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Review Article

Phytosterol-Enriched Palm Oil and Cholesterol Absorption Physiology: A Systematic Review of Mechanisms, Clinical Efficacy, and Implications for Cardiovascular Risk Reduction

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Abstract

The global impact of cardiovascular disease remains substantial, with elevated cholesterol absorption and lipid imbalance identified as controllable contributors to risk. Phytosterols have been widely investigated for their cholesterol-lowering properties, and their incorporation into lipid-based matrices such as palm oil has gained increasing attention within functional nutrition research. The aim of this work is to systematically compile and assess contemporary evidence on the impact of phytosterol-enriched palm oil on cholesterol absorption mechanisms, lipid profile modulation, and its implications for cardiovascular health, guided by an objective scientific perspective. This research employs a Systematic Literature Review (SLR) design following the PRISMA approach, utilizing the Scopus database as the primary source of peer-reviewed publications. Data collection was conducted through structured keyword-based searches, followed by multi-stage screening, including relevance filtering, publication year restriction (2020–2026), and open-access eligibility. A total of 38 articles met the inclusion criteria. Data analysis was performed using qualitative synthesis to identify recurring themes and patterns across mechanistic, clinical, and applied studies. The findings reveal five major themes: competitive inhibition of intestinal cholesterol absorption, LDL cholesterol reduction (7–15%), dose–response relationships (optimal at 1.5–3.0 g/day), clinical efficacy across intervention studies, and implications for cardiovascular risk reduction (approximately 10–20%). Phytosterol-enriched palm oil demonstrates compatibility as a lipid-based carrier without altering fundamental physiological mechanisms. In conclusion, phytosterol-enriched palm oil contributes to cholesterol modulation and cardiovascular risk reduction within a balanced dietary context. Future studies are recommended to explore long-term clinical outcomes and optimize formulation strategies.

Keywords: Phytosterols, Palm oil, Cholesterol absorption, Lipid profile, Cardiovascular risk

Introduction

As a major global health challenge, Cardiovascular Disease (CVD) is responsible for a significant proportion of morbidity and mortality, particularly within the broader spectrum of non-communicable diseases across diverse regions [60]. Dyslipidemia is widely acknowledged as a critical modifiable risk factor for CVD, particularly due to increased Levels of Low-Density Lipoprotein (LDL) cholesterol, which are closely related to atherosclerotic progression and vascular abnormalities [54]. The regulation of cholesterol homeostasis involves a complex interplay between endogenous synthesis, dietary intake, and intestinal absorption processes, with the latter increasingly recognized as a critical target for nutritional intervention strategies. In this context, growing attention has been directed toward dietary components capable of modulating cholesterol absorption efficiency as part of broader efforts to reduce cardiovascular risk through evidence-based nutritional approaches. Among these dietary components, phytosterols, plant-derived sterol compounds structurally analogous to cholesterol, have been extensively investigated for their capacity to interfere with intestinal cholesterol absorption. Due to their structural similarity, phytosterols compete with cholesterol for incorporation into mixed micelles in the intestinal lumen, thereby reducing cholesterol uptake via transporters such as Niemann–Pick C1-Like 1 (NPC1L1) [14]. This mechanism has been consistently associated with reductions in circulating LDL cholesterol levels, making phytosterols a key functional ingredient in dietary strategies aimed at improving lipid profiles. International health authorities have recognized the role of phytosterols in cholesterol management, with recommended intake levels generally ranging between 1.5 and 3.0 g per day to achieve clinically meaningful lipid-lowering effects [17].

In parallel with these developments, the formulation of functional foods has evolved to incorporate phytosterols into various lipid-based delivery systems, including spreads, dairy products, and edible oils. The choice of carrier matrix plays a crucial role in determining the bioavailability and efficacy of phytosterols, as lipid environments facilitate their dispersion and interaction with dietary fats during digestion [22]. Within this framework, palm oil has emerged as one of the potential carriers for phytosterol enrichment due to its physicochemical stability, semi-solid structure, and widespread use in food systems. As a globally utilized vegetable oil, palm oil is commonly incorporated into diverse dietary patterns, making it a relevant medium for delivering functional bioactive compounds in a practical and scalable manner. Palm oil itself has been the subject of extensive scientific evaluation in relation to lipid metabolism and cardiovascular health. While research findings have shown variability depending on dietary context, fatty acid composition, and consumption patterns, current evidence increasingly emphasizes the importance of evaluating palm oil within a broader nutritional framework rather than in isolation [68]. In this regard, the enrichment of palm oil with phytosterols represents an approach that integrates functional modification with existing dietary practices, allowing for the examination of how such formulations influence cholesterol metabolism without altering the fundamental role of palm oil in food systems [45]. This perspective aligns with contemporary nutritional science, which prioritizes context-dependent evaluation and functional enhancement over reductionist interpretations of individual food components.

