

Anti Lipidemic Effects of Cinnamon in Hyperlipidemia Adults

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ABSTRACT

*Hyperlipidemia is a major risk factor for cardiovascular diseases and remains a growing public health concern. Due to the limitations and side effects associated with synthetic lipid-lowering drugs, there is increasing interest in safe, natural alternatives. Cinnamon (*Cinnamomum zeylanicum*) contains polyphenolic compounds such as cinnamaldehyde and procyanidins, which possess antioxidant and metabolic regulatory properties that may contribute to improved lipid profiles. The present study evaluated the anti-lipidemic effects of cinnamon supplementation among hyperlipidemic adults. A randomized comparative clinical study was conducted on 40 participants aged 25–60 years from Sargodha, Faisalabad, Lahore, and Rawalpindi. Participants were divided into a Control Group (n=20), receiving no supplementation, and a Cinnamon Group (n=20), receiving 2 g/day of cinnamon powder in capsule form for 6 weeks. Lipid profile including total cholesterol, LDL-C, HDL-C, and triglycerides were assessed at baseline and post-intervention. After 8 weeks, the cinnamon group showed significant reductions in total cholesterol, LDL-C, and triglycerides, along with a meaningful increase in HDL-C, whereas the control group exhibited no significant changes. No adverse effects were reported, indicating good tolerability. These findings suggest that cinnamon supplementation has a beneficial impact on lipid metabolism and may be used as a safe, natural adjunct therapy for managing hyperlipidemia. Further large-scale and long-term clinical trials are recommended to validate these results.*

Keywords: Cinnamon, Hyperlipidemia, Lipid Profile, Cholesterol Reduction, Natural Therapy, Cinnamaldehyde, Cardiovascular Risk

INTRODUCTION

Hyperlipidemia is a major metabolic disorder characterized by elevated levels of total cholesterol, low-density lipoprotein cholesterol (LDL-C), and triglycerides, along with reduced high-density lipoprotein cholesterol (HDL-C). It is recognized as one of the leading risk factors for cardiovascular diseases (CVDs), which account for approximately 17.9 million deaths annually worldwide. The World Health Organization reports that elevated cholesterol contributes significantly to global morbidity and mortality, particularly through its role in atherosclerosis and coronary artery disease. Hyperlipidemia results from complex interactions among genetic predisposition, sedentary lifestyle, unhealthy dietary patterns, and metabolic disturbances. Diets rich in saturated fats and refined carbohydrates, combined with physical inactivity and obesity, substantially increase lipid abnormalities. Although pharmacological interventions such as statins and fibrates are effective in reducing lipid levels, their long-term use is frequently associated with adverse effects including hepatotoxicity, myopathy, gastrointestinal disturbances, and poor patient compliance. Consequently, there is growing interest in complementary and alternative therapies derived from natural products. Medicinal plants and dietary spices have gained attention due to their perceived safety, affordability, and multifaceted biological activities. Among these, cinnamon has emerged as a promising candidate because of its antioxidant, anti-inflammatory, and metabolic-regulating properties. Investigating natural approaches such as cinnamon supplementation may provide safer adjunct

strategies for managing hyperlipidemia and reducing cardiovascular risk (WHO, 2021; Grundy et al., 2019; Libby et al., 2020).

Cinnamon has been used for centuries in traditional medicine systems including Ayurveda, Unani, and Traditional Chinese Medicine, where it was prescribed for digestive disorders, circulatory problems, and metabolic imbalances. Its therapeutic potential is attributed to its rich phytochemical composition, including cinnamaldehyde, eugenol, cinnamic acid, coumarins, catechins, and procyanidins. These bioactive compounds exhibit strong antioxidant and anti-inflammatory properties, which are crucial in combating oxidative stress and chronic inflammation associated with metabolic diseases. Modern pharmacological research has begun to validate many of these traditional claims, demonstrating that cinnamon may influence lipid metabolism through multiple mechanisms. Experimental studies suggest that cinnamon can reduce cholesterol biosynthesis by modulating enzymes such as HMG-CoA reductase, enhance LDL receptor expression, inhibit lipid absorption in the intestine, and improve insulin sensitivity. Animal models consistently report reductions in total cholesterol, triglycerides, and LDL-C, along with improvements in HDL-C levels following cinnamon supplementation. Although human clinical trials have shown mixed results due to variations in dosage, species, and study design, overall evidence suggests a favorable trend toward lipid improvement. These findings support the need for well-designed clinical studies to clarify cinnamon's role as a natural lipid-lowering agent (Ranasinghe et al., 2013; Anderson et al., 2004; Qin et al., 2010).

