

# Effects of Hydrogel-Based Sodium Bicarbonate Supplementation on Cycling Performance and Acid–Base Balance in Trained Cyclists: a Pilot Randomized Crossover Study

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## Abstract

Sodium bicarbonate (SB) is a widely studied ergogenic aid for enhancing performance during high-intensity exercise. However, its practical use is often limited by gastrointestinal symptoms (GIS). This pilot, randomized, single-blind, placebo-controlled crossover study investigated the effects of SB in hydrogel form (SB-H) compared to a hydrogel placebo (PLA) in a small cohort of trained cyclists. Eight trained male cyclists completed both SB-H and PLA conditions in a crossover design, separated by a 7-day washout period. Performance variables, blood electrolytes, acid–base balance, and GIS were assessed during a time-to-exhaustion cycling test. SB-H supplementation improved performance, with a 7% increase in power output at the 2 mmol/L and a 15% increase at the 4 mmol/L lactate thresholds compared to PLA. Time to exhaustion was significantly longer with SB-H, and heart rate at the 4 mmol/L threshold was lower, suggesting improved cardiovascular efficiency. SB-H also mitigated exercise-induced metabolic acidosis, with higher post-exercise sodium and lower chloride levels, likely due to sweat-related electrolyte shifts. Importantly, GIS scores remained low in both groups, with SB-H demonstrating superior tolerability. This pilot study suggests that SB-H supplementation enhances high-intensity cycling performance, improves acid–base regulation, and reduces gastrointestinal discomfort. These findings provide preliminary effect size estimates and feasibility data that support further investigation in larger, fully powered trials.

**Keywords:** sodium bicarbonate, hydrogel supplementation, ergogenic aid, cycling performance, gastrointestinal tolerance

## Introduction

Sodium bicarbonate (SB) is a widely recognized extracellular buffer used to enhance performance during high-intensity muscular endurance activities such as cycling (Grgic et al., 2021). During anaerobic glycolysis, the accumulation of hydrogen ions (H<sup>+</sup>) reduces intramuscular pH, impairs the activity of glycolytic enzymes, inhibits calcium binding in the sarcoplasmic reticulum, and accelerates the onset of fatigue (Gaskell et al., 2023; Gough et al., 2024; Hilton et al., 2020).

Supplementation with SB increases the concentration of bicarbonate ions (HCO<sub>3</sub><sup>-</sup>) in the blood, increasing the body's ability to buffer excess H<sup>+</sup>, maintain acid-base homeostasis, and sustain exercise performance (Shannon et al., 2024).

To overcome these limitations, alternative delivery strategies have been proposed, including dose titration, enteric-coated capsules, and more recently, hydrogel-based formulations (Gaskell et al., 2023; Hilton et al., 2020; Shannon et al., 2024). A recent review (Grgic et al., 2021) summarized data

from nearly 200 cyclists across three decades and highlighted the limited number of studies with trained athletes, consistent exercise protocols, or novel formulations. Moreover, most investigations used uncoated SB, contributing to inconsistent results regarding performance outcomes such as time to exhaustion and power output (Ferreira et al., 2019; Gough et al., 2022; Horswill et al., 1988; McNaughton et al., 1992; Schauf et al., 1996; Yong et al., 2018).

Few studies have explored the potential of sodium bicarbonate hydrogel (SB-H), which may offer improved tolerability of gastrointestinal (GI) side effects and buffering capacity. Although initial results are promising, the available evidence is scarce and somewhat conflicting. The study by Gough et al. (2022) found no significant effects of SB-H supplementation on blood electrolyte levels, whereas Shannon et al. reported marked alterations in acid–base parameters under comparable conditions (Ferreira et al., 2019; Shannon et al., 2024). These discrepancies may arise from methodological variability and reinforce the need for controlled clinical trials in well-trained populations.

Thus, the objective of this pilot crossover study was to evaluate whether high-dose sodium bicarbonate, administered in hydrogel form, improves blood acid–base balance, enhances performance, and reduces GIS in trained cyclists during a time-to-exhaustion protocol. Given the exploratory nature of this investigation, the study was designed to generate feasibility data and preliminary effect size estimates to inform the design of future fully powered trials.

