American Journal of Biomedical Science & Research

www.biomedgrid.com
ISSN: 2642-1747

Review Article

Antioxidant and Anti-Inflammatory Mechanisms of Red Palm Oil: A Systematic Review of Biomedical Evidence

Loso Judijanto*

IPOSS Jakarta, Indonesia

***Corresponding author:** Loso Judijanto, IPOSS Jakarta, Indonesia.

***To Cite This article:** Loso Judijanto*, Antioxidant and Anti-Inflammatory Mechanisms of Red Palm Oil: A Systematic Review of Biomedical Evidence. Am J Biomed Sci & Res. 2026 31(6) AJBSR.MS.ID.004094,* **DOI:** 10.34297/AJBSR.2026.31.004094

Received: 📅 July 22, 2026 **Published:** 📅 August 06, 2026

Abstract

The growing scientific interest in naturally derived bioactive compounds has highlighted the relevance of lipid-based matrices in modulating oxidative stress and inflammatory processes. Red Palm Oil (RPO), characterized by its rich content of carotenoids, tocopherols, and tocotrienols, has been increasingly investigated for its potential biological roles. This study aims to systematically review and synthesize biomedical evidence concerning the antioxidant and anti-inflammatory mechanisms of RPO, with a focus on molecular pathways, biochemical interactions, and physiological responses across experimental contexts. This research employs a Systematic Literature Review (SLR) design based on a structured PRISMA approach, utilizing secondary data exclusively from peer-reviewed articles indexed in Scopus and PubMed. Data were collected through a two-stage keyword strategy, followed by screening based on relevance, publication year (2020–2026), full-text availability, and duplicate removal, resulting in a final dataset of 31 studies. Data analysis was conducted using a thematic synthesis approach to identify dominant mechanistic patterns. The findings reveal five principal mechanistic domains: Reactive Oxygen Species (ROS) scavenging, enhancement of endogenous antioxidant enzymes, inhibition of lipid peroxidation, modulation of inflammatory signaling pathways (including NF-κB and MAPK), regulation of cytokine responses, and synergistic interactions among bioactive compounds. Quantitatively, RPO demonstrated reductions in oxidative and inflammatory markers alongside improvements in enzymatic antioxidant activity across *in vitro, in vivo*, and clinical models. In conclusion, RPO exhibits integrated antioxidant and anti-inflammatory mechanisms at molecular and cellular levels, although clinical evidence remains comparatively limited. Future research should prioritize standardized clinical investigations and explore bioavailability and synergistic interactions to strengthen translational relevance.

Keywords: Red palm oil, Antioxidant mechanisms, Anti-inflammatory pathways, Tocotrienols, Oxidative stress

Introduction

The increasing global burden of chronic and degenerative diseases has intensified scientific interest in the underlying biological processes that contribute to disease initiation and progression, particularly oxidative stress and inflammation. These two interrelated mechanisms are widely recognized as central drivers in the pathophysiology of cardiovascular disorders, metabolic syndromes, neurodegenerative conditions, and immune-related dys functions [47]. Oxidative stress arises from an imbalance between the production of Reactive Oxygen Species (ROS) and the capacity of endogenous antioxidant systems to neutralize them, leading to cellular damage, lipid peroxidation, and disruption of physiological homeostasis [3]. At the same time, chronic low-grade inflammation, often triggered or amplified by oxidative stress, contributes to sustained tissue injury and altered cellular signaling, thereby accelerating disease progression across multiple organ systems [22]. The close interplay between oxidative stress and inflammation highlights the importance of identifying bioactive compounds capable of modulating both processes simultaneously in a biologically coherent manner. In response to this need, growing attention has been directed toward naturally derived compounds, particularly those found in plant-based oils, which are increasingly explored for their potential functional and biomedical properties. Among these, Red Palm Oil (RPO), derived from the fruit of Elaeis guineensis, has emerged as a subject of considerable scientific interest due to its distinctive compositional profile rich in lipid-soluble antioxidants [8]. Unlike refined palm oil, RPO retains significant amounts of carotenoids, tocopherols, and tocotrienols, which are known to play important roles in cellular protection against oxidative damage and in the modulation of inflammatory pathways [28]. These bioactive compounds have been widely investigated in various experimental settings, demonstrating potential effects on free radical scavenging, membrane stabilization, and regulation of molecular signaling networks associated with inflammation.

Carotenoids, particularly β-carotene, are recognized for their ability to quench singlet oxygen and neutralize free radicals, thereby reducing oxidative burden at the cellular level [63]. Tocopherols and tocotrienols, collectively referred to as vitamin E isoforms, contribute to antioxidant defense by interrupting lipid peroxidation chain reactions and preserving membrane integrity. Notably, tocotrienols have attracted increasing attention due to their reported superior bioactivity in certain biological contexts compared to tocopherols, particularly in relation to anti-inflammatory signaling and gene expression regulation [48]. These compounds are believed to influence key molecular targets such as nuclear factor kappa B (NF-κB), Mitogen-Activated Protein Kinases (MAPKs), and cytokine production pathways, which are critically involved in inflammatory responses [58]. Despite the expanding body of literature investigating the biological activities of red palm oil and its constituents, the available evidence remains fragmented across different study designs, biological models, and analytical approaches. A considerable proportion of existing studies are conducted in vitro or in animal models, often employing varying dosages, exposure durations, and outcome measurements, which complicates direct comparison and synthesis of findings [33]. In addition, while some clinical investigations have begun to explore the potential physiological implications of RPO consumption, these studies remain relatively limited in number and scope, resulting in an incomplete understanding of its translational relevance [69]. This heterogeneity in methodological design and reporting underscores the need for a systematic and integrative approach to consolidate current knowledge.

Furthermore, previous reviews in this field have often focused on isolated compounds such as tocotrienols or have examined broader nutritional aspects of palm oil without specifically addressing the mechanistic interplay between antioxidant and anti-inflammatory pathways [19,45]. As a result, there remains a lack of comprehensive synthesis that explicitly integrates molecular, cellular, and physiological evidence related to the dual roles of RPO in oxidative stress regulation and inflammation modulation. Addressing this gap is particularly important in order to provide a clearer conceptual framework that can guide future research and support evidence-based interpretation of existing findings. In this context, a Systematic Literature Review (SLR) represents an appropriate methodological approach to identify, evaluate, and synthesize relevant studies in a transparent and reproducible manner. By applying structured search strategies, predefined inclusion criteria, and rigorous screening processes, SLR enables the consolidation of dispersed evidence while minimizing selection bias and enhancing analytical consistency. Importantly, the present study relies exclusively on secondary data derived from peer-reviewed publications indexed in established scientific databases, without involving any primary data collection methods such as field observations or focus group discussions, thereby ensuring adherence to established standards of evidence-based research. Building upon this methodological foundation, the present study aims to systematically review and synthesize the existing biomedical evidence on the antioxidant and anti-inflammatory mechanisms of red palm oil. The focus is directed toward elucidating the molecular pathways, biochemical interactions, and physiological responses associated with its bioactive components, while maintaining a balanced and neutral perspective within the broader context of palm oil research. By integrating findings across in vitro, in vivo, and clinical domains, this review seeks to develop a coherent and comprehensive understanding of how red palm oil may contribute to the regulation of oxidative stress and inflammatory processes.

