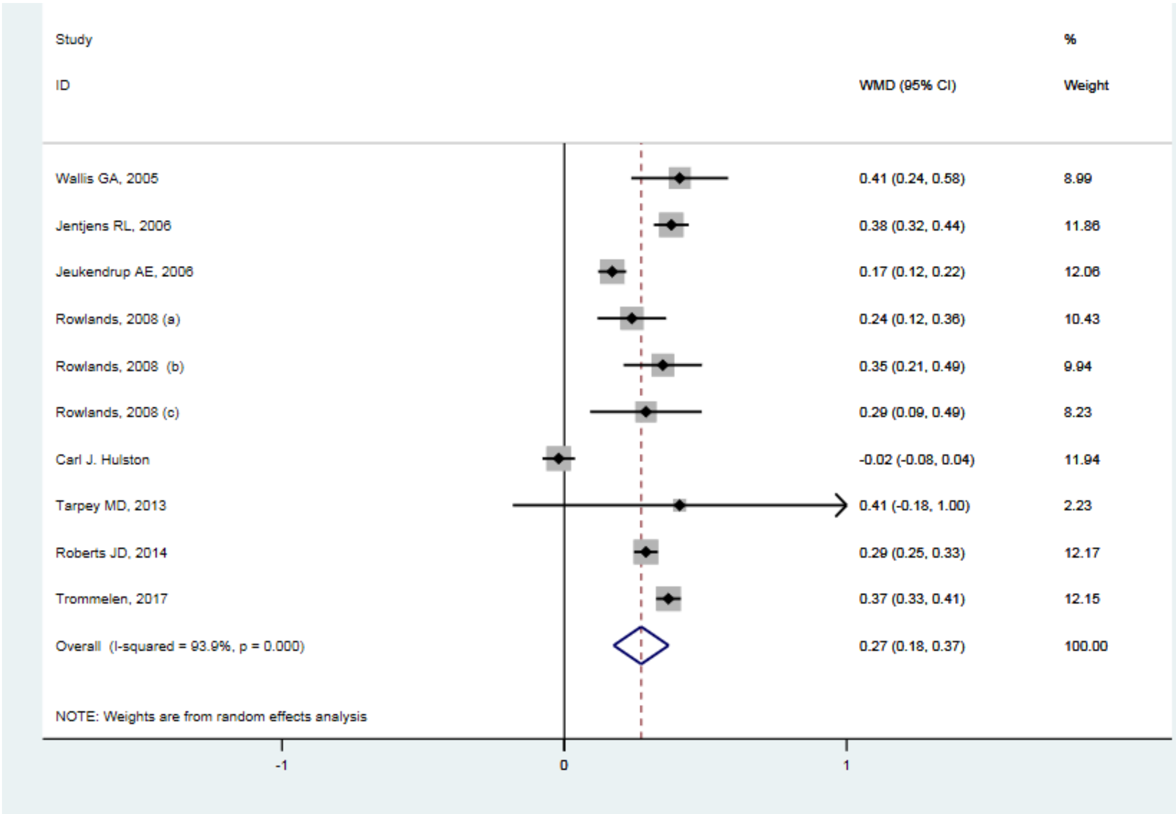

Fig. 5: Effect of Glu-Fru vs. Glu on exogenous carbohydrate oxidation during exercise. The forest plot shows standardized mean differences with 95% confidence intervals (CIs) for 8 studies that included a measurement of the exogenous carbohydrate oxidation rate

Additionally, to understand the cause of heterogeneity for this outcome, we utilized the participants' age, VO2 max, duration of training, G/F ratio, and volume of beverages consumed for subgroup analysis, but as shown in Supplementary Table 1, we could not find sources of heterogeneity. Moreover, removing each of the included studies did not affect the final result (CI: -0.37, -0.24). The overall effect size's stability has been proved by sensitivity analysis. Moreover, Egger's test, Begg's test, and the corresponding funnel plot demonstrated no bias in the publication of trials for this outcome (*P* value = 0.88) (Fig. 3).