## Materials and methods

### Participants and design

Participants were randomly assigned to supplementation conditions using a computer-generated random sequence. The study followed a randomized, longitudinal, single-blind, crossover design, with each participant completing both experimental conditions (SB-H and placebo) in a randomized

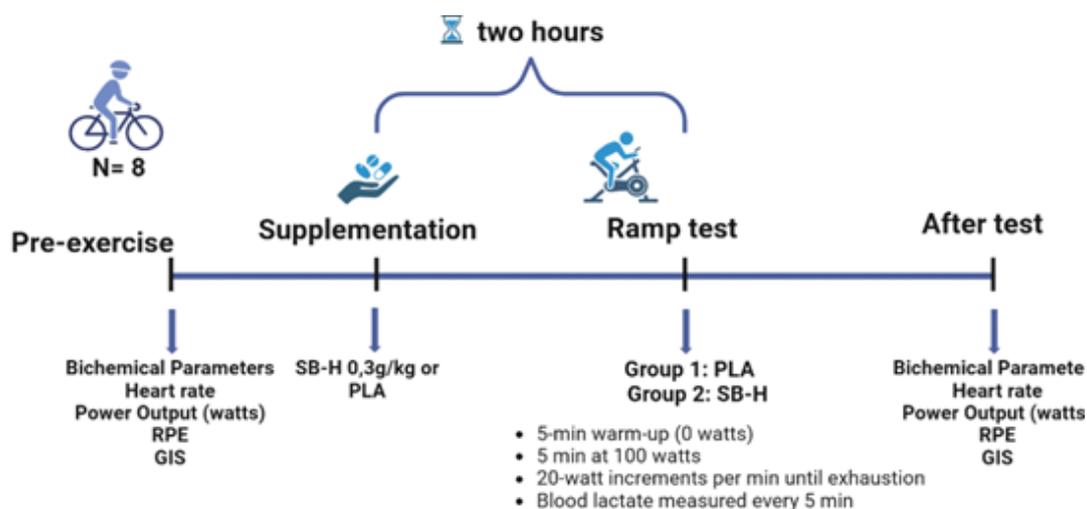
order, separated by a 7-day washout period to avoid carryover effects. The study was single-blind, with participants unaware of the supplement content (SB-H or placebo), while researchers were aware for protocol administration purposes.

Eight trained male cyclists participated in this study (age:  $41.5 \pm 5.7$  years; body mass:  $71.8 \pm 6.5$  kg; height:  $1.72 \pm 0.05$  m; cycling activity:  $11 \pm 9.3$  hours per week). Inclusion criteria required participants to have no history of chronic metabolic or musculoskeletal diseases and to engage in at least 3 hours of cycling per week. The study was approved by the Ethics Committee of FAMERP Medical School (São José do Rio Preto, Brazil; permit number: 661258), and informed consent was obtained from all participants.

### Procedures

Participants initially underwent biochemical analyses to assess serum markers related to metabolic processes and electrolyte balance. This included measurements of serum creatine phosphokinase (CPK), pH, lactate, sodium ( $\text{Na}^+$ ), potassium ( $\text{K}^+$ ), sodium bicarbonate ( $\text{NaHCO}_3$ ), serum creatinine (sCr), and chloride ( $\text{Cl}^-$ ). The anion gap was calculated as previously described (Kraut & Madias, 2007).

Simultaneously, physiological responses during exercise were monitored. Heart rate (HR) was continuously recorded throughout the exercise test to assess fluctuations indicative of cardiovascular strain and adaptation. Power output, a key measure of exercise intensity and performance, was recorded using each participant's bike mounted on a cycling ergometer. The experimental protocol consisted of three non-consecutive sessions: (a) pre-exercise assessment (Pre-Exc); (b) ingestion of  $0.3 \text{ g}\cdot\text{kg}^{-1}$  SB in hydrogel form followed by incremental ramp exercise (SB-H); and (c) ingestion of placebo hydrogel (PLA) without SB followed by the same protocol (Figure 1). The within-subject crossover design was chosen to minimize inter-individual variability and improve statistical power, which is particularly relevant in small sample pilot studies.



