The effect of citrulline on delayed onset muscle soreness (DOMS) and aerobic and anaerobic endurance in sub elite athletes

Efecto de la citrulina sobre el dolor muscular de aparición retardada (DOMS) y la resistencia aeróbica y anaeróbica en atletas de subélite

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Recibido: 23-03-25
Aceptado: 11-08-25

How to cite in APA

Wibowo, S., Wismanadi, H., Rusdiawan, A., Wiriawan, O., Özman, C., Ar Rasyid, M. L. S., Ashadi, K., Lufthansa, L., Ilmah, N. K., & Hidayat, T. (2025). The effect of citrulline on delayed onset muscle soreness (DOMS) and aerobic and anaerobic endurance in sub elite athletes. *Retos, 72*, 598-610. https://doi.org/10.47197/retos.v72.114696

Abstract

Introduction: Athletes can improve their performance by adjusting their diet and consuming citrulline, a nonessential amino acid that affects VO2max by increasing plasma arginine concentration and nitric oxide production.
Objective: This study investigates the impact of citrulline supplementation on athletes' performance and endurance after eccentric exercise, focusing on its effects on VO_2max and DOMS.
Methodology: A quasi-experimental study involved 36 badminton athletes in citrulline (CIT) and placebo (PLA) groups. Citrulline and cornstarch capsules were given daily for seven days before the post-test. Anaerobic and aerobic endurance tests (RAST and MFT) were conducted, and DOMS levels were measured using the Visual Analogue Scale (VAS).
Results: The CIT group experienced significant improvements in anaerobic endurance at posttest 1, but not at posttest 2. In aerobic endurance, the CIT group recorded significant improvements at both posttests, with the largest effect at posttest 2 (d = 1.892). In addition, DOMS soreness levels decreased more rapidly in the CIT group than in the PLA group, with significant differences ($p < 0.05$) at 24, 48, and 72 hours after eccentric exercise.
Discussion: Citrulline supplementation increased aerobic endurance and accelerated DOMS recovery, consistent with the findings of Pérez-Guisado & Jakeman (2010). The small effect on anaerobic endurance, on the other hand, fits with the research of Rhim et al. (2020), showing that response variation depends on parameters.
Conclusions: Citrulline supplementation accelerates muscle soreness recovery and improves aerobic and anaerobic endurance in athletes by increasing nitric oxide production and reducing post-exercise muscle soreness.

Keywords

Citrullline; DOMS; aerobic endurance; anaerobic endurance; badminton.

Resumen

Introducción: Los atletas pueden mejorar su rendimiento ajustando su dieta y consumiendo citrulina, un aminoácido no esencial que afecta al VO2máx al aumentar la concentración plasmática de arginina y la producción de óxido nítrico.
Objetivo: Determinar el efecto de la suplementación con citrulina durante 7 días sobre el DOMS y la resistencia aeróbica y anaeróbica en atletas tras un ejercicio excéntrico. Este estudio investiga el impacto de la suplementación con citrulina en el rendimiento y la resistencia de los atletas después del ejercicio excéntrico, centrándose en sus efectos sobre el VO_2max y el DOMS.
Metodología: Determinar el efecto de la suplementación con citrulina durante 7 días sobre el DOMS y la resistencia aeróbica y anaeróbica en atletas tras un ejercicio excéntrico. Este estudio investiga el impacto de la suplementación con citrulina en el rendimiento y la resistencia de los atletas después del ejercicio excéntrico, centrándose en sus efectos sobre el VO_2max y el DOMS.
Resultados: El grupo CIT experimentó mejoras significativas en la resistencia anaeróbica en la postprueba 1, pero no en la postprueba 2. En la resistencia aeróbica, el grupo CIT registró mejoras significativas en ambas postpruebas, con el mayor efecto en la postprueba 2 (d = 1,892). Además, los niveles de dolor DOMS disminuyeron más rápidamente en el grupo CIT que en el grupo PLA, con diferencias significativas ($p < 0,05$) a las 24, 48 y 72 horas después del ejercicio excéntrico.
Discusión: La suplementación con citrulina aumentó la resistencia aeróbica y aceleró la recuperación del DOMS, de acuerdo con los hallazgos de Pérez-Guisado y Jakeman (2010). El pequeño efecto sobre la resistencia anaeróbica, por otro lado, encaja con la investigación de Rhim et al. (2020), mostrando que la variación de la respuesta depende de los parámetros.
Conclusiones: La suplementación con citrulina acelera la recuperación del dolor muscular y mejora la resistencia aeróbica y anaeróbica en atletas al aumentar la producción de óxido nítrico y reducir el dolor muscular post-ejercicio.