Effect of Glu vs. *Glu-Fru on Total Fat Oxidation*

A meta-analysis of 12 trials (13 arms) revealed a significant increase in total fat oxidation (WMD: -0.06 g/min; 95% CI: -0.11, -0.01; I2: 83.2%; *P* value < 0.05, GRADE: low) in athletes supplemented with Glu beverages during sports competitions (Fig. 6).

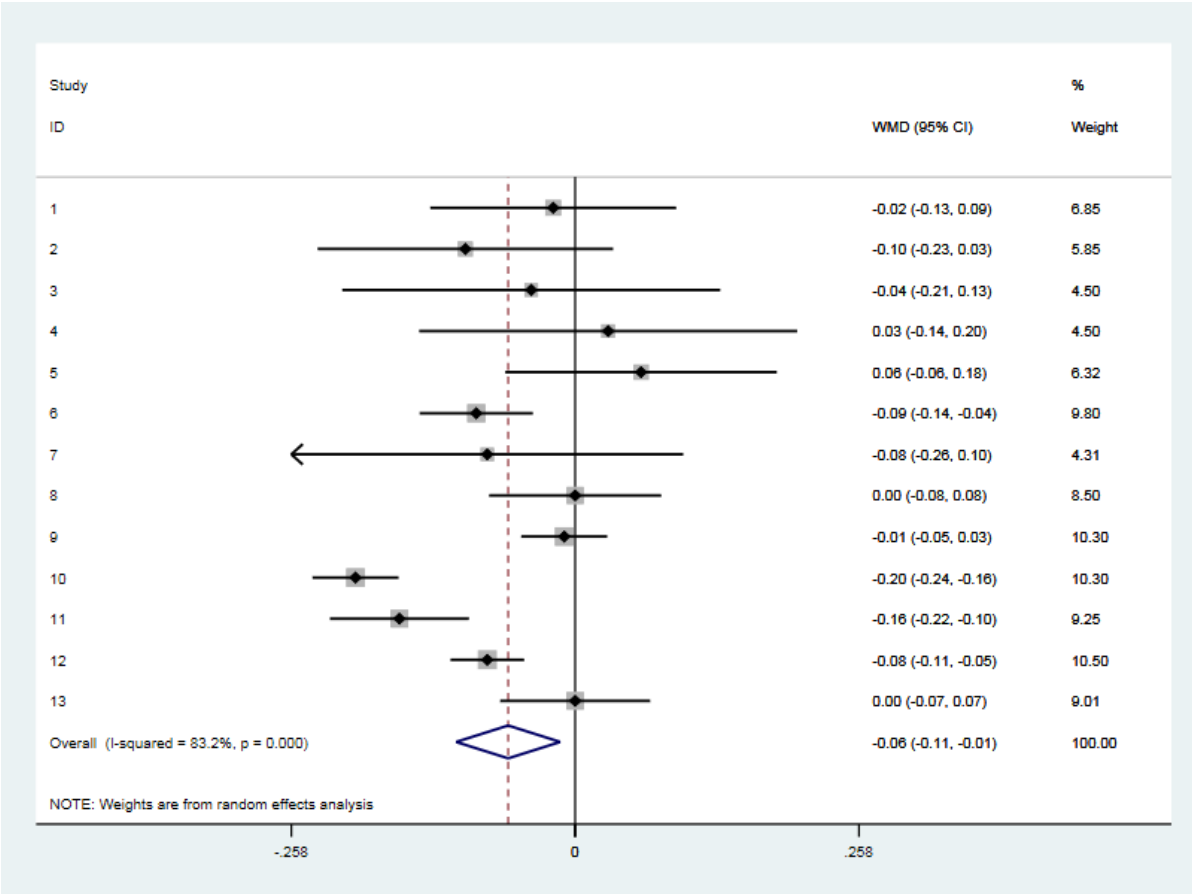

Fig. 6: Effect of Glu-Fru vs. Glu on total fat oxidation during exercise. The forest plot shows standardized mean differences with 95% confidence intervals (CIs) for 11 studies that included a measurement of the total fat oxidation rate