**Figure 1.** Schematic overview of the experimental test

Note. This single-blind, randomized study involved eight cyclists, assessing biochemical parameters, heart rate, power output, perceived exertion (RPE), and gastrointestinal symptoms (GIS). The study groups were as follows: PLA (placebo), SB-H (sodium bicarbonate supplementation in hydrogel form), and pre-exercise (no supplement).

### Supplementation protocol

SB in hydrogel form (Maurten Bicarb System<sup>®</sup>) was administered at 0.3 g/kg body mass, two hours before the exercise protocol (Maurten Bicarb System, 2025). Placebo supplement was formulated to mimic the Maurten brand's sodium bicarbonate hydrogel closely, containing 3 g of xanthan gum, 20 g of maltodextrin, 20 g of sucralose, and 20 g of sugar spheres, ensuring both supplements had an identical appearance. They were distributed to participants in individual packages, each labeled with the participant's name.

### Training protocol

Participants were instructed not to use additional buffering aids or intracellular buffers during training, and to abstain from nutritional, pharmacological, and hormonal ergogenic aids for at least 30 days prior to the study. Participants avoided strenuous exercise for 48 h, did no exercise, and did not drink alcohol for 24 h. Breakfast was consumed 3 h before the start of the warm-up, with caffeine intake restricted. After that, only water intake was allowed.

SB-H or PLA was taken 2 h before the start of the exercise. This timing was selected based on evidence indicating that peak blood bicarbonate concentrations occur approximately 2 h after ingestion, thereby optimizing extracellular buffering during the exercise protocol (Maurten Bicarb System, 2025).

The Wahoo KICKR Power Trainer was used, with the Wahoo Blue SC speed and cadence sensor, validated by Zadow et al. (2016) with power and cadence data accurately captured via Zwift simulation software. All sessions were conducted in the morning under controlled ambient conditions and temperatures.

The protocol began with a five-minute warm-up phase of free exercise, followed by a second five-minute phase of 100 W training. The third phase involved 20-watt per minute increases from 100 W, with blood lactate levels measured every five minutes using a Lactate Plus meter (Nova Biomedical, MA). This ramp protocol is consistent with validated methodologies for determining time to exhaustion and physiological thresholds. Exercise was considered complete when the participant reached exhaustion, defined as the point at which they could no longer produce sufficient power to meet the increasing power demands of the equipment. Post-testing, the Borg CR10 Scale of Perceived Exertion (RPE - 0-10) was used to assess perceived exertion levels during exercise (Williams, 2017).

### GIS - Questionnaire

The GIS assessment tool was employed to quantify self-reported gastrointestinal symptoms, as described previously (Gaskell et al., 2023). Participants were instructed on how to use the GIS rating scale, where a score of 1–4 indicates mild symptoms, 5–9 represents severe symptoms, and a score of 10 indicates extremely severe symptoms necessitating the cessation of exercise. If no symptoms were reported, a score of 0 was recorded. The questionnaire assessed nine symptoms, including bloating, nausea, abdominal pain, belching, flatu-

lence, and vomiting. The tool was administered 30 minutes post-exercise by a trained researcher to capture acute gastrointestinal responses while minimizing reporting bias (Souza et al., 2016).

### Statistical analysis

Normality of quantitative variables was assessed using the Kolmogorov–Smirnov test. Given the crossover design, all comparisons between experimental conditions (SB-H vs. PLA) were performed using paired statistical tests. For normally distributed data, the paired Student's t-test was applied; for non-normally distributed data, the Wilcoxon signed-rank test was used. When more than two conditions were compared (e.g., including Pre-Exc), the repeated-measures Kruskal–Wallis test followed by Dunn's post hoc test was employed.