Palabras clave

Citrulina; DOMS; resistencia aeróbica; resistencia anaeróbica; bádminton.

Introduction

To achieve high performance, athletes need optimal body performance when competing. However, there are several things that interfere with athlete performance, such as fatigue. Fatigue, a decrease in muscle power due to job demands, can lead to a decrease in performance (Kusuma, 2018). An athlete who feels worn out can affect his physical endurance on the field. If fatigue persists, it will cause athletes to have difficulty concentrating, and athlete performance will decrease (Hasanah & Fitranti, 2015).

Furthermore, regulating diet and nutritional intake in athletes plays a significant role in enhancing their performance and achievements (Beck et al., 2015). Additionally, athletes can improve their sports performance by consuming a nutritional intake known as citrulline (Rizal & Segalita, 2018). Nutritional supplementation is a tactic frequently employed by athletes and recreational participants to enhance physical performance (Grala et al., 2021). However, sports practitioners and individuals actively involved in sports remain largely unaware of the crucial role that citrulline plays in enhancing sports performance (Setiowati & Sumartiningsih, 2020). Studies indicate that citrulline supplementation can enhance recovery and performance in athletes, especially during high-intensity activities such as badminton. However, the majority of research has concentrated on the general population or athletes from different sports, with insufficient focus on the dynamics of delayed onset muscle soreness (DOMS) and aerobic-anaerobic capacity. This study addresses this gap and offers evidence-based recommendations to enhance athlete performance and recovery.

Citrulline is a non-essential amino acid that is thought to affect VO2max because it can increase plasma arginine concentration to produce NO (nitric oxide) (Collins et al., 2007), NO plays a role in increasing blood flow (Setiawan & Widyastuti, 2016), and increased blood flow can increase the supply of oxygen and more nutrients to the muscles, thereby increasing VO2max (Botchlett et al., 2019). Citrulline found in yellow watermelon can also improve sports performance, especially anaerobic types, by accelerating blood pressure recovery, lactic acid levels, and anaerobic endurance (Rusdiawan & Habibi, 2020). According to Rhim et al. (2020), citrulline supplements can greatly lower the rate of perceived exertion and muscle soreness after exercise without changing the levels of lactate. Administration of citrulline, whether by supplements or watermelon, for one week or a single hour before a physical activity assessment, is purported to enhance VO_2max, postpone muscle fatigue, and alleviate post-exercise muscle soreness (Rizal & Segalita, 2018).

Numerous studies have demonstrated that citrulline, a non-essential amino acid, plays a crucial role in elevating nitric oxide levels, which in turn regulate blood flow, energy metabolism in muscles, and mitochondrial respiration during sports activities (T. Suzuki et al., 2016). Citrulline is an amino acid that is not a protein. It is involved in three metabolic pathways: getting rid of ammonia through the urea cycle, turning glutamine into arginine in the intestines and kidneys, and making nitric oxide (Rabier & Kamoun, 1995). In addition to being in the form of supplements, the main source of citrulline in food is watermelon (Citrullis vulgaris) (Kaore et al., 2013).

Pérez-Guisado and Jakeman (2010) carried out an examination that specifically demonstrated that citrulline malate supplementation is responsible for increasing anaerobic exercise performance and removing post-exercise muscular soreness. However, these assertions are pending confirmation within the DOMS setting and a wider range of athletes. A study by Suzuki et al. (2016) The addition of citrulline to the barre plan significantly improves the aerobic exercise performance of trained athletes. However, more research should fill this gap. DOMS is characterized by an array of symptoms, including structural damage to the muscles, inflammation, and oxidative stress (Cheung et al., 2003). Apart from its anti-inflammatory effect, citrulline may also pull off DOMS by improving blood circulation, the primary healing and regeneration mechanism (Figueroa et al., 2013).

Although some early studies have shown promising results, there is still a gap in knowledge regarding the optimal dosage, timing, and long-term effects of citrulline supplementation in athletes. In addition, individual variation in response to citrulline supplementation also needs to be taken into account. Therefore, further research is needed to clarify the effects of citrulline on DOMS and aerobic and anaerobic endurance in athletes. This will provide a stronger scientific basis for the use of citrulline in sports nutrition and may help optimize supplementation protocols to improve athlete performance and recovery.

The study specifically examines the hypothesis that supplementing with L-citrulline for seven days will significantly enhance athletes' physical performance. It looks at whether taking citrulline can help improve short bursts of exercise, lessen muscle pain after tough workouts, and boost overall endurance, as shown by VO_2 max tests, when compared to a group that didn't take it. This research seeks to provide real proof about how well citrulline works as a nutritional method to help athletes perform better and recover by testing these three factors at the same time in sub-elite badminton players.