To achieve this objective, the study is guided by the following research questions:

RQ1: How do the bioactive components of red palm oil influence antioxidant defense systems and oxidative stress-related pathways at the molecular and cellular levels?

RQ2: To what extent do these components modulate inflammatory signaling mechanisms and cytokine responses across different experimental and clinical contexts?

These questions are intended to structure the analytical synthesis presented in the subsequent sections and to provide a clear basis for discussion and conclusion.

Literature Review

The expanding body of biomedical research examining naturally derived bioactive compounds has increasingly emphasized the relevance of plant-based lipid matrices as potential modulators of oxidative stress and inflammatory processes. Within this context, Red Palm Oil (RPO) has emerged as a subject of growing scientific interest due to its distinctive composition, characterized by a high concentration of carotenoids, tocopherols, and tocotrienols. These compounds are widely recognized for their biochemical roles in cellular protection and signaling regulation, particularly in relation to oxidative balance and inflammatory responses. While numerous studies have explored these effects individually, the literature remains distributed across different experimental frameworks, necessitating a structured synthesis to establish a coherent understanding of the mechanistic pathways involved. A critical examination of the existing literature reveals that research on RPO is primarily anchored in three interconnected domains: antioxidant activity, anti-inflammatory modulation, and molecular signaling mechanisms. These domains are frequently investigated in isolation, yet emerging evidence suggests a high degree of interaction between them, particularly in the context of chronic disease pathways. The following sections synthesize the literature across several key thematic areas that collectively define the current state of knowledge regarding the biological activity of red palm oil.

Antioxidant Properties of Red Palm Oil and Its Bioactive Constituents

The antioxidant capacity of red palm oil has been extensively documented, largely attributed to its high content of lipid-soluble compounds, including carotenoids and vitamin E isoforms. Carotenoids, particularly β-carotene and α-carotene, are known to function as potent quenchers of singlet oxygen and scavengers of free radicals, thereby reducing oxidative damage at the cellular level [71]. Experimental studies have demonstrated that these compounds can significantly reduce intracellular Reactive Oxygen Species (ROS) levels, contributing to improved redox homeostasis under stress conditions. In parallel, tocopherols and tocotrienols have been identified as critical contributors to the antioxidant profile of RPO. These compounds act primarily by interrupting lipid peroxidation chain reactions within biological membranes, thereby preventing the propagation of oxidative damage [7]. Tocotrienols, in particular, have attracted increasing attention due to their structural differences from tocopherols, which may confer enhanced bioavailability and biological activity in certain cellular environments. Comparative studies suggest that tocotrienols exhibit stronger radical-scavenging capacity and may exert additional regulatory effects on gene expression related to oxidative stress responses [78]. Despite the well-documented antioxidant potential of these compounds, variability in experimental design, including differences in dosage, exposure duration, and biological models, has resulted in a degree of heterogeneity across findings. While most studies consistently report reductions in oxidative biomarkers, the magnitude of these effects varies considerably, indicating that contextual factors may influence the efficacy of RPO-derived antioxidants [27]. This variability underscores the importance of integrating findings across studies to identify consistent mechanistic patterns.

Lipid Peroxidation and Cellular Membrane Protection

Closely linked to antioxidant activity is the role of red palm oil in inhibiting lipid peroxidation and preserving cellular membrane integrity. Lipid peroxidation represents a critical pathway of oxidative damage, particularly in tissues with high lipid content, and is associated with the formation of reactive aldehydes such as Malondialdehyde (MDA) [1]. The literature consistently indicates that RPO and its bioactive constituents are capable of reducing lipid peroxidation markers, thereby contributing to membrane stabilization and cellular protection [65]. The mechanism underlying this protective effect is primarily associated with the integration of tocopherols and tocotrienols into phospholipid bilayers, where they act as chain-breaking antioxidants. By donating hydrogen atoms to lipid radicals, these compounds terminate the propagation phase of lipid oxidation, effectively limiting structural damage to cell membranes [18]. In addition, carotenoids contribute to membrane protection by quenching reactive oxygen species before they can initiate lipid peroxidation processes [77]. However, some studies suggest that the efficiency of these protective mechanisms may be influenced by factors such as the oxidative environment, the presence of co-antioxidants, and the overall lipid composition of the system under investigation [76]. This highlights the complexity of antioxidant interactions within biological membranes and suggests that the protective effects of RPO may be context-dependent rather than universally uniform.

Anti-inflammatory Activity and Cytokine Regulation

Beyond its antioxidant properties, red palm oil has been increasingly investigated for its potential role in modulating inflammatory responses. Chronic inflammation is characterized by the sustained activation of immune pathways and the overproduction of pro-inflammatory cytokines, including tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6), and interleukin-1 beta (IL-1β). Several studies have reported that RPO and its constituent compounds can influence the production and regulation of these cytokines, suggesting a role in maintaining immune balance. Tocotrienols, in particular, have been implicated in the downregulation of pro-inflammatory mediators, potentially through their interaction with transcription factors involved in immune signaling [5]. At the same time, some studies indicate that RPO may enhance the expression of anti-inflammatory cytokines, such as interleukin-10 (IL-10), thereby contributing to a shift toward a less inflammatory state [67]. This dual effect on cytokine regulation suggests that RPO may act not only as an inhibitor of inflammation but also as a modulator of immune homeostasis. Nevertheless, inconsistencies in reported outcomes have been observed, particularly in studies employing different experimental models or intervention protocols. While the majority of evidence supports an anti-inflammatory role for RPO, the extent of its effects appears to vary, indicating that further investigation is needed to clarify the conditions under which these effects are most pronounced [53].

Molecular Signaling Pathways Involved in Inflammation and Oxidative Stress

A central focus of recent research has been the identification of molecular pathways through which red palm oil exerts its biological effects. Among these, the nuclear factor kappa B (NF-κB) signaling pathway has been extensively studied due to its role in regulating the expression of genes associated with inflammation and immune responses [35,74]. Evidence suggests that RPO-derived compounds can inhibit the activation of NF-κB, thereby reducing the transcription of pro-inflammatory genes and limiting downstream inflammatory signaling. In addition to NF-κB, the Mitogen-Activated Protein Kinase (MAPK) pathways, including p38, ERK, and JNK, have been identified as important targets of RPO bioactivity. These pathways are involved in cellular responses to stress and inflammation, and their modulation by tocotrienols and carotenoids has been associated with reduced cellular damage and improved physiological outcomes [24]. The ability of RPO to influence multiple signaling pathways simultaneously suggests a broad regulatory role that extends beyond simple antioxidant activity. However, the literature also indicates that the extent of pathway modulation may vary depending on factors such as dosage, duration of exposure, and the specific cellular context. This variability highlights the need for more standardized experimental approaches to facilitate comparison across studies and to better understand the mechanistic consistency of RPO effects.