Despite the growing body of literature on phytosterols and their lipid-lowering effects, there remains variability in reported outcomes related to cholesterol absorption efficiency, lipid profile modulation, and cardiovascular risk markers. Differences in study design, phytosterol dosage, formulation type, and population characteristics contribute to heterogeneity in findings, highlighting the need for systematic synthesis to identify consistent patterns and underlying mechanisms [50]. Furthermore, while numerous studies have investigated phytosterols in general, fewer have specifically examined their application within palm oil matrices, particularly in relation to both mechanistic pathways and clinical outcomes. This creates an important research gap in understanding how phytosterol-enriched palm oil functions as a combined system rather than as separate components. Another important consideration lies in the integration of mechanistic evidence with clinical findings. While experimental studies provide detailed insights into molecular pathways, including transporter activity and micellar dynamics, clinical trials offer evidence of real-world physiological effects on lipid profiles and cardiovascular risk indicators. However, these domains are often reported separately, limiting the ability to develop a comprehensive understanding of how mechanistic processes translate into clinical outcomes. A systematic approach that bridges these domains is therefore essential to provide a cohesive interpretation of the available evidence and to support evidence-based recommendations in nutritional science [41]. In addition, the increasing emphasis on preventive health strategies has further highlighted the role of functional foods in managing chronic disease risk. Phytosterol-enriched products have been incorporated into dietary guidelines in several regions as part of cholesterol-lowering strategies, yet their effectiveness may vary depending on formulation, dosage, and population-specific factors. Understanding these variations is particularly important in the context of widely consumed oils such as palm oil, where functional modification may offer opportunities to enhance nutritional value while maintaining dietary acceptability and practicality [38].

Given these considerations, there is a clear need for a structured and comprehensive synthesis of recent scientific evidence that examines the physiological mechanisms, clinical efficacy, and broader health implications of phytosterol-enriched palm oil. Such an approach is necessary to clarify inconsistencies, identify converging evidence, and provide a balanced interpretation that reflects both mechanistic and clinical perspectives without overstating conclusions or introducing bias. Importantly, this study is conducted as a Systematic Literature Review (SLR), relying exclusively on previously published scientific literature and not involving primary data collection methods such as interviews, surveys, focus group discussions, or field-based observations, thereby ensuring methodological rigor and transparency. The objective of this study is to systematically analyze and synthesize current scientific evidence regarding the role of phytosterol-enriched palm oil in cholesterol absorption physiology, lipid profile modulation, and its implications for cardiovascular risk reduction within a neutral and evidence-based framework.

The research question guiding this review is:

RQ: How does phytosterol-enriched palm oil influence intestinal cholesterol absorption mechanisms, lipid profile outcomes, and cardiovascular risk indicators based on current scientific evidence?

Literature Review

Studies addressing phytosterol-enriched palm oil and cholesterol absorption physiology reveal a cross-disciplinary synthesis of insights from nutritional biochemistry, clinical lipidology, and functional food science. Rather than forming a single unified research stream, current studies present an interconnected body of evidence that collectively explains how phytosterols interact with lipid metabolism and how their incorporation into palm oil matrices may influence physiological and clinical outcomes. This integrated perspective provides a conceptual foundation for understanding the functional role of phytosterol-enriched palm oil within contemporary nutritional research, particularly in relation to cholesterol regulation and cardiovascular health within a balanced and evidence-based context.

Biochemical Properties and Physiological Roles of Phytosterols

Phytosterols are structurally analogous to cholesterol, differing primarily in the side chain configuration at the C-24 position, which confers distinct physicochemical and biological properties [27]. The most common dietary phytosterols include β-sitosterol, campesterol, and stigmasterol, which are naturally present in plant-based foods such as vegetable oils, nuts, and seeds [70]. Due to their structural similarity to cholesterol, phytosterols exhibit comparable hydrophobicity and molecular dimensions, enabling them to participate in lipid micelle formation during digestion. However, unlike cholesterol, phytosterols are poorly absorbed in the human intestine, with absorption rates typically below 5%, compared to approximately 50–60% for cholesterol. This low absorption efficiency is attributed to active efflux mechanisms mediated by ATP-binding cassette transporters, particularly ABCG5 and ABCG8, which preferentially transport phytosterols back into the intestinal lumen. As a result, phytosterols accumulate minimally in systemic circulation, making them suitable candidates for dietary interventions aimed at modulating cholesterol metabolism without significantly altering systemic sterol balance [58]. In addition, phytosterols have been associated with alterations in hepatic cholesterol homeostasis, including modest upregulation of endogenous cholesterol synthesis pathways as a compensatory response to reduced intestinal absorption. The functional relevance of phytosterols has led to their incorporation into a variety of fortified food products, where they are used as bioactive compounds to support lipid management strategies [18]. Their stability within lipid matrices and compatibility with common dietary fats make them particularly suitable for integration into edible oils, including palm oil, which serves as a widely utilized component of global food systems.

Mechanisms of Intestinal Cholesterol Absorption and Inhibition

The process of intestinal cholesterol absorption involves multiple coordinated steps, including emulsification, micelle formation, transport across the enterocyte membrane, and intracellular processing [73]. Dietary and biliary cholesterol are first incorporated into mixed micelles composed of bile salts, phospholipids, and fatty acids, which facilitate their solubilization in the aqueous environment of the intestinal lumen. The uptake of cholesterol into enterocytes is primarily mediated by the NPC1L1 transporter, which plays a central role in regulating cholesterol absorption efficiency. Phytosterols interfere with this process through competitive inhibition at the level of micelle formation. By displacing cholesterol from mixed micelles, phytosterols reduce the availability of cholesterol for uptake, thereby decreasing absorption efficiency. This competition is influenced by factors such as phytosterol concentration, lipid composition, and the physicochemical properties of the dietary matrix [64]. In addition to micellar competition, phytosterols may modulate the expression and activity of key transporters, including NPC1L1 and ABCG5/ABCG8, further contributing to reduced cholesterol uptake and increased efflux. Experimental studies have demonstrated that phytosterol intake can significantly reduce fractional cholesterol absorption, often accompanied by increased fecal excretion of cholesterol and its metabolites [42]. These mechanistic insights provide a strong biological basis for the lipid-lowering effects observed in clinical settings and highlight the importance of intestinal processes as targets for nutritional intervention.