Method

Participants

This study employs a quantitative, quasi-experimental research design. The research design uses a randomized group pretest and posttest design. The research subjects used in this study were badminton athletes from Universitas Negeri Surabaya (UNESA). The purposive sampling technique determined the research sample based on the following criteria: male gender, age 19-23 years, normal body mass index (BMI) and blood pressure, experience as a badminton athlete for at least 7 years, achievement at the district or city level in the last 5 years, and absence of injury in the last 6 months. The recruitment process yielded 36 UNESA badminton players, who were divided into two equal groups: the CIT Group, which received citrulline, and the PLA Group, which received only a placebo.

When planning the sample size, we considered power for a two-group comparison test (two-sample t-test, two-sided, $\alpha = 0.05$). The following sample size estimates per effect size scenario (Cohen's d) were calculated using general guidelines (G*Power/standard formula): Approximately 26 participants per group (total $N \approx 52$) were needed for a medium effect ($d = 0.8$); about 12 participants per group (total $N \approx 24$) were required for a large effect ($d = 1.2$). We recruited 18 participants per group (total N = 36) due to resource constraints and the relatively large effects on some outcomes reported by prior studies on citrulline supplementation (Pérez-Guisado & Jakeman, 2010 and related studies).

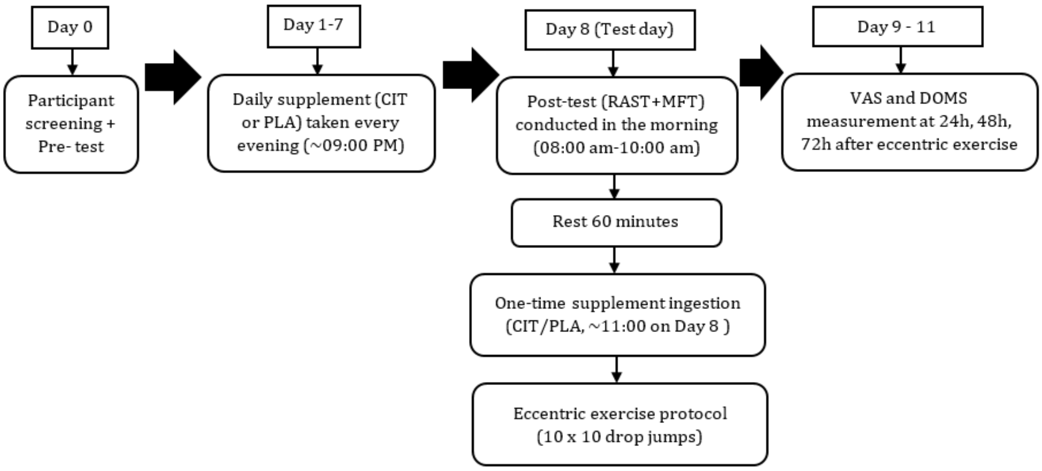
Procedure

Before initiating the research process, the researcher informed the research subjects about the process and objectives of the study, and provided a consent form to conduct the research until its completion. The researcher directed the research subjects who agreed to fill out the research informed consent form. Furthermore, the research subjects underwent an initial health test, namely blood pressure, heart rate, weight and height, and body mass index (BMI). Besides the initial health test, the subjects also completed a form detailing their athlete experience and accomplishments. The research subjects underwent a pre-test (anaerobic endurance using the RAST test and aerobic endurance using the MFT test). All participants used the MFT test to complete a baseline aerobic endurance assessment (VO_2max) before group assignment. Participants were paired according to the closest VO_2max values after the VO_2max scores were sorted in descending order. A computer-generated random number sequence (RAND function, Microsoft Excel) determined group allocation for each matched pair. Citrulline supplementation (CIT) was given to the participant with the higher random number, while a placebo (PLA) was given to the other participant. A research assistant not involved in recruitment, testing, or data analysis created and carried out the randomization sequence to ensure allocation concealment. Until the study was over, neither the participants nor the researchers doing the performance evaluations and data analysis could see the group assignments. Next, we used the ordinal pairing technique to divide the research subjects into two groups of the same number, based on the results of the MFT test. CIT Group has citrulline administration, and PLA group has placebo administration.