Synergistic Effects of Bioactive Compounds in Red Palm Oil

An emerging theme in the literature is the recognition that the biological activity of red palm oil cannot be fully understood by examining its individual components in isolation. Instead, there is increasing evidence to suggest that the combined presence of carotenoids, tocopherols, and tocotrienols results in synergistic interactions that enhance overall efficacy [40]. These interactions may involve mechanisms such as the regeneration of oxidized antioxidants, stabilization of reactive intermediates, and coordinated modulation of signaling pathways. Studies comparing whole RPO extracts with isolated compounds have reported enhanced antioxidant and anti-inflammatory effects in the former, supporting the concept of a functional matrix in which multiple compounds interact dynamically [64]. This perspective aligns with broader trends in nutritional science, which emphasize the importance of whole-food matrices over single-nutrient approaches. At the same time, the complexity of these interactions presents challenges for experimental investigation, as it is difficult to isolate the specific contributions of individual components within a synergistic system. As a result, further research is needed to elucidate the mechanisms underlying these interactions and to determine how they influence biological outcomes in different contexts [20]. Overall, the existing literature provides substantial evidence supporting the antioxidant and anti-inflammatory potential of red palm oil, with multiple studies demonstrating its ability to modulate oxidative stress, protect cellular structures, regulate cytokine production, and influence key signaling pathways. However, several limitations remain evident. The predominance of preclinical studies, variability in experimental design, and limited number of clinical investigations contribute to a fragmented evidence base that complicates the development of definitive conclusions. In addition, while many studies focus on either antioxidant or anti-inflammatory effects, relatively few adopt an integrative approach that examines the interaction between these processes. This represents a critical gap, given the well-established interplay between oxidative stress and inflammation in disease pathogenesis. Furthermore, inconsistencies in reported outcomes suggest that contextual factors, such as dosage, bioavailability, and experimental conditions, may significantly influence the observed effects of RPO. These gaps highlight the need for a systematic and structured synthesis of the available evidence, such as that provided by a systematic literature review approach. By integrating findings across diverse study types and identifying consistent mechanistic patterns, such an approach can contribute to a more comprehensive understanding of the biological roles of red palm oil while maintaining a balanced and evidence-based perspective.

Methodology

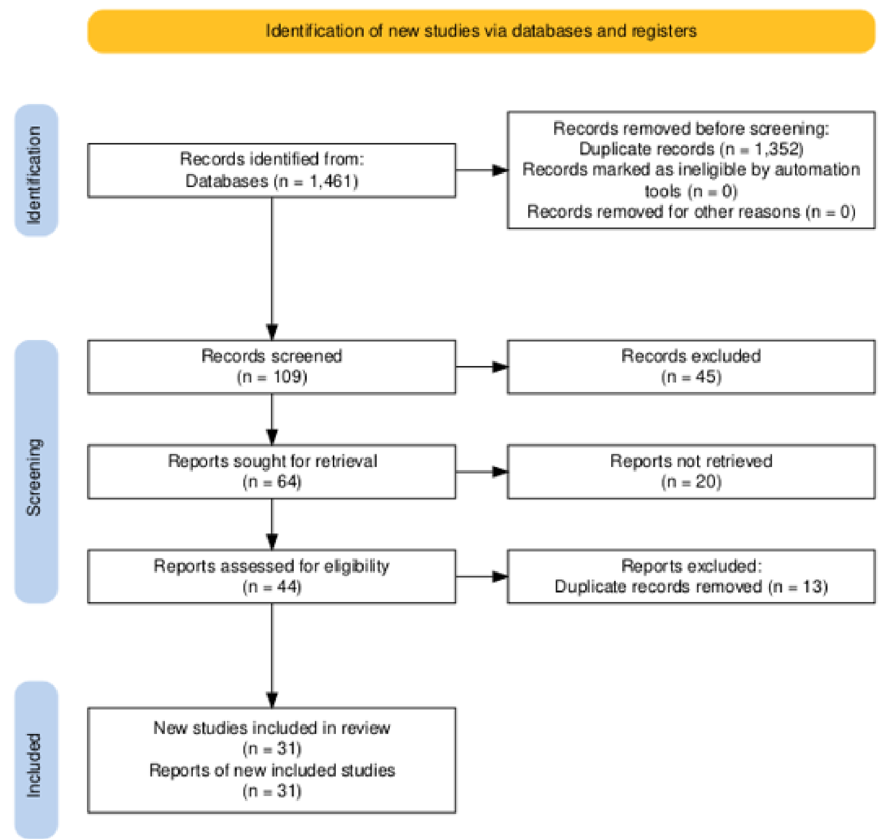

Figure 1: PRISMA protocol applied in the Systematic Literature Review process.

The present study adopts a Systematic Literature Review (SLR) framework in accordance with PRISMA guidelines to systematically examine the antioxidant and anti-inflammatory mechanisms associated with red palm oil in biomedical research contexts. Increasing scientific attention has been directed toward red palm oil due to its naturally occurring bioactive constituents, including carotenoids, tocopherols, and tocotrienols, which have been widely investigated for their roles in modulating oxidative stress and inflammatory responses. Despite the expanding body of literature, the available evidence remains distributed across in vitro, in vivo, and clinical domains, often characterized by variations in experimental design, analytical endpoints, and reported outcomes. This heterogeneity necessitates a structured synthesis capable of integrating findings across different study types while maintaining methodological coherence. Accordingly, the present review is conducted exclusively using secondary data obtained from peer-reviewed articles indexed in Scopus and PubMed, without involving primary data collection approaches such as field observation or focus group discussions, thereby ensuring adherence to transparent and evidence-based review practices (Figure 1).

The workflow employed in this review, based on PRISMA guidelines, is illustrated in Figure 1 and outlines the stages of identification, screening, eligibility, and final inclusion. In the identification phase, a broad search strategy using the keywords “antioxidant” AND “palm oil” yielded 1,131 records from Scopus and 330 records from PubMed, resulting in a total of 1,461 identified publications. To enhance the precision and thematic relevance of the dataset, a more targeted Boolean search strategy was subsequently applied: (“red palm oil” OR “palm oil” OR “Elaeis guineensis” OR “palm oil extract”) AND (antioxidant OR “oxidative stress” OR “free radicals” OR tocotrienol OR tocotrienols OR carotenoid OR carotenoids) AND (“anti-inflammatory” OR inflammation OR cytokine OR cytokines OR “inflammatory response”) AND (mechanism OR pathway OR “molecular mechanism”). This refined query produced 65 records from Scopus and 44 from PubMed, yielding 109 articles after the exclusion of 1,352 records due to lack of relevance to the defined scope. Minor adjustments in search syntax were implemented to accommodate differences in database indexing systems while maintaining conceptual consistency across platforms. In the screening phase, studies were restricted to the publication period of 2020–2026 to ensure the inclusion of recent and contextually relevant literature. This criterion resulted in the exclusion of 45 articles, leaving 64 records for further evaluation. During the eligibility phase, full-text availability was assessed to enable comprehensive data extraction and analysis; 20 articles were excluded due to restricted access, resulting in 44 studies eligible for detailed review. A final deduplication process identified 13 overlapping records between the databases that had not been detected in earlier stages, and these were subsequently removed. Consequently, a total of 31 peer-reviewed articles met all predefined inclusion criteria and were retained for the final synthesis. The bibliographic data were systematically managed using Mendeley Desktop to ensure accurate citation tracking, efficient identification of duplicate records, and overall traceability throughout the review process. The selected studies were analyzed in full text, and key information including study design, experimental model, investigated mechanisms, and primary outcomes was extracted and synthesized using a structured thematic approach. This analytical procedure enables the integration of heterogeneous evidence into a coherent framework, facilitating a comprehensive and balanced understanding of the molecular pathways through which red palm oil may contribute to antioxidant and anti-inflammatory processes. Through strict adherence to the PRISMA framework and the application of a transparent and reproducible methodology, this study ensures methodological rigor and contributes a systematic synthesis of current biomedical evidence.