For categorical variables, comparisons of frequencies were conducted using the McNemar test for paired proportions or Chi-square test when appropriate. Statistical significance was set at  $p < 0.05$ . All analyses were performed using GraphPad Prism, version 9.1 (GraphPad Software Inc., USA). As this was a pilot crossover study, no a priori sample size calculation was performed; instead, effect sizes were estimated to inform the design of future fully powered trials. The randomized crossover design, in which each participant served as their own control, was chosen to reduce interindividual variability and partially compensate for the small sample size, increasing sensitivity for within-subject comparisons.

## Results

Given the pilot nature of the study, the results below emphasize outcomes with the greatest physiological and practical relevance, particularly power output at the 4 mmol/L lactate threshold, HR responses, and time to exhaustion.

### Blood acid-base balance, lactate levels, and electrolyte response

The efficacy of the endurance cycling protocol was evidenced by significant reductions in plasma pH, SB, and chloride levels, along with increases in anion gap, lactate, and blood CPK levels in the PLA and SB-H groups when compared to pre-exercise values (Table 1 and Figure 2). During the pre-exercise phase, blood pH remained within the normal range. However, cycling performance induced metabolic acidosis, resulting in decreased pH in the SB-H and PLA groups ( $p = 0.007$  and  $p = 0.01$ , respectively). This acidosis was accompanied by a four- and five-fold increase in blood lactate levels in the PLA and SB-H groups, respectively, which correlated with an increase in the anion gap of both exercise groups. Despite the acid–base disturbance, performance capacity was preserved, suggesting that SB-H may have contributed to the maintenance of muscular function under acidotic conditions (Figure 2). Higher plasma sodium concentrations (PLA:  $p = 0.04$ ; SB-H:  $p < 0.0001$ ) and lower chloride levels (PLA:  $p = 0.04$ ; SB-H:  $p = 0.0002$ ) were observed in both cycling groups compared to pre-exercise values.

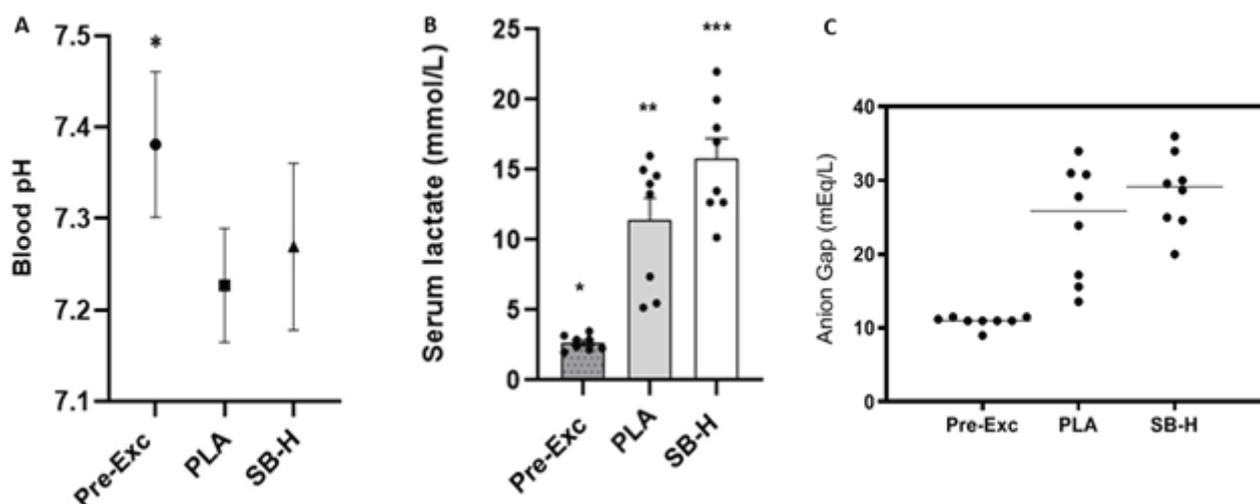
**Table 1.** Blood tests pre and post ingestion of bicarbonate hydrogel (SB-H) or placebo (PLA)

