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REVIEW ARTICLE

# Effect of L-citrulline supplementation on blood pressure: a systematic review and meta-analysis of randomized controlled trials

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## Abstract

The objective of this study was to systematically investigate the efficacy of oral L-citrulline supplementation on systolic and diastolic blood pressure. Studies were identified by a search of electronic databases from inception to April 2018, and combined and stratified analyses were used. Fifteen trials were identified, and data from 424 participants were included. Pooled analysis showed significant reductions in systolic blood pressure by −7.54 mmHg (95% confidence interval (CI): −9.44, −5.63; $P < 0.001$, $I^2 = 14\%$) and diastolic blood pressure by −3.77 mmHg (95% CI: −5.67, −1.86, $P < 0.001$, $I^2 = 42\%$) following oral supplementation of L-citrulline or a watermelon extract. No changes were detected in controls. Significant heterogeneity ($I^2 = 42\%$, $P = 0.04$) was found for diastolic blood pressure, and subgroup analysis showed significant improvements in systolic and diastolic blood pressure, particularly for study durations: ≥6 weeks, lower doses: ≤4 g/day, and in participants with higher baseline values: ≥130/85 mmHg. In conclusion, L-citrulline improves systolic and diastolic blood pressure and may be more efficacious in pre-hypertensive and hypertensive populations.

## Introduction

Hypertension (HTN), or high blood pressure (BP), is a prevalent condition affecting over one billion adults globally, and is a major risk factor for cardiovascular disease (CVD) and all-cause mortality and morbidity [1]. The regulation of BP is under endothelial and autonomic function with pre-hypertensive and hypertensive states presenting abnormally elevated arterial pressures [2]. Dietary approaches with anti-hypertensive potential may be important in the prevention and management of HTN [3]. Several dietary constituents have been reported to reduce BP, including L-arginine, a substrate for endothelial nitric oxide (NO) production [2, 4], and evidence indicates that L-citrulline may be more effective in its ability to reduce brachial BP, aortic BP, and peripheral arterial stiffness via improved endothelial function [5].

L-Citrulline, a non-essential amino acid commonly found in watermelon (*Citrullus vulgaris*) [6, 7], is converted to L-arginine, which enhances NO production, and exhibits potent vasodilatory properties [8]. NO induces vascular smooth muscle relaxation through the NO-cyclic guanosine triphosphate pathway and plays a major role in the regulation of BP [7]. Some evidence suggests that L-citrulline supplementation increases plasma L-arginine and NO levels more efficiently because unlike L-arginine it is not affected by enzymatic degradation [5].

However, evidence from randomized controlled trials (RCTs) is somewhat limited and remain inconclusive with some studies demonstrating potential BP lowering effects [6, 9–13], while others showing no effect following consumption of watermelon or L-citrulline, on brachial and aortic systolic BP (SBP) or diastolic BP (DBP) [14–16]. Therefore, the present systematic review and meta-analysis was conducted to assess the efficacy of L-citrulline on SBP and DBP in RCTs.

## Methods and materials

The current meta-analysis was carried out in accordance with PRISMA guidelines [17].

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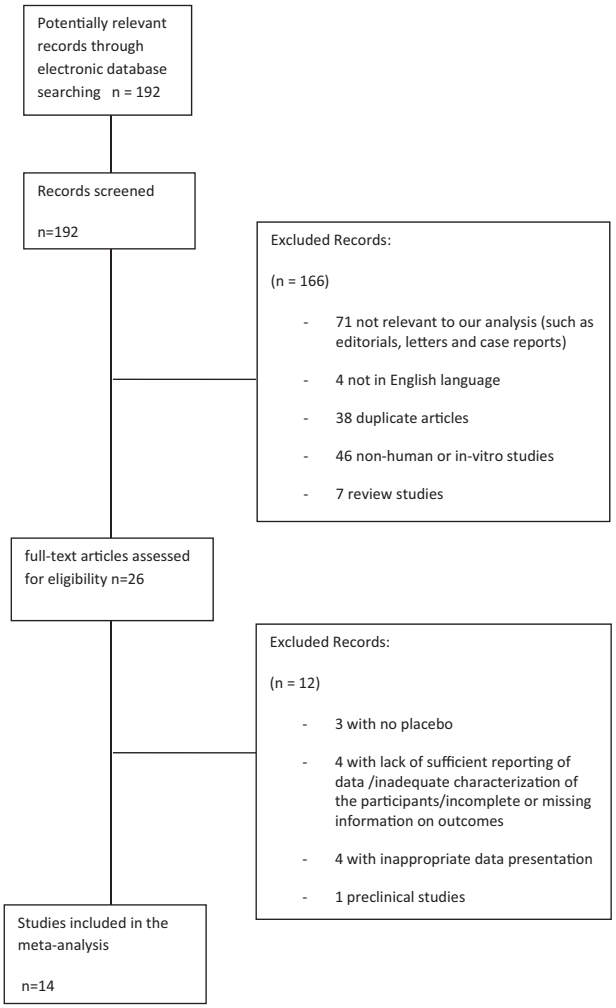