The citrulline and placebo supplements were packaged in identical, opaque, unmarked sachets with the same weight (2.4 g per serving) to maintain blinding. The white powders were ground to a similar fine consistency. Before consumption, both were mixed with 200 ml of flavored, sugar-free sports drink to mask any potential taste or odor differences. This approach ensured participants could not distinguish between the citrulline and placebo based on taste, smell, or appearance. For seven consecutive days prior to the post-test, participants in the CIT group consumed 2.4 grams of L-citrulline (Kyowa Hakko Bio Co., Ltd., Tokyo, Japan), and participants in the PLA group consumed 2.4 grams of cornstarch (Nippon NSC Co., Ltd., Tokyo, Japan) (T. Suzuki et al., 2016). The supplements were consumed once daily at a fixed time in the evening (approximately 21:00), regardless of training schedule, to maintain consistency across participants.

On the eighth day, in the morning (between 08:00–10:00), participants returned to the laboratory to perform the post-test of anaerobic endurance (RAST) and aerobic endurance (MFT). After completing the post-tests and resting for approximately 60 minutes until reaching their baseline heart rate, participants again consumed their assigned supplement (CIT or PLA). Sixty minutes following ingestion, participants performed an eccentric exercise protocol involving 10 sets of 10 maximal drop jumps (Lau et al., 2015), designed to induce Delayed Onset Muscle Soreness (DOMS). Muscle soreness was then measured using the Visual Analogue Scale (VAS) at 24, 48, and 72 hours after the eccentric protocol.

Figure 1 Experimental Timeline of Supplementation and Testing Procedures



All participants abstained from intense physical activity for at least 48 hours before baseline (pre-test) measurements to reduce any possible carryover effects from previous training or competition. To guarantee complete physiological recovery from testing, there was a minimum 72-hour recovery period after the pre-test evaluations before starting the supplementation phase. There was no need for an interventional washout period in between treatments because the current study employed a parallel-group design rather than a crossover design. Aside from the scheduled eccentric exercise regimen, no extra high-intensity sessions were added during the seven-day supplementation period, and training loads were standardized across groups. To preserve the desired DOMS response and allow acute fatigue effects to fade, participants were observed for at least 72 hours following the intervention and eccentric exercise session before final post-test measurements.

Instrument and Data Collection

This study examined aerobic endurance, anaerobic endurance, and pain associated with delayed onset muscle soreness (DOMS). The Running-based Anaerobic Sprint Test (RAST) was used to assess anaerobic endurance. The test consists of six maximal sprints over a distance of 35 meters, each separated by a 10-second passive recovery interval. All sprints were performed on a standard indoor track, with participants instructed to exert maximal effort in each sprint. Sprint times were recorded using a stopwatch, and anaerobic power variables (peak power, mean power, and fatigue index) were calculated according to the standard RAST protocol (Rusdiawan et al., 2020; Rusdiawan & Habibi, 2020).

We used the Multi Fitness Test (MFT) instrument to measure aerobic endurance. Subjects covered a total distance of 20 meters provided by the MFT test in a time corresponding to a gradually increasing beeping rhythm. We opened the test slower than before and gradually progressed it. A "beep sound" signaled a cutoff point in the second half if the participant failed to reach the line after three consecutive attempts. The VO2 max calculator estimated aerobic capacity based on the final success rate. We performed the MFT several hours after the RAST. Participants initially performed dynamic stretching and light sprinting for 5 to 10 minutes to minimize the risk of injury (Paradisis et al., 2014).

Perceived muscle soreness was measured using the Visual Analogue Scale (VAS) (Kafrawi et al., 2024). The scale was anchored with "no pain" at the left end (0 cm) and "worst pain imaginable" at the right end (10 cm). It was a 10 cm horizontal line. Participants were shown how to use the scale and given standardized verbal instructions before the first measurement. Each participant was asked to provide sample ratings for mild, moderate, and severe discomfort based on made-up scenarios to ensure they understood the scale's continuum. This familiarization session was held in a relaxed, seated position to reduce distractions. Without talking to other participants, participants were told to make a single vertical mark on the line representing how sore they felt at the measurement time. The pain score was calculated by measuring the distance in centimeters between the mark and the "no pain" anchor.

Data analysis

The techniques employed for data analysis include descriptive statistical tests, Wilcoxon tests, and Mann-Whitney tests. The Wilcoxon and Mann-Whitney tests were employed due to the Shapiro-Wilk normality test indicating that the study data were not normally distributed ($p < 0.05$). We used Microsoft Excel 2016 and SPSS version 25 software for the data analysis procedure.