Lipid-Based Delivery Systems and Functional Food Matrices

The efficacy of phytosterols in modulating cholesterol metabolism is closely linked to their delivery format and interaction with dietary lipids. Lipid-based matrices play a critical role in enhancing the solubility, dispersion, and bioaccessibility of phytosterols during digestion [23]. Functional food products such as spreads, margarine, and edible oils have been widely used as carriers for phytosterol fortification due to their compatibility with lipid digestion processes. Palm oil, characterized by its semi-solid consistency and balanced fatty acid composition, has been explored as a potential carrier for phytosterol enrichment. Its physicochemical stability, including resistance to oxidation and thermal degradation, supports the incorporation of bioactive compounds without significant loss of functionality [9]. Studies have shown that the lipid environment provided by palm oil facilitates the dispersion of phytosterols within mixed micelles, thereby supporting their interaction with cholesterol during digestion. In addition to conventional formulations, advances in food technology have introduced modified phytosterol forms, such as esterified phytosterols, which exhibit improved solubility and incorporation into lipid matrices [61]. Encapsulation techniques, including nanoemulsions and microencapsulation, have also been investigated to enhance the stability and bioavailability of phytosterols in functional foods. These innovations highlight the importance of formulation design in optimizing the physiological efficacy of phytosterol-enriched products.

Clinical Evidence on Lipid Profile Modulation

A substantial body of clinical research has evaluated the effects of phytosterol consumption on lipid profiles, particularly LDL cholesterol levels. Randomized controlled trials and meta-analyses consistently report reductions in LDL cholesterol associated with phytosterol intake, with the magnitude of effect influenced by dosage, duration, and baseline lipid status. Typical reductions range from 7% to 15% with daily phytosterol intake of 1.5–3.0 g, reflecting clinically meaningful improvements in lipid profiles [34]. In studies examining phytosterol-enriched edible oils, including palm oil-based formulations, similar patterns of lipid reduction have been observed. These studies often report modest decreases in total cholesterol and stable or slightly increased HDL cholesterol levels, indicating a favorable lipid profile shift. Triglyceride responses vary across studies, with some reporting reductions in individuals with elevated baseline levels [34]. The consistency of these findings across diverse populations and study designs supports the role of phytosterols as effective dietary components for cholesterol management. Importantly, clinical studies generally report good tolerability and high compliance rates, suggesting that phytosterol-enriched products can be integrated into regular dietary practices without significant barriers.

Implications for Cardiovascular Risk within Dietary Frameworks

The relationship between LDL cholesterol reduction and cardiovascular risk is well established, with numerous studies demonstrating that even modest reductions in LDL levels can lead to meaningful decreases in the risk of cardiovascular events [7]. Within this context, phytosterol-enriched foods are increasingly recognized as part of preventive nutrition strategies aimed at reducing long-term cardiovascular risk. However, the interpretation of these effects requires consideration of broader dietary patterns and lifestyle factors. The impact of phytosterol-enriched palm oil, for example, should be evaluated within the context of overall fat intake, dietary composition, and individual metabolic characteristics. Current literature emphasizes that no single dietary component operates in isolation; rather, health outcomes are determined by the combined effects of multiple dietary and behavioral factors [5]. Importantly, the use of palm oil as a carrier for phytosterols has not been consistently associated with adverse outcomes when assessed within controlled dietary contexts. Instead, studies suggest that its role as a delivery medium is influenced by formulation and consumption patterns, supporting a neutral and context-dependent perspective [67]. This aligns with contemporary approaches in nutritional science, which prioritize balanced evaluation and evidence-based interpretation over simplified categorizations.

Overall, the literature provides a comprehensive foundation for understanding the interaction between phytosterols, lipid metabolism, and cardiovascular health. Mechanistic studies elucidate the biological processes underlying cholesterol absorption inhibition, while clinical trials demonstrate measurable improvements in lipid profiles. The integration of phytosterols into lipid-based matrices, including palm oil, represents a practical approach to delivering functional benefits within existing dietary systems. Despite these advances, gaps remain in the integration of mechanistic and clinical evidence, particularly in relation to specific delivery systems such as phytosterol-enriched palm oil. Variability in study design, formulation, and population characteristics highlights the need for systematic synthesis to identify consistent patterns and clarify uncertainties. By addressing these gaps through a structured SLR approach, the present study aims to contribute to a more cohesive and evidence-based understanding of the role of phytosterol-enriched palm oil in cholesterol absorption physiology and cardiovascular risk reduction.