**Fig. 1** Meta-analysis flow diagram

## Search strategy and selection

Five databases, including Pubmed™, Cochrane Library™, Google Scholar™, Embase™, and Scopus™, were used to search for relevant publications up to April 2018. We also searched through reference lists of the included studies to identify additional relevant publications. The following keywords were considered: ("Citrulline" OR "L-citrulline" OR "Watermelon" OR L-CIT) AND ("Clinical trial" AND "Hemodynamic parameters" OR "Blood pressure" OR "BP" OR "BP" OR "Systolic blood pressure" OR "SBP" OR "SBP" OR "Diastolic blood pressure" OR "DBP" OR "DBP"). The wild-card term "*" was also used (such as "L-CIT*" OR "CIT*") for improving the sensitivity of the search strategy. Studies were included if they had RCT study design with L-citrulline or citrulline-containing foods such as watermelon, as the intervention. Studies with Persian and English languages were included. Additionally, studies reporting mean changes and associated standard deviations of SBP and DBP, and those with sufficient data on BP at both baseline and end of the study in each group, or data for calculating these indices were considered eligible for the analysis.

## Data extraction

Three reviewers independently extracted data from published studies and any possible disagreements were solved by consensus and discussion with the fourth author. The following items were extracted: author's first name, publication year, study design, origin of the country, sample size of both the intervention and control groups, participants clinical condition, baseline SBP and DBP measurements, intervention/placebo characteristics including L-citrulline doses (g/day or mg/day), duration of supplementation, and observed significant outcomes. We contacted the corresponding authors of studies with no included mean and SD values to request additional data.

## Quality assessment

We used the Jadad scale to evaluate the quality of included trials. The score can range from 0 to 5, with higher scores implying better quality. The Jadad scale includes three parameters: randomization, blinding, and monitoring of subject dropouts. The Jadad scoring method is as follows: one point was given for stating random allocation and one additional point if the method was appropriate. One point was given when it was stated that the trial was blinded and one additional point if the method of blinding was appropriate. One point was withdrawn if the method of randomization or blinding was inappropriate. Reporting of dropouts was given one point if the fate of all participants is known [18].

## Statistical analysis

All analyses were carried out using the Review Manager Software (Review Manager 5.3; Cochrane Collaboration, Oxford, UK).

Mean and SD of SBP and DBP values in baseline and end of study in both intervention and control groups were used. In the case of missed SD values, reported median values with CIs or ranges were converted to mean and SD, based on the method of Hozo et al. [19]. Treatment effects were defined as weighted mean differences (WMDs) and 95% confidence intervals (CIs) were calculated to assess net changes in SBP or DBP values. The statistical heterogeneity was estimated using $I^2$ test ($I^2$ <50%) and $\chi^2$ test on Cochrane's $Q$ statistic. A random-effects model was used if $I^2$ >50% and $P$ <0.05 from $\chi^2$ test. A fixed-effects model was used if $I^2$ <50% and $P$ >0.05 from $\chi^2$ test. Additionally, we conducted sensitivity and pre-specified subgroup

**Table 1** Characteristics of included trials

| Author, year | Design of studies | Country | No. of subjects in case group | No. of controls | Gender | Age (mean) | Follow-up duration | Clinical condition | Dosage | Significant outcome | Baseline BP |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Balderas-Munoz et al, 2012. [22] | Randomized controlled trial | Mexico | 20 | 15 | MF | Cit = 68.2 ± 9.3 Placebo = 65.8 ± 9.5 | 4 months | Men and non-pregnant women with systolic heart failure | L-Citrulline malate powder supplementation 3 g/day2 doses of 1.5 g | In experimental group LVEF increased 20.3% at rest and 12.7% with stress, as well as the RVEF at rest of 15.10% and 14.88% with stress. Functional class improved in 35%, and the MAT/TT index decreased 23.1%. These changes were statistically significant compared with the control group. | 113/70.3 |
| Figueroa et al, 2010. [16] | Randomized, double-blind, two-period, crossover | US | 18 | 18 | M | 22 ± 1 | 4 weeks | Healthy | L-Citrulline supplementation 6 g/day2 doses of 3 g | Significant increases in brachial and aortic BP (SBP, DBP, PP), and a decrease in transit time of the reflected wave from baseline. Compared to placebo, oral L-citrulline treatment decreased brachial SBP, aortic SBP, and aortic PP | 121/83 |
| Figueroa et al, 2011. [23] | Randomized, double-blind, two-period, crossover | US | 9 | 9 | M F | 54 ± 3 | 6 weeks | Prehypertension | Watermelon supplementation L-citrulline/L-arg: 1.35 g/0.65 g 2 times/day | A significant treatment effect (change in the value of watermelon minus placebo from baseline to 6 weeks) on bPP, aSBP | 126/79 |
| Figueroa et al, 2013. [11] | Randomized, two-period, crossover | US | 12 | 12 | F | 57 ± 1 | 6 weeks | Postmenopausal women watermelon extract L-citrulline/L-arg:4/26 g/day3 times/day | Watermelon extract L-citrulline/L-arg:4/26 g/day3 times/day | Aortic SBP and aortic diastolic blood pressure decreased after watermelon supplementation compared with placebo. Reduction in aortic SBP was correlated with reductions in radial SBP2 and aortic SBP2 | 141/88 |
| Figueroa et al, 2012. 2012 [6] | Randomized, two-period, crossover | US | 14 | 14 | M F | 58 ± 1 | 6 weeks | Men and postmenopausal women with prehypertension or stage 1 hypertension | Watermelon supplementation L-citrulline/L-arg:2/16 g/day | Ankle and brachial SBP, DBP, and MAP decreased significantly after watermelon supplementation compared to placebo. Watermelon | 152/89 |