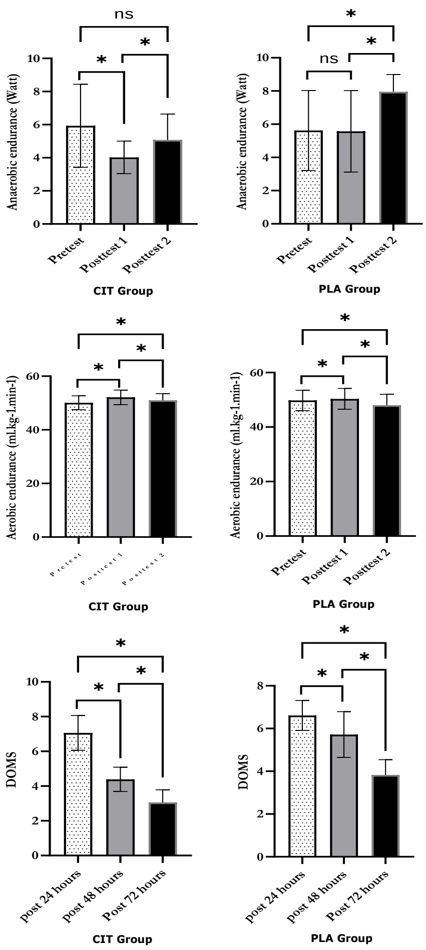
Results

The 36 participants in this study were separated into two equally sized groups, comprising 18 persons in the CIT group and 18 in the PLA group. Table 1 displays the outcomes of descriptive statistical analyses, including the characteristics of participants and dependent variables in this study. The research participants are characterized by height, weight, body mass index (BMI), age, and training experience; the dependent variables are delayed-onset muscle soreness (DOMS), aerobic endurance, and anaerobic endurance. The 36 participants in this study were allocated into two equally sized groups, comprising 18 persons in the CIT group and 18 in the PLA group. Table 1 displays the outcomes of descriptive statistical analyses, encompassing the attributes of participants and dependent variables in this research. The research participants are characterized by height, weight, body mass index (BMI), age, and training experience; the dependent variables are delayed-onset muscle soreness (DOMS), aerobic endurance, and anaerobic endurance.

Table 1. Participant Characteristics and Descriptive Statistics of Dependent Variables in CIT and PLA Groups

Variable	Mean ± SD	
	CIT Group (n=18)	PLA Group (n=18)
Participant characteristic:		
Height (m)	1.70 ± 0.03	1.67 ± 0.06
Weight (Kg)	63.72 ± 4.11	62.33 ± 4.54
BMI (Kg/m^2)	22.16 ± 1.33	22.47 ± 1.52
Age (years)	21.06 ± 0.87	21.17 ± 0.71
Practice Experience (years)	10.17 ± 2.50	9.94 ± 2.24
Dependent Variable:		
Pre test anaerobic endurance	5.93 ± 2.51	5.62 ± 2.41
Post test 1 anaerobic endurance	4.02 ± 0.98	5.57 ± 2.45
Post test 2 anaerobic endurance	5.80 ± 1.56	7.95 ± 1.04
Δ Pre – Post 1 anaerobic endurance	13.63 ± 30.05	-0.05 ± 0.39
Δ Pre – Post 2 anaerobic endurance	-0.13 ± 2.56	2.32 ± 2.63
Δ Post 1 – Post 2 anaerobic endurance	1.78 ± 2.24	2.38 ± 2.69
Pre test aerobic endurance	50.08 ± 2.60	49.76 ± 3.73
Post test 1 aerobic endurance	52.10 ± 2.72	50.34 ± 3.81
Post test 2 aerobic endurance	51.03 ± 2.44	48.04 ± 3.97
Δ Pre – Post 1 aerobic endurance	2.02 ± 1.46	0.58 ± 0.84
Δ Pre – Post 2 aerobic endurance	0.95 ± 1.69	-1.72 ± 1.06
Δ Post 1 – Post 2 aerobic endurance	-1.07 ± 0.88	-2.30 ± 0.76
DOMS 1 (24 hours)	7.06 ± 1.00	6.61 ± 0,70
DOMS 2 (48 hours)	4.39 ± 0.70	5.72 ± 1.07
DOMS 3 (72 hours)	3.06 ± 0.73	3.83 ± 0.71
Δ DOMS 1 – DOMS 2	-2.67 ± 1.28	-0.89 ± 1.18
Δ DOMS 1 – DOMS 3	-4.00 ± 1.46	-2.78 ± 0.94

Figure 2. Changes in aerobic endurance, anaerobic endurance, and DOMS after performing eccentric exercise and being given supplementation



Note: Error bars indicate mean ± SD. * indicates p < 0.05; ns = not significant. Values in parentheses represent 95% Confidence Intervals (CI) for between-group differences.