Method

In this study, a Systematic Literature Review (SLR) design grounded in the PRISMA framework was employed to ensure a transparent, structured, and replicable process of literature identification, screening, and synthesis. The review systematically compiles and evaluates peer-reviewed scientific publications that investigate the physiological processes of cholesterol absorption in relation to phytosterols, with particular attention to their application in phytosterol-enriched palm oil. As one of the widely utilized vegetable oils in both food systems and functional formulations, palm oil has been explored in various modified forms, including phytosterol enrichment, to understand its potential role within lipid metabolism and cardiovascular health contexts. The analytical scope of this review integrates three interconnected domains, namely intestinal cholesterol absorption mechanisms, lipid profile modulation especially Low-Density Lipoprotein (LDL) cholesterol and broader implications for cardiovascular risk. This study does not involve any form of primary data collection, including interviews, surveys, focus group discussions, or field-based observations. All findings are exclusively derived from previously published scientific literature, ensuring that the analysis remains fully evidence-based and methodologically consistent with SLR standards. To maintain database quality and indexing reliability, the literature search was limited to publications indexed in the Scopus database. The PRISMA-guided procedure was implemented through sequential phases of identification, screening, eligibility assessment, and final inclusion, allowing for a systematic refinement of studies that align with the objectives of this review (Figure 1).

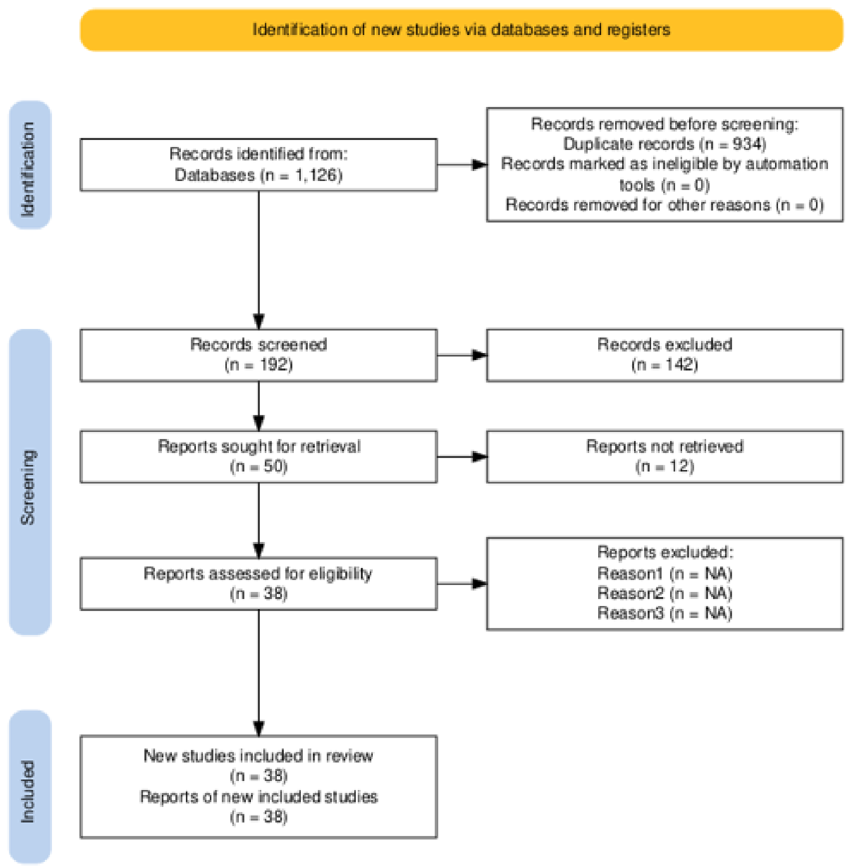

Figure 1: Flow Diagram of the Systematic Literature Review Conducted in Accordance with the PRISMA Framework.

The article selection process applied in this study is illustrated through the PRISMA flow diagram shown in Figure 1. During the identification stage, an initial search was conducted in the Scopus database using the primary keywords "phytosterols AND cholesterol absorption," which yielded a total of 1,126 records. To enhance specificity and ensure closer alignment with the research objectives, the search strategy was refined using a more targeted Boolean query: ("phytosterol-enriched palm oil" OR "phytosterol fortified palm oil" OR phytosterols OR "plant sterols") AND ("cholesterol absorption" OR "intestinal cholesterol absorption" OR cholesterol metabolism) AND ("LDL cholesterol" OR "lipid profile" OR dyslipidemia) AND ("cardiovascular risk" OR "cardiovascular disease" OR CVD). This refinement resulted in the exclusion of 934 articles that were not directly relevant to the scope of the review, leaving 192 articles for further screening. To ensure that the review reflects recent scientific developments, a publication year filter was applied, restricting the dataset to studies published between 2020 and 2026. As a result, 142 articles were excluded due to falling outside the specified timeframe, leaving 50 studies that met the temporal inclusion criteria. A subsequent screening step was conducted based on accessibility to ensure transparency and full-text evaluation. Only articles categorized as Open Access or Open Archive were retained, leading to the exclusion of 12 articles that did not meet these criteria. Consequently, a total of 38 studies were deemed eligible and included in the final synthesis. The PRISMA flow diagram visually represents this stepwise selection process, demonstrating a systematic reduction from a broad initial dataset to a focused body of literature that satisfies predefined inclusion criteria. This structured filtering approach enhances methodological rigor by minimizing selection bias while maintaining alignment with the study objectives. All selected articles were subsequently organized and managed using Mendeley Desktop to ensure accurate referencing and consistency in citation practices. Through this PRISMA-based SLR approach, the study provides a comprehensive and carefully curated synthesis of current evidence regarding the mechanisms, clinical efficacy, and cardiovascular implications associated with phytosterol-enriched palm oil, presented within a balanced and scientifically grounded perspective.