**Table 1** (continued)

| Author, year | Design of studies | Country | No. of subjects in case group | No. of controls | Gender | Age (mean) | Follow-up duration | Clinical condition | Dosage | Significant outcome | Baseline BP |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | supplementation had no significant effect on ABI and HR | |
| Figueroa et al, 2014. [12] | Randomized, double-blind, crossover | US | 13 | 13 | M F | 57.4 ± 1.4 | 6 weeks | Men and postmenopausal women with hypertension | Watermelon supplementation 4 g L-Citrulline/day2 g L-arg/day3 doses/day | Watermelon reduced bSBP, aSBP, P1, and P2 at baseline and CPT compared with placebo. Watermelon did not affect AP, AIx, AIx75, and STI at baseline, but decreased AP and STI during CPT and the increases in AP and AIx75 from baseline to CPT | 139/89 |
| Figueroa et al, 2016. [15] | Randomized, double-blind, placebo-controlled, crossover | US | 16 | 16 | M | 24 ± 6 | 2 weeks | Overweight or obese, healthy males | 4 capsules of 750 mg L-Citrulline2 times/day | No significant effects were evident after L-citrulline at rest. L-Citrulline attenuated the increases in aortic SBP and wave reflection (AP and AIx) during IHG, aortic DBP, MAP, and AIx during PEMI, and aortic SBP, DBP, MAP, AP, AIx, and baPWV during PEMI + CPT compared with placebo. HR and Tr were unaffected by L-citrulline in all conditions | 104/68 |
| Gonzales et al, 2017. [5] | Randomized, double-blind, crossover | US | 13 | 13 | F | 70 ± 5 | 2 weeks | Old adults | L-Citrulline 6 g/day | Citrulline remained unchanged in women | 127/65 |
| Gonzales et al, 2017. [24] | Randomized, double-blind, crossover | US | 12 | 12 | M | 71 ± 5 | 2 weeks | Old adults | L-Citrulline 6 g/day | Citrulline lowered DBP. Blood flow and FVC during exercise at higher workloads were increased following Cit but was not different after placebo | 135/75 |
| Massa et al, 2016. [13] | Randomized, double-blind, experimental and placebo controlled | Brazil | 20 | 20 | M F | Intervention = 48.7 ± 1.9 Placebo = 47.4 ± 1.2 | 6 weeks | Pre-hypertensive and hypertensive | Watermelon extract L-Citrulline/L-arg: 2/16 g/day | Watermelon extract promoted a significant reduction in systolic and diastolic blood pressure, but showed no differences | 137.8/79.2 |

**Table 1** (continued)

| Author, year | Design of studies | Country | No. of subjects in case group | No. of controls | Gender | Age (mean) | Follow-up duration | Clinical condition | Dosage | Significant outcome | Baseline BP |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | compared to the placebo group | |
| Ochiai et al, 2012. [14] | Double-blind, randomized, placebo-controlled parallel-group trial | Japan | 8 | 7 | M | Intervention = 58.5 ± 5.0 Placebo=58 ±3.9 | 1 week | Healthy | L-Citrulline supplementation 5.6 g/day | No significant differences in (BP) were found between the two groups. Plasma citrulline, arginine, and the ratio of arginine/asymmetric dimethylarginine (ADMA), an endogenous inhibitor of NO synthase (arginine/ ADMA ratio) were significantly increased in the L-Citrullinerulline group compared with the placebo group | 135.5/ 82.4 |
| Qiu et al, 2012. [25] | Double-blind, randomized, placebo-controlled group trial | Unclear | 20 | 20 | M F | Unclear | 8 weeks | Pre-hypertensive adult | L-Citrulline supplementation 3 g/ day | L-Citrulline reduced max, min, and office SBP; the maxDBP; and max mean arterial pressure. No significant effects for remaining BP values notably the min DBP. Concentration of NO synthase was significantly up-regulated in the intervention group | 135.26/ 85.42 |
| Sanchez-Gonzalez and co-workers, 2010. [16] | Randomized crossover | US | 16 | 16 | M | 23 ± 3 | 2 weeks | Healthy | L-Citrulline supplementation 100 mg/kg | A significant treatment-by-time interaction for BSBP and ASBP and AIx, such that L-citrulline decreased BSBP, ASBPP as compared with their respective values before the intervention | 112/77 |
| Wong et al, 2015. [9] | Randomized-controlled trial | US | 13 | 14 | F | Intervention = 58 ± 3 Placebo = 58 ± 4 | 8 weeks | Overweight or obese | L-Citrulline supplementation 6 g/ day | All groups similarly decreased brachial and aortic pressures as well as AP, and similarly increased $NO_x$ levels...L-citrulline decreased BP | 133/79 |
| Wong et al, 2016. [27] | Randomized-controlled trial | US | 12 | 11 | F | 58 ± 1 | 8 weeks | Postmenopausal women | | Significant decreases in nLF (sympathetic activity), | 138/81 |