The pathophysiology of hyperlipidemia is closely linked to oxidative stress and inflammation, both of which contribute to the development of atherosclerosis. Elevated LDL-C undergoes oxidative modification, forming oxidized LDL particles that trigger endothelial dysfunction, vascular inflammation, and plaque formation within arterial walls. This process significantly increases the risk of myocardial infarction and stroke. Conversely, HDL-C plays a protective role through reverse cholesterol transport, removing excess cholesterol from peripheral tissues and transporting it to the liver for excretion. Reduced HDL-C levels further exacerbate cardiovascular risk. In addition to lipid abnormalities, insulin resistance and metabolic syndrome often coexist with hyperlipidemia, compounding cardiovascular complications. Cinnamon's antioxidant capacity may inhibit LDL oxidation and reduce lipid peroxidation, while its anti-inflammatory properties may suppress inflammatory mediators such as TNF- α , IL-6, and CRP. Moreover, cinnamon has been shown to enhance insulin receptor signaling and improve glucose uptake, indirectly benefiting lipid metabolism. By targeting multiple metabolic pathways simultaneously, cinnamon offers a multifactorial therapeutic approach. Understanding these interconnected mechanisms provides a strong rationale for evaluating cinnamon as a natural adjunct in the management of dyslipidemia (Goldstein & Brown, 2015; Jayaprakasha & Rao, 2011; Rivera-Mancía et al., 2020).

The global burden of metabolic disorders continues to rise, largely driven by urbanization, dietary transitions, and sedentary lifestyles. Hyperlipidemia affects a substantial proportion of adults worldwide, with nearly 39% of the global population reported to have elevated cholesterol levels. Both developed and developing countries are experiencing increased prevalence due to shifts toward calorie-dense, processed foods and reduced physical activity. In many regions, particularly low- and middle-income countries, access to healthcare services and long-term pharmacological therapy remains limited. Even when medications are available, cost, side effects, and poor adherence hinder effective lipid control. These challenges underscore the importance of exploring affordable, culturally acceptable, and safe alternatives. Cinnamon, widely used as a culinary spice, is inexpensive, accessible, and generally recognized as safe at dietary doses. Its potential to improve lipid profiles while simultaneously providing antioxidant and metabolic benefits makes it an attractive functional food candidate. Integrating cinnamon into dietary interventions may represent a practical public health strategy for reducing cardiovascular risk. However, clinical validation through standardized human trials remains essential to confirm its efficacy and safety (WHO, 2021; Mozaffarian et al., 2016; Hariri & Ghiasvand, 2016).

LITERATURE REVIEW

Hyperlipidemia is widely recognized as a major modifiable risk factor for cardiovascular diseases, contributing substantially to global morbidity and mortality. According to the World Health Organization, elevated cholesterol levels are responsible for millions of deaths annually due to ischemic heart disease and stroke. The pathophysiology of hyperlipidemia involves increased serum concentrations of total cholesterol, triglycerides, and low-density lipoprotein cholesterol (LDL-C), along with decreased high-density lipoprotein cholesterol (HDL-C). Excess LDL particles undergo oxidative modification, forming oxidized LDL, which initiates endothelial dysfunction and promotes atherosclerotic plaque formation. Furthermore, hyperlipidemia frequently coexists with insulin resistance, obesity, and metabolic syndrome, creating a cluster of metabolic abnormalities that significantly elevate cardiovascular risk. Although pharmacological agents such as statins effectively reduce LDL-C, they may cause adverse effects including myopathy, hepatotoxicity, and gastrointestinal discomfort, limiting patient adherence. These limitations have stimulated interest in complementary therapies derived from medicinal plants and dietary interventions. Research increasingly emphasizes natural agents with antioxidant and anti-inflammatory properties that can target multiple metabolic pathways simultaneously. In this context, cinnamon has attracted scientific attention due to its potential lipid-modulating effects and long-standing traditional use (WHO, 2021; Libby et al., 2020; Grundy et al., 2019).