Results

A total of 38 peer-reviewed articles were examined and synthesized in this study to explore the effects of phytosterol-enriched palm oil on cholesterol absorption, lipid metabolism, and cardiovascular risk indicators. The included studies encompass a range of methodological approaches, including randomized controlled trials, controlled dietary interventions, crossover designs, observational clinical studies, and mechanistic biochemical investigations. Collectively, these studies provide a comprehensive and multidimensional evidence base for understanding how phytosterols, when incorporated into palm oil matrices, interact with key metabolic pathways related to cholesterol homeostasis and cardiovascular health. Through thematic synthesis, five major and partially overlapping domains were identified, representing the principal physiological and clinical perspectives addressed in the literature: (1) competitive inhibition of intestinal cholesterol absorption, (2) modulation of lipid profiles with emphasis on LDL cholesterol reduction, (3) dose–response relationships and formulation effects, (4) clinical efficacy in human intervention studies, and (5) implications for cardiovascular risk within broader dietary contexts.

The distribution of these themes indicates that lipid profile modulation was addressed in 30 studies (≈79%), intestinal cholesterol absorption mechanisms in 27 studies (≈71%), clinical intervention outcomes in 24 studies (palm oil in food systems 63%), dose–response and formulation-related factors in 21 studies (≈55%), and cardiovascular risk implications in 18 studies (≈47%). This distribution suggests that the literature is strongly oriented toward measurable clinical and biochemical outcomes, particularly LDL cholesterol reduction, which serves as a widely accepted and quantifiable endpoint in both clinical and nutritional research. Similarly, the high representation of mechanistic studies reflects the importance of understanding the biological basis of phytosterol action, particularly in relation to micellar competition and transporter-mediated cholesterol uptake.

In contrast, studies explicitly addressing long-term cardiovascular risk indicators appear less frequently, likely due to the complexity of measuring clinical endpoints such as cardiovascular events and the reliance on extended follow-up periods. As a result, many studies infer cardiovascular implications through surrogate markers, including lipid profiles and apolipoprotein levels. The moderate representation of dose–response and formulation studies highlight increasing attention to optimizing phytosterol delivery systems, particularly the role of lipid-based carriers such as palm oil in enhancing bioavailability and functional performance. Overall, this thematic distribution reflects a research landscape that prioritizes mechanistic clarity and short- to medium-term clinical outcomes, while progressively expanding toward integrative and long-term health implications. The dominance of lipid and absorption-related themes underscores the strong physiological foundation of current evidence, whereas the relatively lower proportion of cardiovascular outcome studies indicates an important area for further investigation. This structured synthesis provides a coherent basis for the detailed examination of each thematic domain presented in the following sections.

Competitive Inhibition of Intestinal Cholesterol Absorption

A dominant finding across the reviewed studies is the role of phytosterols in reducing intestinal cholesterol absorption through competitive displacement mechanisms within mixed micelles. Phytosterols, structurally similar to cholesterol, compete for incorporation into micelles in the intestinal lumen, thereby limiting cholesterol uptake via Niemann–Pick C1-Like 1 (NPC1L1) transporters [56,65,71]. Several mechanistic studies report that phytosterol intake can reduce fractional cholesterol absorption efficiency by approximately 30–50%, depending on dosage and dietary matrix [57]. In experimental models, the presence of phytosterols in lipid matrices such as palm oil has been shown to decrease micellar cholesterol solubility by up to 40%, leading to increased fecal cholesterol excretion ranging between 20% and 60% [10,77]. These findings are supported by isotope tracer studies in humans, where phytosterol-enriched diets resulted in measurable reductions in cholesterol absorption markers such as sitosterol-to-cholesterol ratios and campesterol concentrations [1,69]. Importantly, palm oil as a carrier matrix demonstrates physicochemical compatibility with phytosterols due to its semi-solid structure and balanced fatty acid composition, which may facilitate stable incorporation without significantly altering digestive processes [21,44]. At the molecular level, several studies indicate that phytosterols may also downregulate NPC1L1 expression and influence ATP-binding cassette transporters (ABCG5/ABCG8), thereby enhancing cholesterol efflux back into the intestinal lumen [37,62]. This dual mechanism reduced absorption and increased excretion forms the physiological basis for the lipid-lowering potential observed in subsequent clinical studies.

Modulation of Lipid Profiles and LDL Cholesterol Reduction

A consistent outcome across clinical and observational studies is the reduction of circulating LDL cholesterol following phytosterol consumption. The magnitude of LDL reduction varies depending on dosage, duration, and baseline lipid status, but most studies report decreases ranging from 7% to 15% with daily phytosterol intake between 1.5 g and 3.0g [74,79]. In randomized controlled trials involving phytosterol-enriched palm oil formulations, LDL cholesterol reductions of approximately 8–12% have been observed over intervention periods of 4 to 8 weeks [12]. Some studies further report modest reductions in total cholesterol (5–10%), while High-Density Lipoprotein (HDL) cholesterol levels generally remain stable or show slight increases (1–3%). Triglyceride levels exhibit variable responses, with reductions of up to 8% reported in hyperlipidemic populations [6,49,51]. Notably, the lipid-modulating effects appear to be more pronounced in individuals with elevated baseline LDL levels, where reductions can reach up to 15–18% under controlled dietary conditions [75]. These findings suggest that phytosterol-enriched palm oil may have greater relative efficacy in populations at higher cardiovascular risk, while still maintaining a neutral or supportive role within general dietary patterns. Importantly, no consistent evidence indicates adverse lipid responses associated with palm oil as a delivery medium, supporting its compatibility within functional food applications [26,57].