**Table 1** (continued)

| Author, year | Design of studies | Country | No. of subjects in case group | No. of controls | Gender | Age (mean) | Follow-up duration | Clinical condition | Dosage | Significant outcome | Baseline BP |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | L-Citrulline supplementation 6 g/day | LnLF/LnHF (sympathovagal balance), and BP as well as a significant increase in nHF (vagal tone) following L-citrulline compared with no changes after control | |

analyses according to the Cochrane guidelines to evaluate possible sources of heterogeneity within the included trials [20]. In the sensitivity analysis, a single study was omitted each time and the effect size was re-calculated to investigate its influence on the overall effect size [21].

We assessed the publication bias by visual inspection of funnel plot test. Asymmetric shape of funnel plots can be indicative of a publication bias. A $P$ value of <0.05 was considered as statistically significant.

## Results

### Search results and study selection

The flow chart describes the process of selection and the references retrieved in the database are presented in Fig. 1. A total number of 192 articles identified in the first step of literature search of electronic databases. After removal of duplicated studies ($n = 38$), non-human or in vitro trials ($n = 46$), reviews ($n = 7$), non-English/Persian papers ($n = 4$), and irrelevant studies such as editorials, letters, and case reports ($n = 71$), 26 potentially relevant articles were considered for full text review. After screening, 12 articles were excluded for the following reasons: L-citrulline was not used as the intervention; insufficient data reporting of outcome measures or primary and/or secondary outcomes other than BP were measured. Finally, a total of 14 studies were included in the present meta-analysis [6, 9, 11–16, 22–27]. Gonzales et al. [5, 24] investigated the effect of L-citrulline on two different groups separated by sex and based on the Cochrane Handbook for Systematic Reviews of Interventions, each group was considered separately in the analysis. Therefore, we analyzed 15 distinct trials extracted from 14 studies in the current meta-analysis.

### Study characteristics and quality assessment

Description of the included trials is presented in Table 1. All studies were published between 2010 and 2017, of which 11 studies were conducted in United States, one study with unknown origin and the remaining three were performed in Mexico, Brazil, and Japan [6, 9, 11–16, 22–27]. Fifteen trials, with 424 participants in total (intervention, $n = 215$ and placebo, $n = 209$), were included in the final meta-analysis and systematic review. All trials were placebo controlled, of which nine trials were randomized and double-blinded [12–16, 23–25]. Of the 15 trials, five trials enrolled postmenopausal women [6, 9, 11, 12, 27], five included healthy males [14–16, 24, 26], and five with pre-hypertensive or hypertensive participants [6, 12, 13, 23, 25]. The estimated age range of participants was from 22 to 71 years, and the average age of study participants was 53.1 ± 3.6

**Table 2** Quality of the included studies based on the Jadad score

| Author, year | Blinding | Randomization | Withdrawals and dropouts descriptions | Score |
|---|---|---|---|---|
| Balderas-Munoz et al, 2012. [22] | 1 | 1 | 1 | 3 |
| Figueroa et al, 2010. [16] | 1 | 1 | 1 | 3 |
| Figueroa et al 2011. [23] | 1 | 1 | 1 | 3 |
| Figueroa et al 2012. [6] | 0 | 1 | 0 | 1 |
| Figueroa et al, 2014.)[12] | 0 | 1 | 0 | 1 |
| Figueroa et al , 2013. [11] | 1 | 1 | 1 | 3 |
| Figueroa et al, 2016. [15] | 1 | 1 | 0 | 2 |
| Gonzales et al, 2017. [5] | 1 | 1 | 0 | 2 |
| Gonzales et al, 2017. [24] | 1 | 1 | 0 | 2 |
| Massa et al, 2016. [13] | 1 | 1 | 0 | 2 |
| Ochiai et al, 2012. [14] | 1 | 1 | 0 | 2 |
| Qiu, 2012 [25] | 0 | 1 | 0 | 1 |
| Sanchez-Gonzalez and co-workers, 2010 [16] | 0 | 1 | 0 | 1 |
| Wong et al, 2015. [9] | 0 | 2 | 1 | 3 |
| Wong et al, 2016. [27] | 0 | 2 | 0 | 2 |

years. Duration of follow-up ranged from 1 week to 16 weeks. L-Citrulline dosing ranged from 2.7 to 8.4 g/day. Formulations were supplied either as a supplement of L-citrulline [9, 14–16, 22, 24–27] or as an extract of watermelon [6, 11–13, 23]. No side effects from L-citrulline was reported from the 15 trials analyzed.