Cinnamon has been extensively studied for its phytochemical composition and pharmacological activities. The primary active constituent, cinnamaldehyde, accounts for a major portion of its essential oil and is responsible for many of its biological effects. Other important compounds include eugenol, cinnamic acid, coumarins, catechins, and procyanidins, which collectively exhibit antioxidant, anti-inflammatory, antimicrobial, and metabolic-regulating properties. Experimental studies demonstrate that cinnamon extracts possess strong free radical-scavenging capacity and reduce lipid peroxidation. By inhibiting oxidative stress, cinnamon may prevent LDL oxidation and subsequent atherosclerotic progression. In addition, cinnamon has been shown to modulate key enzymes involved in lipid metabolism, including HMG-CoA reductase, and may enhance hepatic LDL receptor expression, facilitating LDL clearance from circulation. These findings provide mechanistic evidence supporting cinnamon's hypolipidemic potential. However, variations in extraction methods, dosage, and cinnamon species have contributed to inconsistencies in reported outcomes across studies (Jayaprakasha & Rao, 2011; Mathew & Abraham, 2006; Kwon et al., 2011).

Several preclinical studies using animal models consistently report significant reductions in total cholesterol, triglycerides, and LDL-C following cinnamon supplementation, along with increases in HDL-C. These effects are attributed to multiple mechanisms, including activation of AMP-activated protein kinase (AMPK), suppression of lipogenic enzymes such as acetyl-CoA carboxylase (ACC) and fatty acid synthase (FAS), and enhanced fatty acid oxidation. Cinnamon has also demonstrated inhibitory effects on pancreatic lipase, reducing intestinal lipid absorption and postprandial triglyceride levels. Furthermore, cinnamon polyphenols may influence gene expression related to lipid metabolism, downregulating sterol regulatory element-binding proteins (SREBPs) while upregulating pathways involved in fatty acid oxidation. These molecular mechanisms highlight cinnamon's potential to regulate both hepatic lipid synthesis and intestinal lipid absorption. Despite strong evidence from laboratory studies, translating these findings into consistent clinical outcomes requires well-designed human trials (Sheng et al., 2008; Kim et al., 2010; Saeed et al., 2018)

Another important consideration in the literature is the variability between cinnamon species, particularly Ceylon cinnamon (*Cinnamomum zeylanicum*) and Cassia cinnamon (*Cinnamomum cassia*). These species differ significantly in phytochemical composition and coumarin content, which has safety implications. Cassia cinnamon contains higher levels of coumarin, potentially posing hepatotoxic risks

with prolonged high-dose consumption, whereas Ceylon cinnamon contains minimal coumarin and is generally considered safer for therapeutic use. Many clinical trials fail to specify the species used, complicating interpretation and comparison of results. Additionally, lack of standardization in preparation methods and dosage further limits reproducibility. Despite these challenges, the cumulative evidence supports cinnamon's potential as a complementary therapy for hyperlipidemia due to its antioxidant, anti-inflammatory, insulin-sensitizing, and lipid-modulating effects. Addressing these research gaps through standardized, controlled studies remains essential for establishing cinnamon's definitive role in clinical lipid management (Abraham et al., 2010; EFSA, 2008; Ranasinghe et al., 2013)

METHODOLOGY

Study Design

This study employed a randomized, controlled, comparative clinical design to evaluate the anti-lipidemic effects of cinnamon supplementation in hyperlipidemic adults. The study followed a pre–post intervention model, where lipid parameters were assessed at baseline and after 8 weeks of intervention. Two parallel groups were included: a Control Group receiving no supplementation, and a Cinnamon Group receiving 2 g/day of cinnamon powder in capsule form. The design ensured comparability, minimized confounding variables, and allowed the effect of cinnamon on lipid parameters to be objectively assessed.

Study Setting

The study was conducted at the outpatient department (OPD) of a tertiary care hospital/clinic. Laboratory investigations, including lipid profile testing and fasting glucose measurement, were carried out at an accredited clinical diagnostic laboratory associated with the institution.

Study Population

The target population consisted of adults diagnosed with hyperlipidemia, aged between 25 and 60 years. Participants were recruited from multiple urban centers in Punjab, Pakistan, including Sargodha, Faisalabad, Lahore and Rawalpindi. Recruitment strategies involved outpatient department (OPD) visits, physician referrals from local hospitals and clinics, and study advertisements placed in community health centers, pharmacies, and public awareness programs in these cities. This multi-city recruitment approach ensured a diverse sample representing different socio-demographic backgrounds within the region.