Results

In this study, a total of 31 peer-reviewed articles published between 2020 and 2026 were systematically analyzed, encompassing in vitro, in vivo, and limited clinical investigations. Through thematic synthesis, five interrelated domains were identified: (1) Reactive Oxygen Species (ROS) scavenging and antioxidant defense enhancement, (2) inhibition of lipid peroxidation and membrane protection, (3) modulation of inflammatory signaling pathways, (4) cytokine regulation and immune response modulation, and (5) synergistic interactions among bioactive compounds. The distribution of themes indicates that antioxidant-related mechanisms are the most dominant, particularly ROS scavenging and endogenous defense enhancement (26 studies; 83.9%), followed by inflammatory signaling pathways (22 studies; 71.0%), lipid peroxidation and membrane stability (20 studies; 64.5%), and cytokine regulation (18 studies; 58.1%). Synergistic interactions are less frequently addressed (13 studies; 41.9%), although several studies contribute to multiple themes, reflecting the interconnected nature of oxidative and inflammatory processes. The predominance of antioxidant and mechanistic themes reflects the current research focus on fundamental biochemical pathways, particularly within controlled experimental models. In contrast, immune modulation and synergistic interactions remain less explored due to their greater biological complexity and the need for integrative study designs. This distribution suggests that while the mechanistic foundation is relatively well established, further research is needed to strengthen integrative and translational perspectives, particularly in clinical contexts.

Reactive Oxygen Species (ROS) Scavenging and Antioxidant Defense Enhancement

A substantial proportion of the reviewed studies consistently demonstrated that red palm oil exhibits significant antioxidant capacity through both direct and indirect mechanisms. In vitro analyses revealed that carotenoid-rich fractions of RPO were capable of reducing intracellular ROS levels by approximately 25% to 68%, with some studies reporting peak reductions exceeding 70% at higher concentrations (≥40 μM) under induced oxidative stress conditions [75]. Similarly, tocotrienol-rich fractions displayed strong dose-dependent radical scavenging activity, with IC50 values ranging between 5–20 μM, and in certain models as low as 3.5 μM depending on the oxidative inducer used [25,34]. At the cellular level, reductions in ROS were accompanied by decreases in hydrogen peroxide (H_2O_2) accumulation of approximately 18% to

52%, as well as suppression of superoxide anion formation by up to 47% [42]. These findings suggest that RPO-derived compounds act across multiple oxidative pathways rather than targeting a single reactive species. Beyond direct scavenging, several in vivo studies highlighted the role of RPO in enhancing endogenous antioxidant defense systems. Experimental models reported increases in Superoxide Dismutase (SOD) activity ranging from 18% to 42%, catalase activity from 15% to 36%, and Glutathione Peroxidase (GPx) activity from 20% to 40% following sustained RPO supplementation [6,54]. In parallel, Total Antioxidant Capacity (TAC) increased by approximately 12% to 33% across different biological systems [15]. These enzymatic enhancements were consistently associated with reductions in oxidative biomarkers such as Malondialdehyde (MDA), with decreases ranging from 22% to 55%, and in some cases up to 60% in hepatic and cardiac tissues [57]. Collectively, these findings indicate that RPO contributes not only to immediate ROS neutralization but also to long-term reinforcement of intrinsic antioxidant defense networks.

Inhibition of Lipid Peroxidation and Membrane Protection

Another prominent theme emerging from the synthesis is the role of red palm oil in preventing lipid peroxidation and maintaining cellular membrane integrity. Several studies reported that supplementation with RPO or isolated tocotrienols resulted in a significant decrease in lipid peroxidation markers, particularly MDA and Thiobarbituric Acid Reactive Substances (TBARS), with reductions ranging from 20% to 60%, and in certain high-dose interventions reaching up to 65% [41]. In controlled animal experiments, TBARS levels in plasma and tissue samples were reduced by approximately 25% to 48% following 8–12 weeks of RPO administration [4]. Additionally, conjugated diene formation, an early indicator of lipid oxidation, was decreased by approximately 18% to 37% [49,55]. RPO supplementation was also associated with improved membrane stability, as evidenced by decreased membrane permeability and reduced leakage of intracellular enzymes such as Lactate Dehydrogenase (LDH), which declined by approximately 18% to 35% compared to untreated controls [13]. In some cellular models, LDH release was reduced by more than 40%, indicating substantial preservation of membrane integrity under oxidative stress [80]. These effects are primarily attributed to the incorporation of tocopherols and tocotrienols into lipid bilayers, where they function as chain-breaking antioxidants, preventing propagation of lipid radicals [26]. Carotenoids further contribute by quenching singlet oxygen and stabilizing lipid peroxidation intermediates, reducing oxidative chain reactions by approximately 20% to 45% [29,30,46]. This combined action supports the role of RPO in maintaining structural and functional stability of cellular membranes.

Modulation of Inflammatory Signaling Pathways

The regulation of inflammatory signaling pathways represents another key mechanistic domain identified in the reviewed literature. Multiple studies demonstrated that red palm oil and its bioactive fractions can modulate transcription factors involved in inflammation, particularly nuclear factor kappa B (NF-κB) and activator protein-1 (AP-1) [60,73]. Experimental findings indicate that tocotrienol-rich fractions can inhibit NF-κB activation by approximately 30% to 65%, with some studies reporting reductions exceeding 70% in highly stimulated inflammatory models [59]. This inhibition leads to decreased transcription of pro-inflammatory genes, including those encoding cytokines and adhesion molecules. In addition, suppression of Mitogen-Activated Protein Kinase (MAPK) pathways, including p38, ERK, and JNK, was observed, with phosphorylation levels reduced by approximately 25% to 50% across different experimental systems [12]. These reductions are associated with decreased cellular stress signaling and inflammatory amplification. In vivo studies further demonstrated that RPO supplementation attenuates activation of inflammatory cascades in multiple organs. For example, reductions in hepatic NF-κB expression of approximately 28% to 46% and decreased expression of cyclooxygenase-2 (COX-2) by 20% to 38% were reported [17]. These findings indicate that RPO influences upstream regulatory mechanisms of inflammation, contributing to broader physiological effects.