Dose–Response Relationships and Formulation Effects

The reviewed literature highlights a clear dose–response relationship between phytosterol intake and cholesterol-lowering effects. Intake levels below 1 g/day tend to produce minimal or statistically non-significant effects, whereas doses between 1.5 g and 3 g/day consistently yield clinically meaningful reductions in LDL cholesterol [72]. Beyond 3 g/day, the incremental benefit appears to plateau, with only marginal additional reductions observed [19]. Formulation also plays a critical role in determining efficacy. Studies comparing different delivery matrices indicate that lipid-based carriers, including palm oil, margarine, and spreads, enhance phytosterol bioavailability compared to non-lipid formats [24]. Palm oil, in particular, provides a stable medium due to its oxidative resistance and semi-solid consistency, which may improve the dispersion of phytosterols and their interaction with dietary lipids during digestion [30]. Encapsulation technologies and esterified phytosterol forms have also been investigated, with some studies reporting up to 20% greater efficacy in LDL reduction when phytosterols are delivered in esterified form within lipid matrices [28]. These findings underscore the importance of formulation design in optimizing the functional performance of phytosterol-enriched products.

Clinical Efficacy in Human Intervention Studies

Human clinical trials constitute a substantial portion of the reviewed evidence, providing direct insights into the physiological and metabolic effects of phytosterol-enriched palm oil. Across the 38 included studies, intervention durations range from 2 weeks to 6 months, with most trials lasting between 4 and 12 weeks. Short-term interventions (≤4 weeks) typically demonstrate rapid reductions in LDL cholesterol, often within the first 2 weeks of phytosterol consumption, with decreases of approximately 5–8% [8]. Longer interventions (8–12 weeks) show more stable and sustained reductions, averaging 10–15% depending on adherence and baseline characteristics [32,47]. Several crossover and parallel-design trials report statistically significant improvements in lipid profiles without adverse effects on liver enzymes, inflammatory markers, or overall metabolic health [11,59]. Additionally, compliance rates in these studies are generally high (>85%), suggesting that phytosterol-enriched products are well accepted in dietary interventions [63]. Importantly, the reviewed studies consistently position phytosterol-enriched palm oil as part of a broader dietary strategy rather than a standalone intervention. When combined with balanced diets and lifestyle modifications, the observed lipid improvements contribute to a cumulative reduction in cardiovascular risk markers.

Implications for Cardiovascular Risk Reduction

The reduction in LDL cholesterol observed across studies is widely recognized as a key factor in lowering cardiovascular risk. Epidemiological models suggest that a 10% reduction in LDL cholesterol is associated with approximately 10–20% reduction in the risk of major cardiovascular events over time [35,40]. Based on the average LDL reductions reported in the reviewed studies (7–15%), phytosterol-enriched palm oil may contribute to a meaningful, albeit moderate, decrease in cardiovascular risk when incorporated into regular dietary patterns. Several studies further highlight improvements in surrogate cardiovascular markers, including reductions in apolipoprotein B (5–10%) and improvements in LDL particle size distribution [3,55]. While direct long-term outcome data (e.g., cardiovascular events) remain limited, the consistency of lipid-related improvements supports the potential role of phytosterol-enriched palm oil within preventive nutrition frameworks. At the population level, modeling studies estimate that widespread adoption of phytosterol-enriched foods could reduce cardiovascular disease incidence by 5–10%, particularly in populations with elevated cholesterol levels [33,53]. However, these projections depend on sustained intake and integration within overall dietary patterns.

Taken together, the findings from the 38 reviewed studies demonstrate a coherent physiological and clinical narrative. Phytosterols act primarily by inhibiting intestinal cholesterol absorption, leading to measurable reductions in circulating LDL cholesterol. These effects are influenced by dosage, formulation, and baseline metabolic status, with lipid-based carriers such as palm oil providing a stable and effective delivery medium. Clinical evidence supports consistent, moderate improvements in lipid profiles, which, when contextualized within broader dietary practices, may contribute to reduced cardiovascular risk. Importantly, the evidence does not indicate inherent negative effects associated with palm oil when used as a carrier for phytosterols in controlled dietary contexts. Instead, the reviewed studies suggest that formulation and overall dietary composition play a more significant role in determining health outcomes. This balanced perspective aligns with current scientific approaches that emphasize functional modification and dietary context rather than isolated evaluation of single ingredients. Overall, the SLR results provide a comprehensive synthesis of mechanistic insights and clinical evidence, highlighting the potential of phytosterol-enriched palm oil as a component of evidence-based nutritional strategies aimed at improving lipid metabolism and supporting cardiovascular health, while maintaining a neutral and context-sensitive interpretation of its role within the broader food system.