The mean height of the CIT group was 1.70 ± 0.03 meters, slightly higher than the PLA group, which had a mean of 1.67 ± 0.06 meters. In terms of body weight, the CIT group had an average body weight of 63.72 ± 4.11 kg, slightly heavier than the PLA group with a body weight of 62.33 ± 4.54 kg. The BMI of both groups was almost the same: 22.16 ± 1.33 kg/m2 in the CIT group and 22.47 ± 1.52 kg/m2 in the PLA group. The mean age of the study subjects in both groups was almost the same, which was 21.06± 0.87 years in the CIT group and 21.17± 0.71 years in the PLA group. The mean training experience in the CIT group was 10.17 ± 2.50 years, slightly more than the PLA group, which had an average experience of 9.94 ± 2.24 years. The results showed significant differences in anaerobic and aerobic endurance variables between the two groups. The results showed a decrease in power output for the CIT group in the anaerobic endurance test, from 5.93 ± 2.51 watts in the pre-test to 4.02 ± 0.98 watts in the 1st post-test, followed by an increase to 5.80 ± 1.56 watts in the 2nd post-test. In contrast, 5.62 ± 2.41 watts for the PLA group in the pre-test, 5.57 ± 2.45 watts in the first post-test, and significantly 7.95 ± 1.04 watts in the second post-test. In the area of aerobic endurance and in the CIT group, there was an increase in the first post-test from 50.08 ± 2.60 ml/kg/min in the pre to 52.10 ± 2.72 ml/kg/min; however, it was followed by a decrease in the second post-test (51.03 ± 2.44 ml/kg/min). The PLA group showed a small increase in the first post-test, from 49.76 ± 3.73 ml/kg/min to 50.34 ± 3.81 ml/kg/min, but decreased in the second post-test to 48.04 ± 3.97 ml/kg/min.

Furthermore, measurements of DOMS (Delayed Onset Muscle Soreness) or muscle pain demonstrated a faster reduction in pain for the CIT versus the PLA group. 24 h such that the CIT group reported DOMS of 7.06 ± 1.00 in comparison to PLA with 6.61 ± 0.70. (Data from DOMS were reduced from 5.72 ± 1.07 in the PLA group to 4.39 ± 0.70, i.e., reduced to 23.26%.) At 72 hr postexercise, DOMS for the CIT group was significantly lower at 3.06 ± 0.73 compared with 3.83 ± 0.71 for the PLA group. The findings suggest that the use of citrulline may reduce soreness from the workout, as well as improve performance in endurance.

Table 2. The CIT and PLA groups differ in terms of aerobic and anaerobic endurance and DOMS

Variable	Group	p-value		Effect Size Cohen's d
		Wilcoxon	Mann-Whitney	
Pre – Post 1 Anaerobic Endurance	CIT Group PLA Group	0.001 0.499	0.161	0.643
Pre – Post 2 Anaerobic Endurance	CIT Group PLA Group	0.679 0.003	0.006	0.944
Post 1 – Post 2 Anaerobic Endurance	CIT Group PLA Group	0.006 0.002	0.406	0.242
Pre – Post 1 Aerobic Endurance	CIT Group PLA Group	0.001 0.011	0.004	1.209
Pre – Post 2 Aerobic Endurance	CIT Group PLA Group	0.020 0.000	0.000	1.892
Post 1 – Post 2 Aerobic Endurance	CIT Group PLA Group	0.000 0.000	0.000	1.496
DOMS 1 – DOMS 2	CIT Group PLA Group	0.000 0.008	0.000	1.446
DOMS 1 – DOMS 3	CIT Group PLA Group	0.000 0.000	0.013	0.099
DOMS 2 – DOMS 3	CIT Group PLA Group	0.001 0.001	0.226	0.483

Note: significant difference at $p<0.05$

The CIT group's anaerobic endurance went up significantly between pre-test and post-test 1 (p = 0.001), but there was no significant difference between the two groups at post-test 2 (p = 0.679). By contrast, the change in post-test 2 for the PLA group was significant (p = 0.003). For aerobic endurance, the CIT group displayed a significant increase from pre-test to post-test 1 (p = 0.001) and from pre-test to post-test 2 (p = 0.020). The increase from pre-test to the two post-tests was also significant for the PLA group (p = 0.011 and p = 0.000). Supplementing with citrulline significantly enhances aerobic endurance, surpassing its impact on anaerobic endurance, with post-test 2 registering the highest effect (Cohen's d = 1.892). Moreover, DOMS analysis reported a significant reduction in soreness from DOMS 1 to DOMS 2 (p = 0.000) and from DOMS 2 to DOMS 3 (p = 0.001) for the CIT group. The PLA group also experienced a reduction in soreness, albeit not to the same statistically significant extent as the CIT group. Citrulline is effective in reducing DOMS and markedly increasing aerobic endurance in athletes, according to this study.