Variables	Pre-Exc	PLA	SB-H	*p-value (Pre-Exc vs Pla)	**p-value (Pre-Exc vs SB-H)	***p-value (SB-H vs Pla)
NaHCO <sub>3</sub> (mmol/L)	28±1.5	19±5.3	19±3.6	0.0005	<0.0001	0.84
Serum creatinine (mg/dL)	1±0.18	1±0.42	1±0.19	1	1	1
CPK (U/L)	192±173	260±221	427±420	0.008	0.03	0.07
Plasma Na <sup>+</sup> (mM)	141±1.3	143±2	146±2.4	0.04	<0.0001	0.009
Plasma K <sup>+</sup> (mEq/L)	4.7±1.2	4±0.31	4.3±0.4	0.1	0.37	0.10
Plasma Cl <sup>-</sup> (mEq/L)	102±1.3	100±2.8	99 ±1.55	0.04	0.0002	0.25

Note. NaHCO<sub>3</sub>: Sodium bicarbonate; CPK: Creatine Phosphokinase; Na<sup>+</sup>: sodium; K<sup>+</sup>: potassium; Cl<sup>-</sup>: Chloride. p\*=significance between: Pre-Exc and placebo groups; p\*\*=significance between Pre-Exc and SB-H groups; p\*\*\*=significance between SB-H and PLA groups. Data are presented as mean±SD.

Serum creatinine and plasma K<sup>+</sup> levels remained unchanged pre- and post-exercise in both groups. However, CPK levels increased significantly, with a 35% rise in the PLA group and a 122% rise in the SB-H group compared to pre-exercise levels (p=0.008 and p=0.03, respectively). These increases sug-

gest a physiological response to prolonged or intense physical activity. The marked increase in CPK, particularly in the SB-H condition, may reflect a greater muscular effort and metabolic stress response, possibly associated with enhanced exercise performance.