Based on several previous meta-analysis studies, which indicated the studies with Jadad score of more than 3 as high-quality studies [21, 28, 29], five trials were categorized as high-quality trials [9, 12, 16, 22, 23] and the remaining ten as low-quality trials [6, 11, 13–15, 24–27] (Table 2).

## The effects of L-citrulline on BP

The pooled analysis was generated from the data of 424 participants from 15 trials reporting changes in BP (intervention, $n = 215$ and placebo, $n = 209$) [6, 9, 11–16, 22–27]. The meta-analysis of the included trials revealed a significant reduction in SBP by −7.54 mmHg (95% CI: −9.44, −5.63, $P = 0.0001$) following L-citrulline compared with placebo (Fig. 2) with no heterogeneity among the studies ($I^2 = 14\%$, $P = 0.3$). A significant reduction in DBP by −3.77 mmHg (95% CI, −5.67, −1.86, $P = 0.0001$) was also found following L-citrulline compared with placebo; however, a significant heterogeneity was detected after the meta-analysis of DBP ($I^2 = 42\%$, $P = 0.04$). Consequently, we used the random-effects model for pooling data and subgroup analysis was carried out to explore the potential sources of heterogeneity.

## Subgroup analysis

To detect the source of heterogeneity, we performed a subgroup analysis based on clinical condition (Table 3). A significant decrease was observed in heterogeneity of both indicators, SBP and DBP after L-citrulline supplementation among trials at all subgroup analyses; duration of study (≥6 weeks), baseline BP (≥130/85), dosage (L-citrulline dose: ≤4 g/day), and quality of study (Table 3). In the subgroup analysis of trials with ≥6 weeks follow-up duration, the average reductions for SBP and DBP were 7.35 mmHg ($I^2 = 0\%$, $P$ for heterogeneity = 0.88) and 3.69 mmHg ($I^2 = 0\%$, $P$ for heterogeneity = 0.61), respectively. Additionally, in the subgroup analysis by dosage of ≤4 g/day of L-citrulline, the mean reduction in SBP and DBP was 8.86 mmHg ($I^2 = 0\%$, $P$ for heterogeneity = 0.99) and 4.42 mmHg ($I^2 = 0\%$, $P$ for heterogeneity = 0.67), respectively. The pooled mean net change in SBP for participants with basal BP of ≥130/85 was −8.85 mmHg ($I^2 = 0\%$, $P$ for heterogeneity = 0.89). Moreover, the colligated estimate showed a significant decrease in DBP in participants with a higher BP (WMD = −4.42 mmHg, $I^2 = 0\%$, $P$ for heterogeneity = 0.86).

## Publication bias

In the current meta-analysis, funnel plots of the effect of L-citrulline on SBP and DBP from the 15 trials were examined to assess publication bias. Funnel plots were symmetric, indicating a rare possibility for selection of publication as a source of bias (Fig. 3).

# Discussion

Data from 424 normotensive, pre-hypertensive and hypertensive adults from 15 trials were included in the current