Discussion

This discussion reviews the impacts of citrulline on delayed onset muscle soreness (DOMS) as well as aerobic and anaerobic exercise performance in athletes. Enhancing athletic performance is an important area of focus in the pursuit of sporting success. Muscle fatigue is one aspect that can often constrain performance and limit the physical endurance of athletes (Behrens et al., 2022). Researchers have extensively studied citrulline, a non-essential amino acid, for its NO-inducing effect on circulation, which promotes athletic endurance (Aguayo et al., 2021; A. M. ; Gonzalez et al., 2023). Nitric oxide is important because it facilitates blood flow, which ultimately leads to an increase in oxygen and nutrient delivery to the muscles, as well as an increase in VO2max, a crucial indicator of aerobic endurance (Ahmad et al., 2018; Premont et al., 2020).

Because they are involved in the urea cycle, they may be able to help increase endurance. Strong evidence suggests that citrulline can enhance both aerobic and anaerobic performance. However, researchers are still investigating the effectiveness of citrulline for improving endurance output, with some studies reporting positive effects (Forbes et al., 2023). In supplement form or from the consumption of foods high in citrulline, such as watermelon, citrulline can help improve performance in athletes (Rusdiawan & Habibi, 2020). Research has demonstrated that citrulline malate enhances anaerobic endurance and alleviates post-exercise muscle soreness (A. M. Gonzalez & Trexler, 2020; Gough et al., 2021). Additionally, a few studies have also reported beneficial effects of citrulline in enhancing aerobic endurance, particularly in prolonged events involving aerobic performance (Gough et al., 2021; Viribay et al., 2022). In this study, the subjects on Citrulline exhibited considerable improvements on anaerobic and aerobic tests over the placebo group.

Afterward, as with any nonessential amino acid, citrulline may enhance aerobic and anaerobic performance through multiple mechanisms. The body converts citrulline to arginine, which then transforms into nitric oxide (NO), a vasodilator. The NO-mediated vasodilation facilitates improved blood flow and increased oxygen delivery to muscle during exercise (Kiani et al., 2022; Stuehr, 2004; Theodorou et al., 2021). This enhances aerobic capacity as muscles have a more effective oxygen supply, enabling the body to maintain prolonged activity. A study by Gentilin *et al.*, (2022) showed that administering citrulline malate for seven days increased the time to exhaustion during a cycling test, indicating an increased aerobic capacity. Furthermore, citrulline also indirectly increases the synthesis of creatine, another important molecule in the cellular energy production process during high-intensity workouts like sprinting (A. M. Gonzalez & Trexler, 2020; Sun et al., 2022). This significantly enhances anaerobic metabolic capacity, enabling an individual to perform better during high-intensity repetitive movements (Kreider & Stout, 2021; Viribay et al., 2022; Vulturar et al., 2021; Wyss & Kaddurah-Daouk, 2000). Studies have also demonstrated its ability to alleviate fatigue (I. Suzuki et al., 2019)., thereby freeing up more time for aerobic, anaerobic, or overall endurance activities.

Citrulline has also been shown to reduce post-exercise across-the-board delayed onset muscle soreness (DOMS), particularly after eccentric activity (Kim & Lee, 2014; Rhim et al., 2020; Wilke & Behringer, 2021). Eccentric exercise, which involves lengthening of muscle fibers, can lead to delayed-onset muscle soreness, the peak of which occurs 24–72 h after exercising (Hody et al., 2019; Tomalka, 2023). Citrulline supplements, which increase nitric oxide production, may help reduce the severity of DOMS. Nitric oxide increases blood flow, reduces inflammation, and accelerates muscle recovery (Hody et al., 2019; Theodorou et al., 2021; Valaei et al., 2021). Studies have shown that citrulline can significantly reduce soreness for up to 72 hours after eccentric exercise compared to placebo. These benefits make citrulline a promising strategy for enhancing athlete recovery and performance.

This study showed that the group taking citrulline experienced faster pain relief compared to the placebo group, which supports the hypothesis that citrulline supplementation has anti-inflammatory effects and helps improve blood flow to the muscles to speed up recovery (Allerton et al., 2018; Flores-Ramírez et al., 2021). Researchers recommend citrulline supplementation to alleviate exercise-induced muscular soreness, potentially through enhanced blood flow (da Silva et al., 2017; Wax et al., 2015). This could have a significant impact on subsequent performance in sports that restrict recuperation between bouts, such as track and field, and also on the overall quality and quantity of chronic training. A large study with 41 male participants found that taking 8 grammes of citrulline an hour before strength training reduced muscle soreness by 40% after 24 hours and by 41% after 48 hours, compared to a placebo (Pérez-Guisado and Jakeman, 2010)