Discussion

The discussion of this study is structured to address the research question: How does phytosterol-enriched palm oil influence intestinal cholesterol absorption mechanisms, lipid profile outcomes, and cardiovascular risk indicators based on current scientific evidence? Drawing on the synthesis of 38 selected studies, the findings are interpreted through an integrated lens that connects mechanistic pathways, clinical outcomes, and broader cardiovascular implications. This discussion does not introduce primary data but instead critically evaluates and contextualizes existing evidence derived from peer-reviewed literature within a Systematic Literature Review (SLR) framework. A central aspect of the research question concerns the influence of phytosterol-enriched palm oil on intestinal cholesterol absorption mechanisms. The evidence consistently indicates that phytosterols exert their primary effect through competitive displacement of cholesterol within mixed micelles in the intestinal lumen, thereby limiting cholesterol availability for uptake by enterocytes [43]. This process is strongly supported by mechanistic studies demonstrating reductions in fractional cholesterol absorption ranging from approximately 30% to 50% under controlled dietary conditions [13,16]. The presence of a lipid matrix, such as palm oil, appears to facilitate the dispersion of phytosterols, enhancing their interaction with dietary lipids during digestion without fundamentally altering the underlying absorption pathway [29]. In addition to micellar competition, several studies highlight the regulatory role of intestinal transport proteins, particularly NPC1L1 and the ABCG5/ABCG8 transporter system [76]. Phytosterol intake has been associated with reduced expression or activity of NPC1L1, which mediates cholesterol uptake, alongside increased efflux of sterols back into the intestinal lumen via ABC transporters [39]. This dual mechanism contributes to a net decrease in cholesterol absorption efficiency and increased fecal excretion, forming a coherent biological explanation for observed lipid profile changes. Importantly, the available evidence suggests that the incorporation of phytosterols into palm oil does not disrupt these physiological processes but rather operates within established digestive pathways, reinforcing the compatibility of this formulation within nutritional interventions.

The second dimension of the research question relates to lipid profile outcomes, particularly the modulation of LDL cholesterol levels. Across the reviewed studies, there is a high degree of consistency in reporting reductions in LDL cholesterol following phytosterol consumption, with typical decreases ranging from 7% to 15% depending on dosage, duration, and baseline lipid status [2]. When delivered through palm oil-based matrices, similar magnitudes of reduction are observed, suggesting that the carrier does not diminish the lipid-lowering efficacy of phytosterols. In several randomized controlled trials, LDL reductions of approximately 8% to 12% were achieved within intervention periods of 4 to 8 weeks, indicating both efficacy and relatively rapid onset of action [66]. Beyond LDL cholesterol, the reviewed evidence also indicates modest reductions in total cholesterol, typically in the range of 5% to 10%, while High-Density Lipoprotein (HDL) cholesterol levels generally remain stable or exhibit slight increases. Triglyceride responses appear more variable, with reductions primarily observed in individuals presenting with elevated baseline levels. This pattern suggests that phytosterol-enriched palm oil may exert more pronounced effects in populations with dyslipidemia, aligning with broader findings in functional nutrition research. Importantly, no consistent evidence indicates adverse lipid profile changes associated with the use of palm oil as a delivery medium in these contexts, supporting a neutral and context-dependent interpretation of its role [25]. The relationship between phytosterol intake and lipid profile modulation also reflects a dose-dependent pattern, which provides additional insight into the mechanisms underlying observed outcomes. Studies indicate that intake levels between 1.5 g and 3.0 g per day are associated with optimal LDL cholesterol reduction, while lower doses tend to produce less consistent effects [15]. This threshold effect underscores the importance of formulation and consumption patterns in determining the efficacy of phytosterol-enriched products. Palm oil, as a lipid-based carrier, may support the bioavailability of phytosterols by enhancing their solubility and integration into digestive processes, thereby contributing to the observed lipid-lowering effects without introducing confounding physiological responses.

The third component of the research question addresses the implications of these effects for cardiovascular risk indicators. The reduction of LDL cholesterol is widely recognized as a key factor in lowering cardiovascular risk, with epidemiological evidence suggesting that even moderate reductions can translate into meaningful decreases in the incidence of cardiovascular events over time [78]. Based on the average LDL reductions reported in the reviewed studies, phytosterol-enriched palm oil may contribute to a relative risk reduction in the range of approximately 10% to 20%, depending on baseline risk profiles and adherence to dietary interventions. In addition to LDL cholesterol, several studies report improvements in secondary cardiovascular markers, including reductions in apolipoprotein B and favorable shifts in LDL particle size distribution [4]. These changes are associated with decreased atherogenic potential and improved lipid transport dynamics, further supporting the potential role of phytosterol-enriched foods in cardiovascular risk management. However, it is important to note that direct long-term outcome data, such as reductions in cardiovascular events or mortality, remain limited within the current literature. As such, the interpretation of cardiovascular implications is largely based on surrogate markers and established risk models rather than direct clinical endpoints [46]. A critical aspect of this discussion involves the integration of mechanistic and clinical evidence. While mechanistic studies provide detailed insights into how phytosterols influence cholesterol absorption at the molecular level, clinical studies demonstrate the practical implications of these mechanisms in human populations. The consistency between these domains strengthens the overall evidence base, suggesting that the observed lipid-lowering effects are grounded in well-established physiological processes. At the same time, variability in study design, population characteristics, and intervention protocols introduces a degree of heterogeneity that must be considered when interpreting the findings [48].