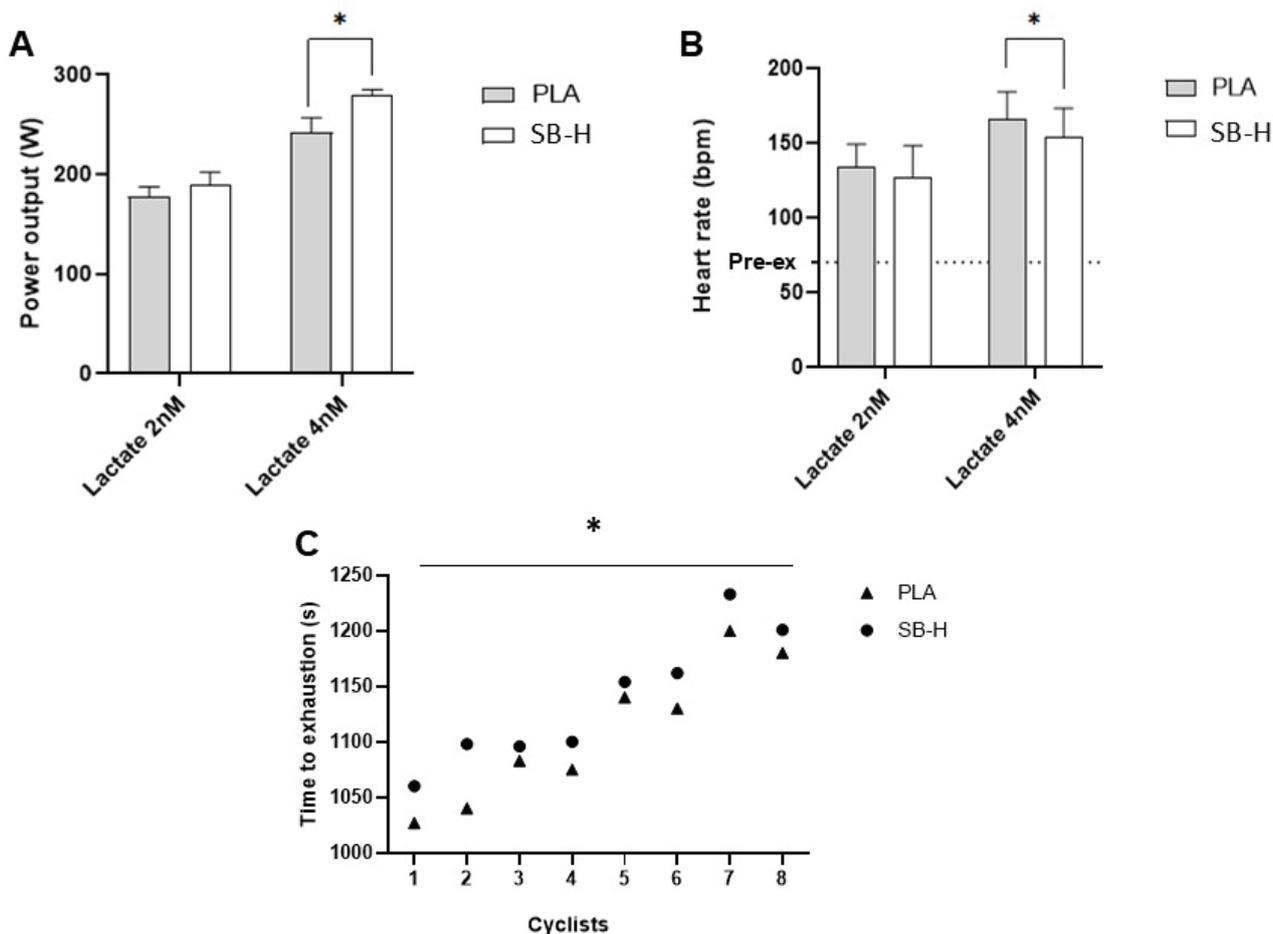
**Figure 2.** Effects of sodium bicarbonate in hydrogel form (SB-H) and placebo (PLA) physiological responses

Note. Blood pH (A), serum lactate (B), and anion gap (C) before exercise (Pre-Exc) and after placebo (PLA) or sodium bicarbonate hydrogel (SB-H) supplementation. (A) Pre-Exc had higher pH than PLA and SB-H (\*P=0.007, 0.01). (B) Serum lactate was higher in PLA than Pre-Exc and SB-H groups (\*P=0.001, \*\*P=0.04, \*\*\*P=0.002). (C) Anion gap was higher in Pre-Exc than PLA and SB-H groups (\*P=0.007 and 0.01 respectively). Data are presented as mean±SEM.

**Exercise performance**

The effects of SB-H supplementation on power output, HR, and time to exhaustion at lactate concentrations of 2 and 4 mM are presented in Figure 3. At 2 mM lactate, the SB-H group exhibited a 7% increase in power output (equivalent to 12 W) compared to the PLA group, although this difference

was not statistically significant. Nevertheless, this magnitude of improvement may hold biological relevance, particularly in submaximal or pacing-based efforts where small gains in power can yield performance advantages. At 4 mmol/L lactate, the SB-H group demonstrated a significantly higher power output than the PLA group, highlighting a clear energetic advantage associated with supplementation.



**Figure 3.** Impact of bicarbonate supplementation on power output, heart rate (HR) and time to exhaustion

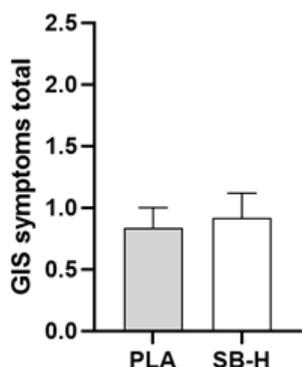
Note. A) Power output at lactate 2mM and 4mM, \* $p=0.02$ ; B) HR at the 2mM and 4mM lactate level, \* $p=0.009$  (values of Pre-Exc are set at 70 bpm); C) Time to exhaustion comparison between PLA and SB-H, \* $p=0.001$ . Data are presented as mean  $\pm$  SD.