The discrepancies between our findings and those of da Silva et al. (2017) and Chappell et al. (2018) may be attributed to several methodological and contextual differences rather than random variation. Both previous studies used resistance training protocols (e.g., leg press, hack squat, German Volume Training) in untrained or moderately trained participants, whereas our study involved well-trained sub-elite badminton athletes performing high-intensity intermittent activities, which impose different physiological demands and nitric oxide–mediated responses. Furthermore, while da Silva et al. (2017) and Chappell et al. (2018) administered citrulline in a single acute dose (6–8 g) approximately one hour before exercise, our protocol employed a 7-day continuous supplementation strategy, which may enhance bioavailability and sustain plasma arginine levels. Differences in the outcome measures are also notable: previous studies focused on resistance exercise performance and subjective soreness ratings, whereas we assessed both aerobic and anaerobic endurance in addition to DOMS. These distinctions in participant training status, sport-specific energy demands, supplementation regimen, and performance metrics likely contribute to the divergent results, underscoring the importance of matching study design to the target athletic population when evaluating citrulline's efficacy. The other mechanism relates to citrulline's potential to diminish the accumulation of ammonia and lactate in muscles during high-intensity exercise, which are known to be associated with muscle fatigue and breakdown (Harnden et al., 2023; Kiyici et al., 2017; Nyawose et al., 2022). This then helps citrulline manage the buildup of these substances via the urea cycle—an important metabolic pathway for eliminating nitrogenous waste from the system (Imbard et al., 2023). Citrulline lowers this metabolic load and speeds muscle recovery after intensive exercise.

Practically speaking, badminton sub-elite athletes may experience significant benefits from the observed increases in aerobic endurance, specifically a VO_2max enhancement of approximately 2.02 ml/kg/min, as well as a quicker reduction in delayed onset muscle soreness (DOMS), with recovery occurring up to 33% faster within 72 hours. Enhanced VO_2max contributes to longer match endurance and improved oxygen delivery, particularly advantageous in high-intensity intermittent sports like badminton. Furthermore, athletes can increase their training frequency and reduce their risk of injury by recovering from muscle soreness more rapidly, allowing them to return to full training intensity sooner. These benefits are especially relevant during busy competition schedules or rigorous training periods, when recovery time is often limited.

It is important to acknowledge the various limitations of this study. Firstly, the results may not be generalisable to other populations, such as elite or female athletes, as the sample was restricted to male sub-elite badminton players from a single university. Secondly, while a 7-day supplementation protocol was implemented in the study, longer intervention periods might yield different or more sustained effects, particularly regarding anaerobic performance. Thirdly, the study employed the Visual Analogue Scale (VAS) to subjectively assess Delayed Onset Muscle Soreness (DOMS), which can be influenced by individual pain perception, despite being a recognised and reliable measurement tool. Finally, variability in physiological responses to supplementation may have occurred due to the lack of strict regulation regarding dietary intake and physical activity outside the planned testing sessions.

Furthermore, this study did not directly measure any physiological mediators that might be involved in the effects of citrulline, such as plasma arginine levels, plasma nitric oxide concentration, or other relevant biomarkers (like lactate or creatine kinase). Although earlier research has shown a connection between citrulline supplementation, nitric oxide production, and improved blood flow, our findings regarding these pathways remain speculative and are based on previous research rather than biochemical analysis from this study. Future research could gain a clearer mechanistic understanding and better explain the observed performance and recovery results by including such measurements. To improve on these issues, future studies should look at how citrulline supplementation affects performance and recovery over a longer time, manage other influencing factors, and include a wider variety of athletes.

Conclusions

Among male sub-elite badminton players, seven days of L-citrulline supplementation at 2.4 grams daily was associated with improvements in aerobic and anaerobic endurance and a faster reduction in delayed onset muscle soreness (DOMS). The study's quasi-experimental design, small sample size, and sport-specific cohort make it difficult to draw firm causal conclusions or generalize these results to other athletic populations, so they should be interpreted with caution. Additional randomized controlled trials involving various athlete groups and mechanistic biomarkers are necessary to confirm the optimal supplementation practices and clarify the extent of performance benefits. The dosage and duration used here reflect the study protocol and should not be considered a universal recommendation.

Acknowledgements

I would like to thank the badminton athletes of Surabaya State University who have been willing to be samples in this study. In addition, I would also like to thank the Sport & Exercise Research Centre, which has helped in data collection and analysis of this study. I would also like to thank the Directorate of Research, Technology, and Community Service (DRTPM), which has given me the opportunity to conduct this research and funded it.

Financing

Through the provision of a national research grant, the Directorate of Research, Technology, and Community Service (DRTPM) provided financial support for this research.

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