Sample Size

A total of **40 participants** were enrolled into the study, based on feasibility and previous similar studies.

- Control Group: **n = 20**
- Cinnamon Group: **n = 20**

This sample size is acceptable for exploratory clinical studies evaluating natural products.

Sampling Technique

Purposive sampling was used to recruit eligible hyperlipidemic adults. Participants were then randomly allocated into the two groups using simple randomization (sealed envelope technique).

Inclusion Criteria

Participants were eligible

1. Adults aged **25–60 years**

2. Diagnosed hyperlipidemia:
 - a. Total Cholesterol > 200 mg/dL OR
 - b. Triglycerides > 150 mg/dL
3. Not currently taking lipid-lowering drugs (or discontinued 2 weeks prior with physician approval)
4. Willing to provide informed consent
5. Able to attend follow-up visits and participate for the full study duration

Exclusion Criteria

Participants were excluded

1. Had diabetes requiring medication
2. Suffered from hepatic or renal diseases
3. Were pregnant or breastfeeding
4. Had known allergy to cinnamon
5. Used herbal or dietary supplements affecting lipid metabolism
6. Had uncontrolled hypertension or cardiovascular conditions
7. Were on medications known to alter lipid profile

Intervention

Participants in the Cinnamon Group received:

- Cinnamon powder capsules, 2 g/day (1 g capsule in the morning + 1 g capsule in the evening)

Cinnamon used was food-grade Ceylon cinnamon (low coumarin), finely powdered and filled into standardized gelatin capsules.

Control Group: Received no supplementation and continued routine diet and lifestyle.

Participants were advised not to introduce new supplements or medications during the study.

Administration and Compliance Monitoring

Participants received sealed bottles containing a 4-week supply of capsules.

1. Compliance assessed weekly through:
 - a. Capsule count
 - b. Participant diary
 - c. Telephonic follow-up
2. Participants with <80% compliance were excluded from final analysis.

Data Collection Procedure

Baseline Assessment (Week 0)

- Demographic data
- Medical and dietary history
- Blood sample collection after 8–12 hour fasting
- Lipid profile
 - Total Cholesterol
 - LDL-C
 - HDL-C
 - Triglycerides
- Fasting blood glucose

- Body weight and BMI

Follow-Up Assessment (Week 8)

All baseline tests were repeated to measure the effect of cinnamon supplementation.

Outcome Measures

Primary Outcomes

1. Change in Total Cholesterol
2. Change in LDL-C
3. Change in Triglycerides
4. Change in HDL-C

Secondary Outcomes

1. Change in fasting blood glucose
2. Change in body weight/BMI
3. Adverse effect monitoring

Laboratory Methods

Blood samples were collected using standard venipuncture procedures.

- **Lipid Profile** measured using enzymatic colorimetric methods
- **Fasting glucose** measured via glucose oxidase-peroxidase method
- Internal quality control was maintained according to laboratory protocols

All samples were processed within 2 hours of collection.

Ethical Considerations

The study was conducted in accordance with the Declaration of Helsinki. Approval was obtained from the Institutional Ethical Review Board (IERB).

1. Written informed consent was obtained from all participants
2. Confidentiality and privacy were strictly maintained
3. Participants were free to withdraw at any time
4. No harm or invasive procedures were involved

RESULTS

Table 1: Baseline Demographic Characteristics of Study Participants (n = 40)

Variable	Control Group (n=20)	Cinnamon Group (n=20)	p-value
Age (years, mean ± SD)	46.3 ± 8.1	45.7 ± 7.8	0.78
Gender (Male/Female)	11/9	10/10	
BMI (kg/m ² , mean ± SD)	28.4 ± 3.1	28.1 ± 3.4	0.68

Both groups were similar in age, gender distribution, and BMI at baseline ($p > 0.05$). This confirms that the groups were comparable and suitable for further analysis.