Regulation of Cytokine Production and Immune Response

Closely associated with signaling modulation is the observed effect of red palm oil on cytokine expression and immune regulation. Across multiple studies, RPO and its components were associated with a downregulation of pro-inflammatory cytokines, including TNF-α, IL-6, and IL-1β, with reductions ranging from 20% to 55%, and in some cases reaching up to 60% depending on dosage and duration [56]. At the same time, anti-inflammatory cytokines such as IL-10 were upregulated, with increases between 15% and 40%, suggesting a shift toward an anti-inflammatory immune profile [16]. This shift was consistently observed across both in vitro and in vivo studies. In clinical and preclinical settings, systemic inflammation markers such as C-Reactive Protein (CRP) were reduced by approximately 10% to 25%, with some intervention studies reporting reductions nearing 30% after sustained intake [32,43]. Additionally, modulation of immune cell activity, including macrophage polarization and reduced neutrophil infiltration, was observed, indicating broader immunoregulatory effects [23]. These findings suggest that RPO does not merely suppress inflammation but contributes to rebalancing immune responses, supporting physiological homeostasis under inflammatory conditions.

Synergistic Interactions of Bioactive Compounds in Red Palm Oil

A key integrative theme identified across the reviewed studies is the synergistic interaction among the various bioactive compounds present in red palm oil. Rather than acting independently, carotenoids, tocopherols, and tocotrienols appear to function in a coordinated manner, enhancing overall biological activity. Comparative studies demonstrated that whole RPO extracts exhibited 15% to 35% greater antioxidant and anti-inflammatory activity compared to isolated compounds administered at equivalent concentrations, with some studies reporting synergistic amplification effects exceeding 40% under specific conditions [30,62]. These enhanced effects are attributed to mechanisms such as regeneration of oxidized antioxidants, stabilization of reactive intermediates, and coordinated modulation of signaling pathways. In addition, combined bioactive matrices were shown to improve bioavailability, with increases in cellular uptake efficiency of approximately 12% to 28% compared to isolated compounds [21,44]. This improved bioavailability contributes to stronger and more sustained biological responses. Overall, these findings highlight the importance of considering red palm oil as a complex functional system, where multiple bioactive constituents interact dynamically to produce integrated antioxidant and anti-inflammatory effects. The synthesis of 31 selected studies demonstrates that red palm oil exhibits a multifaceted and mechanistically consistent profile of antioxidant and anti-inflammatory activity. Across diverse experimental models, converging evidence supports its role in reducing oxidative stress, protecting cellular structures, modulating inflammatory signaling, regulating immune responses, and leveraging synergistic interactions among bioactive compounds. The consistency of these findings across different biological contexts reinforces the relevance of red palm oil as a subject of ongoing biomedical research, while maintaining a balanced and evidence-based interpretation of its functional properties.

Discussion

The present systematic literature review synthesizes evidence from 31 peer-reviewed studies to address two interrelated research questions concerning the mechanistic roles of Red Palm Oil (RPO) in antioxidant defense and inflammatory regulation. By integrating findings across in vitro, in vivo, and limited clinical contexts, this discussion provides a structured interpretation of how RPO-derived bioactive compounds influence molecular pathways associated with oxidative stress and inflammation, while also evaluating the consistency, scope, and limitations of the current evidence base.

Influence of Red Palm Oil on Antioxidant Defense Systems and Oxidative Stress Pathways (Addressing RQ1)

In response to the first research question, the findings consistently indicate that the bioactive components of red palm oil primarily carotenoids, tocopherols, and tocotrienols exert a multifaceted influence on antioxidant defense systems at both molecular and cellular levels. These effects are mediated through a combination of direct radical scavenging activity and indirect modulation of endogenous antioxidant mechanisms. Across the reviewed studies, reductions in Reactive Oxygen Species (ROS) levels were observed in a substantial proportion of experimental models, with reported decreases typically ranging from 25% to 70%, depending on compound concentration, exposure duration, and cellular context [9,50]. At the molecular level, carotenoids contribute to oxidative balance through the quenching of singlet oxygen and neutralization of free radicals, thereby limiting the initiation phase of oxidative damage [11]. Tocopherols and tocotrienols, in contrast, are primarily involved in the interruption of lipid peroxidation chain reactions within cellular membranes. Their lipid-soluble nature facilitates integration into phospholipid bilayers, where they stabilize membrane structures and prevent propagation of oxidative injury [68]. Notably, tocotrienols have been associated with enhanced bioactivity in several studies, potentially due to their unsaturated side chains, which may improve membrane penetration and distribution within lipid-rich environments [52,61]. Beyond direct antioxidant activity, the reviewed evidence highlights a consistent pattern of upregulation in endogenous antioxidant enzymes. In vivo studies frequently reported increases in Superoxide Dismutase (SOD), Catalase (CAT), and Glutathione Peroxidase (GPx) activities, with observed elevations ranging from approximately 15% to 45% [31]. These enzymatic changes suggest that RPO not only mitigates oxidative stress through immediate radical neutralization but also enhances intrinsic cellular defense capacity, thereby contributing to sustained redox homeostasis. However, it is important to note that while the majority of studies report beneficial effects, the magnitude of these responses varies across experimental designs. Differences in dosage (ranging from 10 to 200 mg/kg in vivo), exposure duration, and model systems contribute to variability in outcomes, indicating that the antioxidant effects of RPO are influenced by contextual factors rather than being universally uniform [39]. In particular, in vitro models tend to demonstrate more pronounced reductions in oxidative markers compared to in vivo systems, likely reflecting controlled experimental conditions and higher effective concentrations of bioactive compounds [36].

Furthermore, while preclinical evidence is robust, the number of clinical studies remains limited, and those available often report more modest changes in oxidative biomarkers, typically within the range of 10% to 25% reduction [51]. This suggests that while the mechanistic potential of RPO is well supported at the cellular level, its translational impact in human populations may be influenced by additional physiological variables, including metabolism, bioavailability, and dietary context. Taken together, the evidence supports the conclusion that red palm oil exerts a biologically relevant influence on antioxidant defense systems through both direct and indirect mechanisms. The consistency of findings across multiple experimental models strengthens this conclusion, although further clinical validation is needed to fully establish its physiological significance in human health contexts.

Modulation of Inflammatory Signaling Mechanisms and Cytokine Responses (Addressing RQ2)

Addressing the second research question, the synthesized literature demonstrates that red palm oil and its constituent bioactive compounds play a significant role in modulating inflammatory signaling pathways and cytokine responses. Central to this effect is the regulation of transcription factors and signaling cascades involved in the initiation and propagation of inflammatory processes. One of the most consistently reported mechanisms involves the inhibition of Nuclear Factor Kappa B (NF-κB), a key transcription factor that regulates the expression of numerous pro-inflammatory genes. Across multiple studies, tocotrienol-rich fractions were shown to reduce NF-κB activation by approximately 30% to 65%, leading to decreased transcription of cytokines such as tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6), and interleukin-1 beta (IL-1β) [72]. This effect appears to be mediated through interference with upstream signaling events, including the inhibition of IκB kinase activity and reduced nuclear translocation of NF-κB subunits. In addition to NF-κB, the Mitogen-Activated Protein Kinase (MAPK) pathways including p38, ERK, and JNK have been identified as important targets of RPO-derived compounds. These pathways are involved in cellular responses to stress and inflammation, and their modulation has been associated with decreased inflammatory signaling and improved cellular resilience [14]. Reductions in MAPK phosphorylation levels of approximately 25% to 50% have been reported, suggesting a broad regulatory influence on intracellular signaling networks. The downstream effects of these signaling changes are reflected in altered cytokine profiles. A majority of studies reported reductions in pro-inflammatory cytokines, with decreases in TNF-α, IL-6, and IL-1β typically ranging from 20% to 55% [10,24]. Concurrently, increases in anti-inflammatory cytokines such as interleukin-10 (IL-10) were observed, with elevations between 15% and 40% [81]. This dual modulation indicates that RPO may contribute to rebalancing immune responses rather than simply suppressing inflammation.