Additionally, we used the participants' age and VO2 max, G/F ratio, beginning volume of consumed beverages, and time of each drinking interval for subgroup analysis. All of the above-mentioned factors are known sources of heterogeneity (shown in Supplementary Table 1). Therefore, participants who had a G/F ratio less than 2, consumed beverages every 15 minutes, consumed less than 600 ml, had a VO2 maximum less than or equal to 61 ml/kg/min and were aged 30 years or older were considered sources of heterogeneity. Additionally, eliminating none of the RCTs influenced the pooled results (CI: 0.01, 0.11). Sensitivity analysis verified that the overall effect size is stable.

In addition, according to the data from Egger's test, Begg's test, and the corresponding funnel plot, there was no publication bias for this outcome (*P* value = 0.32) (Fig. 3).

Discussion

This study explored how Glu-Fru versus Glu supplementation affects four outcomes: total carbohydrate oxidation, endogenous carbohydrate oxidation, exogenous carbohydrate oxidation, and total fat oxidation. We hypothesized that carbohydrate source selection during exercise significantly impacts athletes' metabolic responses and performance. Findings indicated that Glu-Fru significantly enhanced total carbohydrate oxidation compared to glucose, increased endogenous carbohydrate and total fat oxidation, and reduced exogenous carbohydrate oxidation (44).

offers a pertinent example, shedding light on its substantial correlation with increased fat oxidation. This finding underscores the intricate interplay between habitual calcium levels and the effectiveness of interventions targeting substrate utilization. Similarly, A systematic review and meta-analysis (45) on acute caffeine intake provides vital insights into fat oxidation during submaximal-intensity exercise. The juxtaposition of these studies elucidates the multifaceted nature of nutritional influences on oxidation. Another meta-analysis on effect of sports drink on carbohydrate oxidation rate (46) revealed Carbohydrate-electrolyte solutions have been found to notably boost carbohydrate oxidation, while not significantly influencing fat oxidation. Carbohydrate-caffeine energy drinks improve maximal oxygen uptake and endurance, while caffeine alone reduces fat oxidation. Carbohydrate-electrolyte drinks favor carbohydrate use, and caffeine promotes fat metabolism. Glucose-fructose supplementation significantly increased total carbohydrate oxidation during exercise compared to glucose. This finding aligns with the findings of previous studies (32, 33, 36, 39), further reinforcing the pivotal role of Glu-Fru in augmenting substrate utilization. Since fructose uses a different intestinal transport pathway, combining it with glucose should improve overall carbohydrate absorption. We hypothesize that fructose-glucose combination will increase total carbohydrate oxidation during extended exercise (29). Conversely, dissenting results represented by (30, 31, 37) challenge the purported impact of Glu-Fru versus Glu on total carbohydrate oxidation during exercise. Metabolism is highly individualized, affected by genetics, lifestyle, and training. Participants with different metabolic profiles could account for variations in carbohydrate oxidation rates (47). Factors such as enzyme activity, hormonal responses, age-related differences, premeal nutrition, and external conditions like temperature and pressure—which were not reported—significantly influence carbohydrate metabolism. These individualized factors likely contribute to the varying results observed in the studies, underscoring the complexity of carbohydrate metabolism (48).

Our study highlights a noteworthy increase in exogenous carbohydrate oxidation during exercise with Glu-Fru supplementation, which contrasts with the increase in glucose. This result is consistent with the findings of supporting studies (29, 37, 39, 40, 49), indicating a 35%–55% increase in exogenous carbohydrate oxidation rates with the concurrent intake of fructose compared to that with the consumption of glucose alone during exercise (40, 41). Combining fructose with glucose boosts plasma lactate production and oxidation, with minimal direct oxidation of fructose. This combination enhances intestinal absorption, leading to liver conversion of fructose into lactate, which is then oxidized. Research shows that higher exogenous glucose oxidation rates are linked to better performance in extended, moderate- to high-intensity exercise (50).