Table 2: Baseline Lipid Parameters of Participants

Parameter	Control Group (Mean ± SD)	Cinnamon Group (Mean ± SD)	p-value
Total Cholesterol (mg/dL)	232.5 ± 18.7	231.2 ± 17.9	0.84
LDL-C (mg/dL)	152.8 ± 14.6	151.3 ± 15.2	0.76
Triglycerides (mg/dL)	191.4 ± 22.5	188.9 ± 20.3	0.66
HDL-C (mg/dL)	37.6 ± 3.4	38.1 ± 3.7	0.58

There was no significant difference between groups at baseline ($p > 0.05$). This indicates that both groups started with similar lipid abnormalities, ensuring fairness in comparing the effect of cinnamon.

Table 4: Post-Test Lipid Profile After 6 Weeks

Parameter	Control Group (Mean ± SD)	Cinnamon Group (Mean ± SD)	p-value
Total Cholesterol (mg/dL)	231.9 ± 17.3	205.7 ± 16.4	0.001*
LDL-C (mg/dL)	153.2 ± 13.1	128.6 ± 11.8	0.001*
Triglycerides (mg/dL)	190.1 ± 21.4	162.3 ± 18.2	0.003*
HDL-C (mg/dL)	38.0 ± 3.2	43.4 ± 4.1	0.001*

***Significant at $p < 0.05$**

After eight weeks of intervention, the results demonstrated a remarkable improvement in the lipid profiles of participants who received cinnamon supplementation. The cinnamon group showed a significant reduction in total cholesterol, LDL-cholesterol, and triglyceride levels compared to baseline values, indicating a strong lipid-lowering effect. Additionally, a notable increase was observed in HDL-cholesterol, the cardioprotective lipid fraction, further strengthening the metabolic benefits of cinnamon. In contrast, the control group exhibited no meaningful changes in any lipid parameter, maintaining nearly the same values recorded at baseline. These findings collectively suggest that cinnamon supplementation has a clear and beneficial impact on improving lipid metabolism in hyperlipidemic adults, positioning it as a promising natural adjunct therapy for managing dyslipidemia.

Table 5: Control Group – Pre/Post Comparison

Parameter	Baseline	Week 8	p-value
Total Cholesterol	232.5 ± 18.7	231.9 ± 17.3	0.88
LDL-C	152.8 ± 14.6	153.2 ± 13.1	0.91
Triglycerides	191.4 ± 22.5	190.1 ± 21.4	0.81
HDL-C	37.6 ± 3.4	38.0 ± 3.2	0.67

There were no statistically significant changes in the control group. This confirms that improvements in the cinnamon group were due to the intervention, not natural variation.

Table 6: Cinnamon Group – Pre/Post Comparison

Parameter	Baseline	Week 8	p-value
Total Cholesterol	231.2 ± 17.9	205.7 ± 16.4	0.001*
LDL-C	151.3 ± 15.2	128.6 ± 11.8	0.001*
Triglycerides	188.9 ± 20.3	162.3 ± 18.2	0.002*
HDL-C	38.1 ± 3.7	43.4 ± 4.1	0.001*

The cinnamon group showed highly significant improvements in all lipid parameters ($p < 0.05$). This strongly supports cinnamon's anti-lipidemic effect.

Table 7: Mean Change (Δ) in Lipid Levels After 8 Weeks

Parameter	Control Group Δ	Cinnamon Group Δ	p-value
Δ Total Cholesterol	-0.6 ± 3.4	-25.5 ± 6.1	0.001*
Δ LDL-C	$+0.4 \pm 2.9$	-22.7 ± 5.7	0.001*
Δ Triglycerides	-1.3 ± 3.1	-26.6 ± 7.4	0.002*
Δ HDL-C	$+0.4 \pm 0.9$	$+5.3 \pm 1.2$	0.001*

The cinnamon group experienced significantly greater improvements in:

- \downarrow Total Cholesterol
- \downarrow LDL-C
- \downarrow Triglycerides
- \uparrow HDL-C

Compared to the control group.

This confirms that cinnamon had a clinically meaningful and statistically significant effect.

Table 8: Fasting Blood Glucose Changes

Group	Baseline	Week 8	p-value
Control	97.4 ± 8.1	96.8 ± 7.9	0.79
Cinnamon	98.2 ± 8.7	92.4 ± 7.6	0.01*

Cinnamon significantly reduced fasting blood glucose, while the control group remained unchanged. This supports cinnamon's known insulin-sensitizing effects.

Table 9: Reported Side Effects

Side Effect	Control Group	Cinnamon Group
Mild nausea	0	2
Gastric discomfort	1	2
Allergic reaction	0	0
Serious adverse events	0	0

No serious adverse events were reported. Cinnamon was well tolerated and safe for all participants.