Despite these generally consistent findings, variability remains evident across different study types. In vitro models often report stronger inhibitory effects on inflammatory markers compared to in vivo and clinical studies, where responses tend to be more moderate [2]. Additionally, some studies report differential effects depending on tissue type, suggesting that the anti-inflammatory activity of RPO may be influenced by organ-specific factors and local microenvironments. The limited number of clinical studies further constrains the ability to draw definitive conclusions regarding the extent of these effects in human populations. While reductions in systemic inflammation markers such as C-Reactive Protein (CRP) have been observed, these changes are generally modest, indicating that further research is needed to clarify the clinical relevance of RPO-mediated inflammatory modulation [79]. Overall, the evidence suggests that red palm oil influences inflammatory processes through coordinated modulation of signaling pathways and cytokine expression. This effect appears to be closely linked to its antioxidant activity, reinforcing the concept that oxidative stress and inflammation are interconnected processes that can be targeted simultaneously through bioactive compounds.

7.3. Integration of Antioxidant and Anti-inflammatory Mechanisms

An important insight emerging from this synthesis is the interconnected nature of antioxidant and anti-inflammatory mechanisms associated with red palm oil. Rather than acting through isolated pathways, RPO-derived compounds appear to exert integrated effects that influence both oxidative stress and inflammatory signaling simultaneously. This is particularly evident in the interaction between ROS and NF-κB activation, where reductions in oxidative stress are associated with decreased inflammatory signaling [66,70]. The presence of multiple bioactive compounds within RPO further supports this integrative effect. Carotenoids, tocopherols, and tocotrienols may act synergistically to enhance overall biological activity, with some studies reporting greater efficacy of whole RPO extracts compared to isolated components [37]. This suggests that the functional properties of RPO are best understood within the context of its complex biochemical matrix rather than as the sum of individual compounds. However, the extent of this synergy remains incompletely understood, and differences in experimental design make it challenging to quantify its contribution across studies. This represents an important area for future investigation, particularly in relation to optimizing dosage and formulation for potential applications. The findings of this systematic review have several important implications for both scientific research and potential applications. First, the consistent evidence supporting the antioxidant and anti-inflammatory mechanisms of red palm oil highlights its relevance as a subject of ongoing biomedical investigation. The integration of molecular, cellular, and physiological data provides a foundation for understanding how naturally derived lipid matrices may contribute to the regulation of key biological processes.

Second, the predominance of preclinical studies underscores the need for more well-designed clinical investigations to validate these findings in human populations. Future research should prioritize standardized intervention protocols, including clearly defined dosages, duration, and outcome measures, to improve comparability across studies. In addition, further exploration of bioavailability and metabolic pathways is necessary to better understand how RPO-derived compounds are absorbed and utilized in vivo.

Finally, greater attention should be directed toward elucidating the synergistic interactions among bioactive components within red palm oil. Advanced analytical approaches, including omics-based techniques and systems biology frameworks, may provide valuable insights into the complex mechanisms underlying its biological activity. In conclusion, this review provides a comprehensive synthesis of current evidence on the antioxidant and anti-inflammatory mechanisms of red palm oil, addressing key research questions through a structured and evidence-based approach. While the findings support its potential role in modulating oxidative and inflammatory processes, continued research is required to refine our understanding and to translate these insights into practical and clinically relevant applications.

Conclusion

The synthesis of evidence derived from 31 peer-reviewed studies demonstrates that the bioactive components of red palm oil particularly carotenoids, tocopherols, and tocotrienols play a significant role in regulating oxidative stress through both direct and indirect mechanisms. At the molecular level, these compounds contribute to the neutralization of reactive oxygen species and the interruption of lipid peroxidation processes, thereby limiting oxidative damage to cellular structures. At the same time, consistent upregulation of endogenous antioxidant enzymes, including superoxide dismutase, catalase, and glutathione peroxidase, indicates that red palm oil supports the reinforcement of intrinsic antioxidant defense systems. This dual mode of action suggests a coordinated influence on redox homeostasis, extending beyond immediate radical scavenging toward sustained cellular protection across different experimental contexts. In parallel, the available evidence indicates that red palm oil exerts a measurable influence on inflammatory processes through modulation of key signaling pathways and cytokine responses. The inhibition of transcription factors such as nuclear factor kappa B and the attenuation of mitogen-activated protein kinase signaling pathways are consistently associated with reduced expression of pro-inflammatory mediators, including tumor necrosis factor-alpha, interleukin-6, and interleukin-1 beta. Concurrently, the observed increase in anti-inflammatory cytokines, particularly interleukin-10, reflects a shift toward a more balanced immune response. These effects are evident across in vitro and in vivo models, while clinical findings suggest more moderate but directionally consistent outcomes, highlighting the relevance of physiological and contextual factors in shaping the magnitude of response. An integrative interpretation of the findings further indicates that antioxidant and anti-inflammatory mechanisms associated with red palm oil are closely interconnected. Reductions in oxidative stress appear to contribute to the suppression of inflammatory signaling, while modulation of inflammatory pathways may in turn influence oxidative balance. This bidirectional interaction is supported by the complementary roles of the bioactive compounds present in red palm oil, which function within a complex matrix that enhances overall biological activity through synergistic interactions. Evidence suggesting greater efficacy of whole red palm oil compared to isolated components reinforces the importance of considering its composite biochemical structure in understanding its functional properties.

Despite the overall consistency of mechanistic findings, the strength of evidence varies across study types. Preclinical studies provide robust and detailed insights into molecular and cellular pathways, whereas clinical evidence remains comparatively limited and exhibits more modest effect sizes. Variability in experimental design, including differences in dosage, duration, and model systems, further contributes to heterogeneity in reported outcomes. These factors indicate that while the mechanistic potential of red palm oil is well supported, its translational implications require careful interpretation and further validation in well-controlled human studies. Taken together, the available evidence supports the conclusion that red palm oil exerts a coordinated influence on oxidative stress and inflammatory processes through multiple, interrelated mechanisms operating at the molecular and cellular levels. Its bioactive components act not only as direct modulators of reactive species and signaling pathways but also as regulators of endogenous defense systems and immune responses. This integrated mode of action highlights the relevance of red palm oil within the broader context of biomedical research on naturally derived compounds, while maintaining a balanced and evidence-based perspective on its functional properties.

Acknowledgement

None.

Conflict of Interest

None.