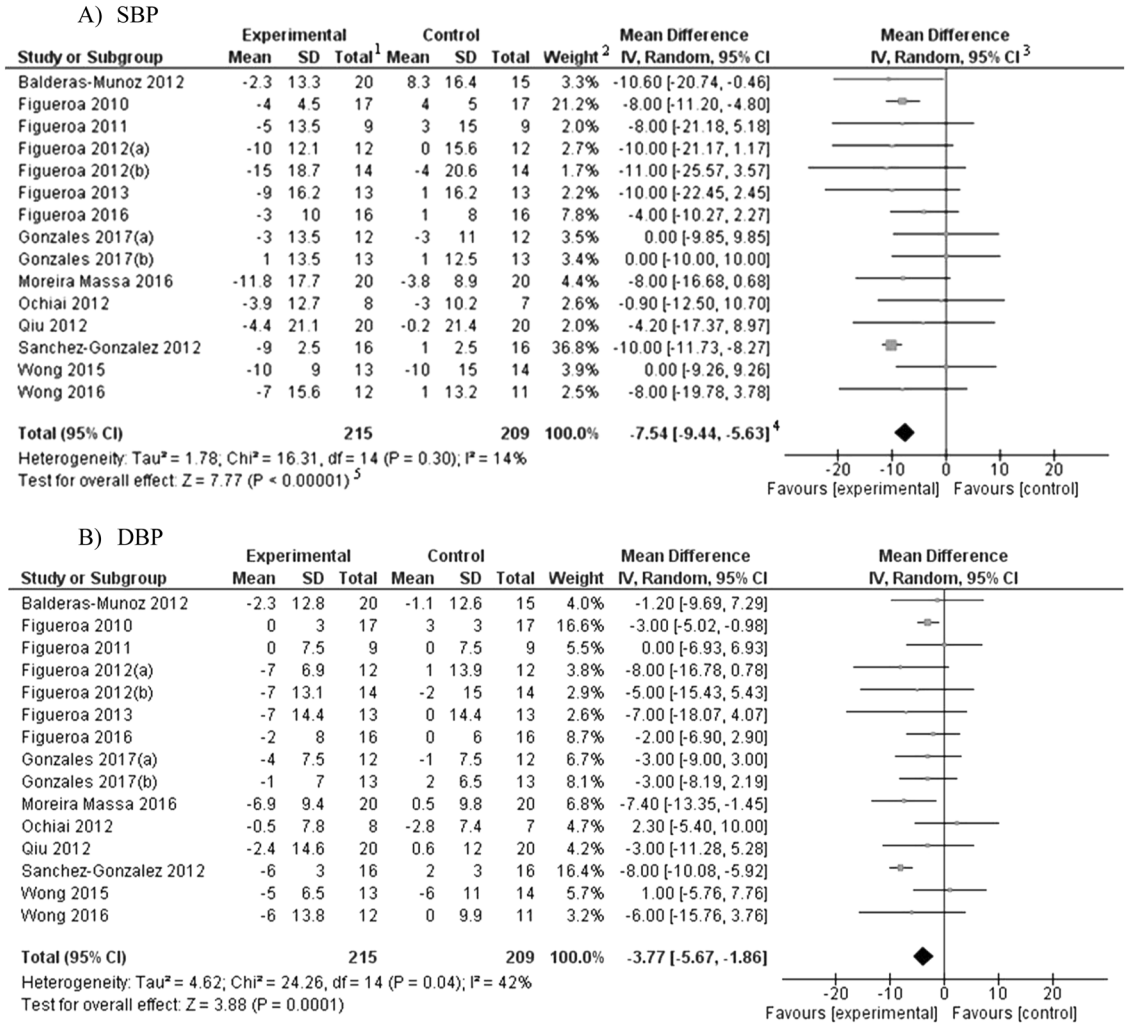


**Fig. 2** Forest plots showing the effect of L-citrulline on (**a**) systolic blood pressure and (**b**) diastolic blood pressure. Random-effects model was used to pool the mean change of indicators. CI confidence interval; $I^2$ inconsistency. 1, total number of participants; 2, influence of studies on overall meta-analysis; 3, outcome of interest in picture and in number; 4, overall effect; 5, *P* value indicating level of statistical significance

meta-analysis. General results of this research suggest a potential role of L-citrulline as a BP lowering agent in spite of considerable heterogeneity. Both SBP and DBP decreased significantly following L-citrulline supplementation. The overall findings were consistent with 11 of the 15 individually included RCTs in this study [6, 11–13, 15, 16, 22, 25]. There were no adverse effects reported from the 15 trials examined, suggesting their potential ability to act as natural BP lowering agents. The potential use of an amino acid supplement which is safe, and relatively inexpensive, could have an important role in the management of chronic hypertensive conditions, especially gestational HTN, which is associated with significant complications (i.e., pre-eclampsia and fetal growth restriction). Treatment options are restricted during pregnancy and non-pharmacological interventions could be more readily accepted, with data from early phase clinical trials demonstrating significant reductions in BP after 3 weeks of L-citrulline (3 g/day), which continued until the end of pregnancy.

Subgroup analysis confirmed that studies with a longer duration (≥6 weeks) and lower dose (≤4 g/day) reported greater improvements in both SBP and DBP with acceptable homogeneity. Similarly, participants with a higher baseline BP (≥ 130/85) also experienced greater improvements in clinical outcomes, indicating the possibility that L-citrulline might be more efficacious in pre-hypertensive and hypertensive populations. These findings could influence the decision to use L-citrulline, particularly in pre-hypertensive, hypertensive and gestational hypertensive populations (as discussed above) as it does not seem to exert further benefit in those with normal BP.

Several studies highlight the benefit of lifestyle approaches in reducing BP including the DASH (Dietary Approaches to Stop Hypertension) diet and physical