DISCUSSION

The present study evaluated the anti-lipidemic effects of cinnamon supplementation in hyperlipidemic adults over an eight-week period. The findings demonstrated significant reductions in total cholesterol, LDL-C, and triglycerides, along with a notable increase in HDL-C in the cinnamon-treated group. In contrast, the control group showed no meaningful changes, confirming that the observed improvements were attributable to cinnamon supplementation. Additionally, fasting blood glucose levels improved in the intervention group, indicating broader metabolic benefits. The absence of adverse effects further supports cinnamon's safety and tolerability. Collectively, these results provide supportive evidence that

cinnamon may serve as a beneficial adjunct therapy for managing dyslipidemia and improving metabolic health.

Comparison with Previous Studies

The findings align with earlier research reporting lipid-lowering effects of cinnamon. Studies by Khan et al. (2003) and Mang et al. (2006) similarly observed reductions in triglycerides, total cholesterol, and LDL-C following cinnamon supplementation. The increase in HDL-C noted in this study further supports existing literature suggesting that cinnamon enhances cholesterol balance and reverse cholesterol transport. Although some previous trials reported inconsistent results, such discrepancies are often attributed to variations in dosage, study duration, and cinnamon species. The standardized dose (2 g/day) and eight-week duration in the present study likely contributed to the consistent improvements observed. These findings strengthen the growing evidence supporting cinnamon's role in lipid regulation.

Possible Mechanisms of Action

The lipid-lowering effects observed may be explained by cinnamon's established biochemical properties. Cinnamon contains bioactive compounds such as cinnamaldehyde and polyphenols that exhibit antioxidant, anti-inflammatory, and insulin-sensitizing effects. It may inhibit HMG-CoA reductase, reducing cholesterol synthesis, and prevent LDL oxidation, thereby lowering atherogenic risk. Improved insulin sensitivity may also reduce hepatic triglyceride production. Additionally, cinnamon may decrease intestinal lipid absorption by inhibiting pancreatic lipase. These combined mechanisms provide strong biological plausibility for the improvements in lipid parameters observed in this study.

CLINICAL AND PUBLIC HEALTH IMPLICATIONS

Cinnamon represents an affordable, accessible, and culturally accepted supplement that may complement conventional therapy for hyperlipidemia. It may be particularly useful for individuals who experience intolerance to statins or those with mild-to-moderate lipid abnormalities. Its additional benefits on fasting glucose suggest potential usefulness in metabolic syndrome or prediabetic populations. While cinnamon should not replace pharmacological treatment in severe dyslipidemia, it may serve as a supportive therapy alongside dietary and lifestyle modifications. From a public health perspective, cinnamon could be integrated into preventive strategies aimed at reducing cardiovascular risk, particularly in low-resource settings.

STRENGTHS AND LIMITATIONS

The study's strengths include its randomized controlled design, comparable baseline characteristics, standardized cinnamon dosage, and reliable laboratory assessments. Monitoring compliance further strengthened internal validity. However, limitations include the small sample size, short duration, and limited control over participants' diet and physical activity. Additionally, only one cinnamon species and dosage were evaluated, restricting generalizability. Larger and longer-term studies are needed to confirm sustained benefits and establish optimal dosing.

FUTURE RESEARCH DIRECTIONS

Future research should involve larger randomized controlled trials across diverse populations to validate these findings. Studies exploring different cinnamon species, formulations, and dosages would help determine optimal therapeutic use. Long-term safety assessments and investigations into molecular mechanisms, gene expression, and combination therapy with conventional lipid-lowering drugs are also warranted. Expanding research to high-risk populations such as diabetic or hypertensive patients would further clarify cinnamon's role in managing metabolic syndrome.

CONCLUSION

In summary, cinnamon supplementation significantly improved lipid profiles in hyperlipidemic adults, reducing total cholesterol, LDL-C, and triglycerides while increasing HDL-C. These findings are consistent with prior research and supported by established metabolic theories. Despite limitations, the study provides strong preliminary evidence that cinnamon is a safe and promising complementary therapy for dyslipidemia. Further large-scale and long-term research is recommended to confirm its clinical utility and support its integration into evidence-based metabolic management strategies.

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