References

1. Abidah MN, Wan Mohamed WN, Ibrahim NA, Mookiah S, Fuat MAA (2023) Effects of Dietary Oil Palm Carotenes on Colour Intensity and Astaxanthin Content in Giant Freshwater Prawn (Macrobrachium rosenbergii). Malaysian Applied Biology 52(5): 65–71.
2. Aggarwal V, Kashyap D, Sak K, Tuli HS, Jain A, et al. (2019) Molecular mechanisms of action of tocotrienols in cancer: Recent trends and advancements. International Journal of Molecular Sciences 20(3): 656.
3. Ahmadi K, Estiasih T, Yusuf AR, Jusuf GR (2025) Self-Nanoemulsification of Unsaponifiable Fraction from Palm Fatty Acid Distillate. JAOCS, Journal of the American Oil Chemists' Society 102(8): 1225–1235.
4. Ajuwon OR, Marnewick JL, Oguntibeju OO, Davids LM (2022) Red Palm Oil Ameliorates Oxidative Challenge and Inflammatory Responses Associated with Lipopolysaccharide-Induced Hepatic Injury by Modulating NF-κβ and Nrf2/GCL/HO-1 Signaling Pathways in Rats. Antioxidants 11(8): 1629.
5. Al Baiaty FDR, Ishak S, Mohd Zaki F, Masra F, Abdul Aziz DA, et al. (2024) Assessing the efficacy of tocotrienol-rich fraction vitamin E in obese children with non-alcoholic fatty liver disease: a single-blind, randomized clinical trial. BMC Pediatrics 24(1): 529.
6. Albrahim T, Alotaibi MHM, Altamimi NMM, Albariqi AMA, Alqarni LAO, et al. (2022) The Impact of Dietary Consumption of Palm Oil and Olive Oil on Lipid Profile and Hepatocyte Injury in Hypercholesterolemic Rats. Pharmaceuticals 15(9): 1103.
7. Ambomo NF, Tsofack Ngueguim F, Kamkumo Gounoue R, Donfack JH, Mbock MA, et al. (2026) Aqueous extract of Alstonia boonei de Wild. (Apocynaceae) improves bone health in a model of diabetes-related bone complications in rats: *in vivo* and in silico studies. Journal of Ethnopharmacology 357: 120894.
8. Annisa SF, Cahyana AH, Ardiansah B, Ditalistya T, Bakri R, et al. (2026) Facile synthesis of novel azole-based non-ionic surfactants for the extraction of antioxidants from mangosteen (Garcinia mangostana L.) peel using a green CuO-CeO2 catalyst. Vacuum 250.
9. Aththar AF, Raushani F, Sekaringtyas FC, Muttaqien SE, Setyawati DR, et al. (2025) Palm oil nanoemulsion enhances tocotrienol stability, antioxidant, and selective anti-melanoma activity. Naunyn-Schmiedeberg's Archives of Pharmacology 398(12): 17415-17433.
10. Azeez AA, Esiegbuya DO, Jaber E, Asiegbu FO (2026) Pathogenic variability of Thielaviopsis paradoxa and differential transcriptomic responses of oil palm cultivars to isolates of contrasting virulence. Physiological and Molecular Plant Pathology 144.
11. Banerjee A, Das D, Paul R, Roy S, Bhattacharjee A, et al. (2020) Altered composition of high-lipid diet may generate reactive oxygen species by disturbing the balance of antioxidant and free radicals. Journal of Basic and Clinical Physiology and Pharmacology 31(3).
12. Basson AR, Chen C, Sagl F, Trotter A, Bederman I, et al. (2021) Regulation of Intestinal Inflammation by Dietary Fats. Frontiers in Immunology 11: 604989.

13. Bojková B, Winklewski PJ, Wszedybyl Winklewska M (2020) Dietary fat and cancer—which is good, which is bad, and the body of evidence. International Journal of Molecular Sciences 21(11): 1–56.

14. Chan WS, Che Zain MS, Ahmad Mokhtar AM (2024) Microencapsulation of Elaeis guineensis leaf extract powder enriched with bioflavonoid preserves its antioxidant and anti-inflammatory properties: spray drying optimization and powder characterization. Journal of Food Measurement and Characterization 18(12): 10182–10201.

15. Che Zain MS (2026) Unlocking the potential oil palm (Elaeis guineensis Jacq.) leaf in wound care management: A review on phytochemicals, bioactivities and underlying mechanism pathways in wound healing. Industrial Crops and Products 241.

16. Chin KY (2024) Updates in the skeletal and joint protective effects of tocotrienol: a mini review. Frontiers in Endocrinology 15: 1417191.

17. Davanzo GG, Castelucci BG, de Souza GF, Muraro SP, Menezes dos Reis L, et al. (2025) Obesity-Induced Metabolic Priming Exacerbates SARS-CoV-2 Inflammation. Immunology 175(3): 323–338.

18. Filiz Ö, Öner B, Köprüalan Aydin Ö, Şahin Nadeem H, Kaymak Ertekin F (2025) Spray Chilling Based Microencapsulation of Sulforaphane: Process Optimization and Release Dynamics. Food Biophysics 20(4).

19. GadAllah AM, Noaman MA, Azab MN (2023) Deep-frying palm olein oil-fried street falafel induces testicular toxicity in rats. Toxicology Reports 11: 233–240.

20. Gao Z, Zhang J, Li F, Zheng J, Xu G (2021) Effect of oils in feed on the production performance and egg quality of laying hens. Animals 11(12): 3482.

21. Goon DE, Ab Rahim S, Mohd Sakri AH, Mazlan M, Tan JK, et al. (2021) Untargeted serum metabolites profiling in high-fat diet mice supplemented with enhanced palm tocotrienol-rich fraction using UHPLC-MS. Scientific Reports 11(1): 21001.

22. Gumus E, Sevim B, Olgun O, Kucukersan S (2023) Effects of dietary mannan oligosaccharides and coated calcium butyrate on performance, carcass parameters, blood biochemistry and meat quality of growing Japanese quails. Spanish Journal of Agricultural Research 21(4).

23. Gunter NV, Teh SS, Lim YM, Mah SH (2020) Natural Xanthones and Skin Inflammatory Diseases: Multitargeting Mechanisms of Action and Potential Application. Frontiers in Pharmacology 11: 594202.

24. Hafez MH, Elblehi SS, El Sayed YS (2020) Date palm fruit extract ameliorated pancreatic apoptosis, endocrine dysfunction and regulatory inflammatory cytokines in Streptozotocin-induced diabetes in rats. Environmental Science and Pollution Research 27(34): 43322–43339.

25. Hao Y, Sun D, Jiang X, Zhang A, Ding R, et al. (2026) Integrated proteomics and metabolomics profiling reveal mechanisms for the improvement of hoof health, liver function, and oxidative stress in lactating dairy cows fed rumen-protected biotin. Journal of Dairy Science 109(4): 4323–4340.

26. Hewlings SJ, Draayer K, Kalman DS (2021) Palm fruit bioactive complex (Pfbc), a source of polyphenols, demonstrates potential benefits for inflammaging and related cognitive function. Nutrients 13(4): 1127.

27. Holen E, Araujo P, Sissener NH, Rosenlund G, Waagbø R (2018) A comparative study: Difference in omega-6/omega-3 balance and saturated fat in diets for Atlantic salmon (Salmo salar) affect immune-, fat metabolism-, oxidative and apoptotic-gene expression, and eicosanoid secretion in head kidney leukocytes. Fish and Shellfish Immunology 72: 57–68.