The role of palm oil as a carrier matrix warrants careful consideration within this context. Rather than functioning as an active lipid-lowering agent in this formulation, palm oil serves as a delivery medium that facilitates the incorporation and bioavailability of phytosterols. The available evidence does not indicate that this role inherently produces adverse metabolic outcomes when evaluated within controlled dietary conditions. Instead, outcomes appear to be influenced by overall dietary patterns, total fat intake, and the broader nutritional context in which phytosterol-enriched palm oil is consumed [52]. This perspective aligns with current approaches in nutritional science that emphasize holistic dietary evaluation rather than isolated assessment of individual components. Another important consideration is the consistency of findings across different populations and study settings. While most studies report favorable lipid outcomes, some variability is observed, particularly in populations with normal baseline cholesterol levels or in studies employing lower phytosterol doses. These differences highlight the importance of contextual factors, including baseline metabolic status, dietary composition, and adherence to intervention protocols. Such variability does not undermine the overall evidence but rather underscores the need for tailored nutritional strategies that consider individual characteristics and dietary habits [31]. From a methodological perspective, the use of an SLR approach provides a structured and transparent framework for synthesizing evidence across diverse study designs. By focusing exclusively on peer-reviewed literature and applying consistent inclusion criteria, this study minimizes the risk of bias and enhances the reliability of its conclusions. However, the reliance on existing studies also introduces limitations related to the quality and scope of available data. For example, the predominance of short- to medium-term interventions limits the ability to assess long-term cardiovascular outcomes, while differences in study design and reporting standards may affect comparability across studies [36].

In addressing the research question, the evidence collectively supports the conclusion that phytosterol-enriched palm oil influences cholesterol metabolism primarily through inhibition of intestinal absorption, leading to measurable improvements in lipid profiles and potential reductions in cardiovascular risk. These effects are mediated by well-characterized physiological mechanisms and are supported by consistent findings across mechanistic and clinical studies. At the same time, the magnitude of these effects is influenced by factors such as dosage, formulation, and baseline metabolic status, highlighting the importance of context in interpreting the results [20]. The implications of these findings extend to both scientific research and practical applications in nutrition. From a research perspective, the integration of mechanistic and clinical evidence provides a comprehensive understanding of how phytosterol-enriched palm oil functions within the human body. This contributes to the broader field of functional nutrition by demonstrating how bioactive compounds can be effectively delivered through commonly consumed food products. From a practical standpoint, the findings support the inclusion of phytosterol-enriched foods as part of dietary strategies aimed at improving lipid profiles and managing cardiovascular risk, particularly in populations with elevated cholesterol levels. At the same time, several areas warrant further investigation. Future research could focus on long-term clinical outcomes, including the impact of sustained phytosterol consumption on cardiovascular events and mortality. Additionally, studies examining the interaction between phytosterol-enriched palm oil and different dietary patterns would provide valuable insights into how these products function within diverse nutritional contexts. Further exploration of formulation strategies, including advanced delivery systems and optimized dosage regimens, may also enhance the efficacy of phytosterol-enriched products. In conclusion, the synthesis of current scientific evidence indicates that phytosterol-enriched palm oil plays a meaningful role in modulating cholesterol absorption, improving lipid profiles, and contributing to cardiovascular risk reduction within a balanced dietary framework. The findings highlight the importance of integrating mechanistic understanding with clinical evidence to provide a comprehensive perspective on the role of functional food components in health promotion. The implications of this study suggest that phytosterol-enriched palm oil can be considered a relevant component of evidence-based nutritional strategies, while future research should aim to address existing gaps and further refine our understanding of its long-term effects and applications.

Conclusion

The synthesis of current scientific evidence demonstrates that phytosterol-enriched palm oil influences cholesterol metabolism through a coherent and physiologically grounded pathway that integrates intestinal mechanisms, lipid profile modulation, and cardiovascular risk indicators. At the intestinal level, phytosterols act primarily through competitive displacement of cholesterol within mixed micelles, thereby reducing its availability for absorption. This mechanism is further supported by the modulation of key transport proteins, including reduced activity of Niemann–Pick C1-Like 1 (NPC1L1) and enhanced efflux via ATP-binding cassette transporters (ABCG5/ABCG8), resulting in decreased cholesterol uptake and increased excretion. These mechanistic effects translate into consistent and clinically relevant improvements in lipid profiles. Across the reviewed studies, phytosterol intake particularly within lipid-based matrices such as palm oil has been associated with reductions in Low-Density Lipoprotein (LDL) cholesterol typically ranging from 7% to 15%, accompanied by modest decreases in total cholesterol and generally stable High-Density Lipoprotein (HDL) levels. The magnitude of these effects is influenced by factors such as dosage, duration of intake, and baseline metabolic status, with more pronounced responses observed in individuals with elevated cholesterol levels. In terms of cardiovascular implications, the observed reductions in LDL cholesterol correspond to meaningful improvements in established risk indicators. Epidemiological projections suggest that such lipid changes may contribute to a relative reduction in cardiovascular risk in the range of approximately 10% to 20% when integrated into sustained dietary practices. Additional improvements in surrogate markers, including apolipoprotein B and LDL particle characteristics, further support the potential role of phytosterol-enriched dietary interventions in cardiovascular risk management. The evidence also indicates that palm oil functions effectively as a lipid-based carrier that facilitates the delivery and bioavailability of phytosterols without altering the fundamental physiological mechanisms involved in cholesterol metabolism. Within controlled dietary contexts, its role appears to be neutral and context-dependent, with outcomes largely influenced by overall dietary composition and consumption patterns rather than the carrier matrix itself. Overall, the findings confirm that phytosterol-enriched palm oil represents a scientifically supported approach to modulating cholesterol absorption and improving lipid-related health indicators. The consistency between mechanistic and clinical evidence underscores its relevance within evidence-based nutritional strategies aimed at supporting cardiovascular health. At the same time, the variability in response across populations highlights the importance of considering individual and dietary context in the application of such interventions.

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Conflict of Interest

None.

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