**Table 3** Subgroup analysis[a]

| Subgroup | No. of trials | WMD (95% CI) | Test for overall effect | Test for heterogeneity | $I^2$ (%) |
|---|---|---|---|---|---|
| *Duration of study (weeks)* | | | | | |
| <6 weeks | 6 | | | | |
| SBP | | −6.17 (−9.51, −2.84) | $P = 0.0003$ | $P = 0.03$ | 59 |
| DBP | | −3.55 (−6.45, −0.64) | $P = 0.02$ | $P = 0.004$ | 71 |
| ≥6 weeks | 9 | | | | |
| SBP | | −7.35 (−11.07, −3.64) | $P = 0.0001$ | $P = 0.88$ | 0 |
| DBP | | −3.69 (−6.36, −1.02) | $P = 0.007$ | $P = 0.61$ | 0 |
| L-Citrulline dose (g/day) | | | | | |
| ≤4 | 7 | | | | |
| SBP | | −8.86 (−13.18, −4.55) | $P < 0.0001$ | $P = 0.99$ | 0 |
| DBP | | −4.42 (−7.46, −1.37) | $P = 0.004$ | $P = 0.67$ | 0 |
| >4 | 8 | | | | |
| SBP | | −5.71 (−8.85, −2.56) | $P = 0.0004$ | $P = 0.03$ | 55 |
| DBP | | −3.28 (−5.92, −0.64) | $P = 0.02$ | $P = 0.005$ | 65 |
| *Baseline BP (mmHg)* | | | | | |
| <130/85 | 11 | | | | |
| SBP | | −6.67 (−9.16, −4.18) | $P < 0.00001$ | $P = 0.11$ | 36 |
| DBP | | −3.34 [−5.59, −1.09) | $P = 0.004$ | $P = 0.010$ | 57 |
| ≥130/85 | 4 | | | | |
| SBP | | −8.85 (−15.18, −2.52) | $P = 0.006$ | $P = 0.89$ | 0 |
| DBP | | −5.58 (−10.30, −0.86) | $P = 0.02$ | $P = 0.86$ | 0 |
| *Quality of studies* | | | | | |
| High quality | 5 | | | | |
| SBP | | −7.58 (−10.34, −4.82) | $P < 0.00001$ | $P = 0.54$ | 0 |
| DBP | | −2.54 (−4.34, −0.75) | $P = 0.005$ | $P = 0.65$ | 0 |
| Low quality | 10 | | | | |
| SBP | | −6.60 (−9.59, −3.61) | $P < 0.0001$ | $P = 0.18$ | 28 |
| DBP | | −4.75 (−7.06, −2.45) | $P < 0.0001$ | $P = 0.13$ | 35 |

*BP* blood pressure, *SBP* systolic blood pressure, *DBP* diastolic blood pressure, *WMD* weighted mean difference, *CI* confidence interval, $I^2$ percentage score for heterogeneity

activity. In a meta-analysis of 17 RCTs, the DASH diet contributed to significant reductions in mean SBP and DBP (−6.74 and −3.54 mmHg), respectively [30]. Similarly, aerobic exercise significantly reduced mean SBP and DBP (−3.84 and −2.58 mmHg), respectively [31]. This paper suggests that L-citrulline supplementation results in significant decrease in mean SBP and DBP (−7.54 and −3.77 mmHg), respectively. Our findings are in line with those of previous lifestyle approaches, suggesting the possibility that L-citrulline could also be considered as a potential anti-hypertensive agent.

L-Citrulline is strongly associated with arginine and its metabolism involves a complex biochemical process comprising three main metabolic routes: the intrahepatic transformation of ammonia to urea, NO production, and the de novo synthesis of arginine from glutamine in the gut and kidney (Fig. 4).

Several mechanisms may explain putative BP lowering effects of L-citrulline. This is a natural precursor of L-arginine, a substrate of NO production, which is important in the regulation of BP and endothelial function [32–34]. Low levels of L-arginine contributes to endothelial cell (EC) dysfunction, and previous studies have shown their ability to ameliorate conditions related to EC dysfunction including HTN, heart failure, atherosclerosis, and diabetic vascular disease [35, 36]. BP lowering effect has been shown in some studies after L-arginine supplementation, particularly in hypertensive patients [37, 38]. One of the main concerns with L-arginine is its rapid degradation by arginase I in the intestinal tract [39] and the efficacy of oral L-arginine supplementation remains questionable [34]. L-Citrulline precludes pre-systemic metabolism [40] and efficiently converts to L-arginine, thus enhancing plasma concentrations [41, 42]. This substance is considered as a precursor in

the L-arginine-NO pathway [40] and some evidence has shown improvements in exercise performance [43, 44] and erectile dysfunction, following its supplementation [45].

We performed quantitative analysis for all studies except for two, where there was insufficient quantitative data or unavailable full texts. All studies were placebo controlled except for one [22] that was an open-label, non-placebo-controlled trial. Nonetheless, most of the studies reported beneficial effects of L-citrulline on BP, hemodynamics of aortic pressure, arterial function, and brachial and/or aortic responses, and in some studies L-citrulline was more effective in male hypertensives [24]. There is some evidence suggesting that it could act as as co-adjuvant in the treatment of systolic heart failure [22]. Oral L-citrulline was generally well accepted, tolerated, and considered to be safe [34]. There were no reports of any adverse events or withdrawals in the included trials.