In contrast, conflicting findings from (33) challenge the presumed impact of Glu-Fru versus glucose on exogenous carbohydrate oxidation during exercise. Differences in study methods may explain the varied outcomes between Glu-Fru and Glu supplementation. Factors such as exercise duration, intensity, and type, as well as the timing and form of carbohydrate ingestion, significantly affect carbohydrate use. Additionally, varying fasting durations and preexercise meal compositions could contribute to these discrepancies. Consistent with these findings (39, 41), our study demonstrated a notable increase in endogenous carbohydrate oxidation with the ingestion of glucose compared to that with the ingestion of glucose-fructose. However, the interpretative landscape is not devoid of discordant notes (32, 33). This nuanced dichotomy may be rooted in the multifaceted interplay of methodological disparities, participant nuances, and the intricacies of training parameters.

Our study revealed a notable increase in total fat oxidation through glucose consumption. This finding aligns with prior research (29, 32, 33, 41), which also emphasized the role of glucose-fructose supplementation in enhancing overall fat oxidation during exercise.

Conversely, these results (30, 50) challenge the purported influence of glucose-fructose versus glucose on total fat oxidation during exercise. Here, the intricacies of metabolism are influenced by factors ranging from genetic predispositions to lifestyle choices and training backgrounds. The individualized nature of these factors could contribute to the contrasting results observed, highlighting the complexity inherent in understanding total fat oxidation during exercise.

A glucose-fructose solution showed 65% higher carbohydrate absorption than a glucose-only solution, due to their separate intestinal transport mechanisms. Glucose also boosts fructose absorption, potentially increasing the availability and oxidation rates of exogenous carbohydrates in the bloodstream (51).

Compared with an equivalent caloric intake of glucose, coingesting fructose has been found to enhance rates of exogenous carbohydrate oxidation and has improved performance in various studies (31, 36, 49) Excessive glucose intake during exercise can saturate SGLT1 transporters, limiting further glucose absorption and oxidation. This saturation typically occurs around 1.0–1.2 g/min. In contrast, fructose is absorbed via GLUT-5 transporters, which function separately from SGLT1, allowing different absorption dynamics (51).

Our study has several strengths, including the use of the ROB 2 tool for assessing bias, inclusion of studies regardless of publication year or language, and Egger's regression showing no publication bias. We also conducted a thorough subgroup analysis to explore sources of heterogeneity. However, we acknowledge limitations, such as the lack of established thresholds for minimal clinically important differences, which prevented us from assessing the clinical significance of our results. We did not explore the impact of geographical and ethnic variables on patient characteristics, particularly in the context of endurance exercise (52, 53). Our study's findings apply specifically to endurance athletes performing steady-state exercise, limiting generalizability to other populations. Significant heterogeneity, despite subgroup analysis, challenges clinical interpretation and may stem from variations in participant characteristics and dosages. The sample size of 125 participants in the meta-analysis, while relatively small for broader clinical research, is noteworthy within the context of sports science studies. Moreover, while we recognize that pre-exercise food intake could influence oxidation rates, we were unable to account for this variable in our analysis.

Conclusion

Glu-Fru supplementation increases total carbohydrate oxidation and exogenous carbohydrate oxidation while decreasing endogenous carbohydrate oxidation and total fat oxidation. These results highlight the complex nature of nutrient utilization during exercise. Given the limited evidence, further well-designed studies are needed to confirm these findings and enhance our understanding of athletic performance and nutrition.

Funding Sources

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Conflict of Interest Statement

None.

Data availability

All supplementary materials not presented here may be asked from the corresponding author based on reasonable apply.

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transportable carbohydrates. *Curr Opin Clin Nutr Metab Care,* 13 (4):452-7.
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