Regarding HR, no significant differences were observed between the groups at 2 mmol/L lactate. At 4 mmol/L lactate, however, the SB-H group exhibited a significantly lower HR, suggesting reduced cardiovascular strain and potentially enhanced physiological efficiency during high-intensity efforts.

The time to exhaustion was longer in the SB-H group compared to the PLA group ( $p=0.001$ ), further indicating that SB-H supplementation may extend endurance capacity under increasing workload conditions.

### Gastrointestinal side effects

The responses to the GIS questionnaire revealed no statistically significant differences in total symptom scores between the SB-H and PLA groups, as shown in Figure 4. Both groups reported generally low levels of GIS across the evaluated metrics. For example, stomach bloating was reported with mild frequency in both groups, while symptoms such as flatulence, nausea, and belching exhibited slight variations but remained minimal overall. No severe gastrointestinal symptoms, such as diarrhea and vomiting, were reported by any participant in either group.



**Figure 4.** Comparison of gastrointestinal symptoms (GIS) total scores between PLA (placebo) and SB-H (sodium bicarbonate in hydrogel form) groups

Note. The GIS total score represents the incidence and severity of symptoms reported by participants, with no significant differences observed between the groups. Data are presented as mean  $\pm$  SD.

## Discussion

SB supplementation has been widely recognized for its ergogenic properties, primarily due to its ability to buffer metabolic acidosis and sustain anaerobic energy production during high-intensity efforts (Lancha et al., 2015). The extracellular buffering provided by SB delays the drop in intramuscular pH, preserving enzymatic activity and calcium handling, thereby supporting muscle contractility and delaying fatigue (Lancha et al., 2015).

Although SB supplementation did not restore blood pH to pre-exercise levels, it allowed cyclists to improve their ergogenic performance despite elevated blood lactate concentrations and comparable anion gap values relative to the PLA group. This reflects the capacity of SB-H to enhance systemic buffering without fully normalizing pH, suggesting effective compensation rather than total correction. This alkalinizing effect facilitates the neutralization of hydrogen ions ( $H^+$ ) produced during intense exercise, thereby delaying muscle fatigue (Grgic & Mikulic, 2022; Lancha et al., 2015).

The higher lactate levels observed in the SB-H group, when compared to PLA, suggest increased glycolytic flux and greater reliance on anaerobic metabolism (Correia-Oliveira et al., 2017; Zagatto et al., 2012). Importantly, this was not accompanied by premature exhaustion, indicating that SB-H supported sustained metabolic activity even under high lactate conditions. These dual effects reinforce the role of SB not only in buffering acidosis but also in sustaining energy output during high-intensity exercise, in line with previous research (Grgic & Mikulic, 2022; Lancha et al., 2015).

Performance improvements were especially evident at the 4 mmol/L lactate threshold, where the SB-H group demonstrated significantly higher power outputs. This supports the hypothesis that SB-H supplementation enhances extracellular buffering, improves metabolic efficiency, and delays neuromuscular fatigue under anaerobic stress (Correia-Oliveira et al., 2017; Grgic & Mikulic, 2022).

Furthermore, the longer time to exhaustion and the reduced HR at the 4 mmol/L threshold reinforce SB-H's ergogenic potential. The lower HR may reflect improved cardiovascular efficiency or enhanced peripheral muscle oxygen utilization, both of which are critical to prolonged performance in endurance and high-intensity interval modalities (Brisola et al., 2015; Cameron et al., 2010; Carr et al., 2011; Freis et al., 2017; Gurton et al., 2021). From an applied perspective, a lower HR at a fixed lactate threshold may allow cyclists to sustain higher workloads with reduced cardiovascular strain, thereby facilitating more efficient pacing during threshold and high-intensity efforts.