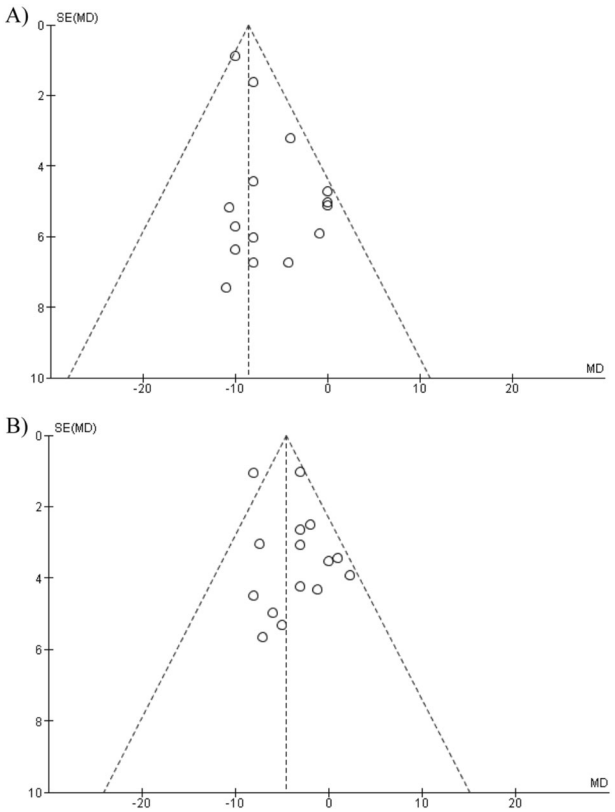


**Fig. 3** Funnel plot of studies included in the meta-analysis for the outcome of systolic blood pressure (**a**) and diastolic blood pressure (**b**). MD mean difference, SE standard error

Our research faces several limitations. A considerable number of included trials were small in sample size. As described by Sterne and Egger [46], it is probable for smaller studies to report larger benefits in intervention arms than larger studies. Therefore, the effect size in the present study could be considered an overestimation. However, authors have to note that 7 of the 15 studies analyzed had a crossover study design [6, 11, 16, 23, 24, 26], which would account for their smaller sample size than those following a parallel study design. Moreover, it is relatively common for many dietary interventions to follow a crossover study design, and include a smaller sample size. For this reason, meta-analyses of smaller studies are not always consistent with those of larger studies since different levels of bias occur in different studies. This diversity is an inevitable issue that all meta-analyses encounter. Publication bias is also a fundamental concern in meta-analysis, since positive findings have a greater likelihood of publication than negative results. Publication bias was taken into account by funnel plots, and discussed elsewhere in this article.

The measures of bioactive substances (including NO, L-citrulline, and L-arginine) were reported in only four studies [5, 9, 13, 25]. The effective dosage of L-citrulline was not established in the trials, and watermelon extract was reported to have a dose-dependent effect on BP [6]. However, administration of 6 g/day oral L-citrulline appeared to

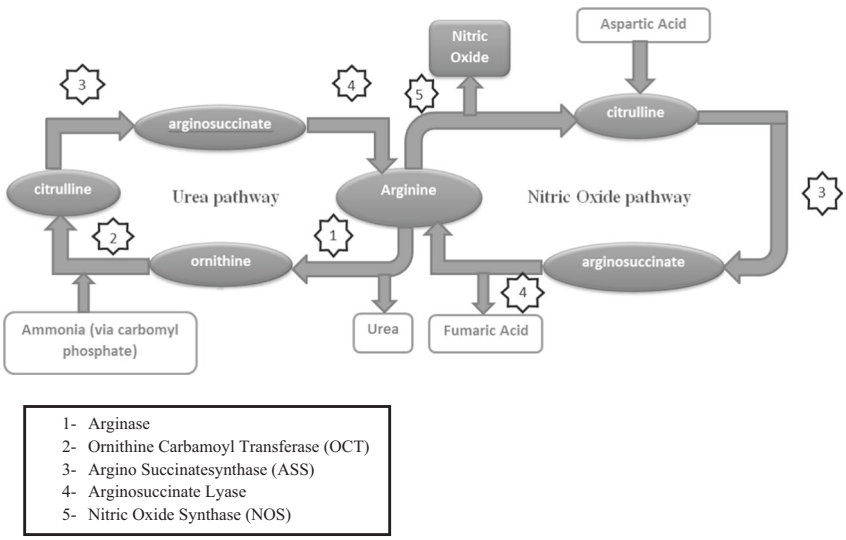


**Fig. 4** The multiple metabolic pathways of L-citrulline as a common precursor for both arginine and nitric oxide

be the optimum dose due to the large number of trials administering this dosage, and we also demonstrated in our subgroup analysis that doses of >4 g/day of L-citrulline showed significantly greater reductions in SBP and DBP with appropriate homogeneity. Confounders such as diet and physical activity can influence BP and were not controlled in trials. Of the 15 studies included in this meta-analysis, 5 were ranked as high-quality studies according to JADAD score [18]. In spite of limitations, our report has several strengths. Our study is the first to assess the potential role of L-citrulline supplementation for reducing BP in adult population as a systematic review and meta-analysis. To deal with observed heterogeneity, random-effects model was used for analysis. Besides, subgroup analyses were performed in order to detect the source. Based on our findings, L-citrulline has potential in clinical settings for pre-hypertensive and hypertensive subjects since no adverse events were reported and effect sizes were considerable. We recommend that future trials are conducted in accordance with CONSORT guidelines, to include higher quality and larger sample sizes. Since HTN is a major risk factor for CVD [47, studies focusing on L-citrulline in affected populations could help researchers to reach valuable and practical findings.

In conclusion, the present paper suggests the potential for improving SBP and DBP following L-citrulline consumption, particularly in pre-hypertensive and hypertensive patients. However, due to limited availability of studies with hypertensive cases and relatively small sample sizes, well-designed trials with adequate sample sizes aimed at hypertensive populations is recommended.

## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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