Our results align with those of Shannon et al. (2024), who also demonstrated improved cycling performance and superior GI tolerability using a hydrogel-based bicarbonate formulation. While their study emphasized prolonged aerobic performance, ours focused on high-intensity anaerobic conditions, extending the translational relevance of SB-H to sprint-based or threshold training contexts. Notably, the 7% increase in power output at 2 mmol/L lactate, although not statistically significant, holds biological relevance, particularly in settings where submaximal effort optimization is critical

for pacing strategies and endurance outcomes.

The low incidence of GIS reported with SB-H underscores the practicality of this delivery method. Mitigating the common adverse effects of bicarbonate such as bloating, cramping, and nausea has been a longstanding challenge, and the hydrogel formulation appears to overcome this barrier effectively (Carr et al., 2011; Hilton et al., 2020; Shannon et al., 2024).

In our view, the absence of a traditional SB comparison group does not represent a methodological gap, as the effects of uncoated or conventional SB supplementation are already extensively described in the literature (Ferreira et al., 2019; Grgic et al., 2021; Yong et al., 2018). Rather, this study was specifically designed to evaluate the performance and physiological response to a hydrogel formulation, which remains underexplored despite promising results in previous trials. Our findings contribute to this underrepresented area and provide additional insights into the utility of SB-H in high-intensity settings.

The lack of significant alterations in sCr, potassium, and the absence of clinical muscle damage (despite elevated CPK) further support the safety profile of SB-H supplementation (Grgic et al., 2021; McKenna et al., 2008; McNaughton et al., 2008; Wang et al., 2020). This is particularly relevant given recent concerns regarding the renal and muscular impact of chronic supplementation protocols in athletes.

Previous studies have yielded mixed findings regarding the performance-enhancing effects of SB (Mildenhall et al., 2023) observed attenuation of acid-base disturbances without improvements in supramaximal cycling performance, while Correia-Oliveira et al. (2017) found that pre-exercise alkalosis preserved anaerobic energy output during a 4-km time trial. Our findings add to this body of evidence, indicating that the hydrogel formulation provides a viable compromise between efficacy and tolerability, with measurable benefits under controlled, incremental-intensity exercise protocols.

A major strength of this study lies in its randomized crossover design, which allows each participant to serve as their own control, thereby eliminating interindividual variability. This statistical advantage increases sensitivity to detect within-subject differences, even in small samples, and enhances the reliability of effect-size estimation especially relevant in pilot trials where feasibility and biological plausibility are primary goals.

Nonetheless, this study has several limitations inherent to its pilot design. The small sample size limits generalizability and statistical power for some comparisons, and the cohort was composed exclusively of male participants, which precludes sex-specific analysis. Although the randomized crossover design strengthens internal validity by reducing interindividual variability, the absence of a conventional sodium bicarbonate comparison group should also be acknowledged.

Despite these limitations, the findings suggest that SB-H enhances performance in high-intensity cycling by improving power output, extending time to exhaustion, stabilizing acid-base balance, and minimizing GIS. These results should be interpreted as preliminary and hypothesis-generating, and support SB-H as a promising and well-tolerated ergogenic aid,

with direct implications for training and competition strategies in endurance and high-performance athletes.

## Conclusions

Hydrogel-based sodium bicarbonate supplementation improved key performance outcomes during high-intensity cycling, including higher power output at the 4 mmol/L lactate threshold and longer time to exhaustion, while preserving cardiovascular efficiency and minimizing gastrointestinal discomfort. Although metabolic acidosis was not fully corrected, SB-H effectively enhanced extracellular buffering capacity, supporting sustained glycolytic activity and delaying fatigue under progressively demanding workloads. The absence of adverse renal or electrolyte disturbances further reinforces the safety profile of this formulation. Overall, SB-H emerges as a practical and well-tolerated ergogenic strategy, with particular relevance for threshold-based efforts, time trials, and high-intensity or anaerobically demanding cycling contexts.

### Acknowledgments

There are no acknowledgments.

### Conflicts of interest

The authors declare no conflict of interest.

**Received:** 03 December 2025 | **Accepted:** 17 January 2026 | **Published:** 01 February 2026

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