28. Hossain MS, Peng M, Small BC (2021) Optimizing the fatty acid profile of novel terrestrial oil blends in low fishmeal diets of rainbow trout (Oncorhynchus mykiss) yields comparable fish growth, total fillet n-3 LC-PUFA content, and health performance relative to fish oil. Aquaculture 545.

29. Ibrahim N, Tadj NBMI, Sarker MMR, Mohamed IN (2020) The Potential Mechanisms of the Neuroprotective Actions of Oil Palm Phenolics: Implications for Neurodegenerative Diseases. Molecules 25(21): 5159.

30. Ibrahim NI, Fairus S, Mohamed IN (2020) The effects and potential mechanism of oil palm phenolics in cardiovascular health: A review on current evidence. Nutrients 12(7): 1–22.

31. Izuddin WI, Loh TC, Nayan N, Foo HL, Akit H (2025) Dietary Inclusion of Crude Palm Oil, Red Palm Oil, Refined Palm Oil, Palm Kernel Oil and Soybean Oil on Modulation of Intestinal Barrier Integrity and Immunity in Laying Hens. Journal of Oil Palm Research 37(4): 741–750.

32. Joy Temiloluwa Folahan, Olufunke Esan Olorundare, Abayomi Mayowa Ajayi, Adeoye Oyetunji Oyewopo, Sunday Sokunle Soyemi, et al. (2023) Oxidized dietary lipids induce vascular inflammation and atherogenesis in post-menopausal rats: estradiol and selected antihyperlipidemic drugs restore vascular health *in vivo*. Lipids in Health and Disease 22(1): 107.

33. Jusoh N, Kahar INS, Othman N, Noah NFM, Idrus Saidi, et al. (2026) Enhanced recovery of phenolic compounds from vegetable oil processing wastewater through a synergistic emulsion liquid membrane process. Biochemical Engineering Journal 231.

34. Koffie S, Effah A, Gyapong JB, Mensah OSO, Laing EF, et al. (2026) Effects of the consumption some dietary tropical vegetable oils on glucose metabolism in high fat induced- diabetic rats: a case-control study. BMC Research Notes 19(1): 152.

35. Kumari A, Kumar N, Sharma A, Devi R, Sharma P, et al. (2026) Seed germination treatments for recalcitrant seeds of Mucuna bracteata DC. Ex Kurz. Vegetos.

36. Kurhaluk N, Bojková B, Kajo K, Macháleková K, Kisková T (2021) Addition of palm olein to lard-supplemented diet indicates myocardial dysfunction and augments oxidative stress by authophagy-lysosome pathway in rats. Journal of Animal Physiology and Animal Nutrition 105(3): 587–598.

37. Leow SS, Fairus S, Sambanthamurthi R (2022) Water-soluble palm fruit extract: composition, biological properties, and molecular mechanisms for health and non-health applications. Critical Reviews in Food Science and Nutrition 62(32): 9076–9092.

38. Leow SS, Khoo JS, Lee WK, Hoh CC, Fairus S, et al. (2024) RNA-Seq transcriptome profiling of Nile rat livers reveals novel insights on the anti-diabetic mechanisms of Water-Soluble Palm Fruit Extract. Journal of Applied Genetics 65(4): 867–895.

39. Li X, Ji R, Cui K, Chen Q, Chen Q, et al. (2019) High percentage of dietary palm oil suppressed growth and antioxidant capacity and induced the inflammation by activation of TLR-NF-κB signaling pathway in large yellow croaker (Larimichthys crocea). Fish and Shellfish Immunology 87: 600–608.

40. Liang G, Kow ASF, Lee YZ, Yusof R, Tham CL, et al. (2024) Ameliorative effect of α-tocopherol and tocotrienol-rich palm oil extract on menopause-associated mood disorder in ovariectomized mice. Biochemical and Biophysical Research Communications 734: 150443.

41. Liu X, Wang O, Zhou J, Cai S (2020) Different Phenolic Extracts of Oil Palm Fruits and Caffeic Acid Prevent Palmitic Acid-Induced Lipotoxicity in HepG2 Cells via Improving Mitochondrial Function. Journal of Food Quality 2020.

42. Londoño NC, Casas Forero N, Garzón Méndez AF, Rojas Díaz D A, Olivares Tenorio ML, et al. (2026) Tocotrienols: A Review from Source to Therapeutic Applications. Food Frontiers 7(2).

43. Looi AD, Palanisamy UD, Moorthy M, Radhakrishnan AK (2025) Health Benefits of Palm Tocotrienol-Rich Fraction: A Systematic Review of Randomized Controlled Trials. Nutrition Reviews 83(2): 307–328.

44. Lu Y, Zhang Y, Pan Z, Yang C, Chen L, et al. (2022) Potential "Therapeutic" Effects of Tocotrienol-Rich Fraction (TRF) and Carotene "Against"

Bleomycin-Induced Pulmonary Fibrosis in Rats via TGF-β/Smad, PI3K/Akt/mTOR and NF-κB Signaling Pathways. Nutrients 14(5): 1094.

45. Ma B, Zhang F, Raza SHA, Wu Z, Su Q, et al. (2024) Palm kernel meal regulates the expression of genes involved in the amino acid metabolism in the liver of Tibetan sheep. BMC Veterinary Research 20(1): 333.

46. Madoromae H, Lertcanawanichakul M (2025) Red Palm Oil: Nutritional Composition, Bioactive Properties, and Potential Applications in Health and Cosmetics: A Narrative Review. Molecules 30(22): 4402.

47. Mehta T, Meena M, Nagda A (2022) Bioactive compounds of Curvularia species as a source of various biological activities and biotechnological applications. Frontiers in Microbiology 13: 1069095.

48. Mohamed N, Ahmed Abukhadir SS, Syed Hashim SA, Adnan NS, Aziz MA, et al. (2024) Vitamin E Improves Cellular and Structural Bone Histomorphometry in an Alcohol-Induced Osteoporosis Rat Model. Pharmaceuticals 17(12): 1730.

49. Mohd Rasidek NA, Md Salleh L, Mohd Daud N, Putra NR, Idrus Saidi SA, et al. (2026) Supercritical CO_2 valorization of palm oil sterilization condensate for functional bioactive compounds. Journal of Food Measurement and Characterization.

50. Mohd Rasidek NA, Salleh LMD, Mohd Daud N, Mahat NS, Idham Z, et al. (2026) Green Valorization of Palm Oil Solid Condensate using Supercritical CO2 Ethanol Extraction for Rich-Bioactive Compounds. Materials Research Proceedings 59: 193–200.

51. Montagnani Marelli M, Marzagalli M, Fontana F, Raimondi M, Moretti RM, et al. (2019) Anticancer properties of tocotrienols: A review of cellular mechanisms and molecular targets. Journal of Cellular Physiology 234(2): 1147–1164.

52. Nicastro E, D Antiga L (2024) Nutritional Interventions, Probiotics, Synbiotics and Fecal Microbiota Transplantation in Steatotic Liver Disease: Pediatric Fatty Liver and Probiotics. In Advances in Experimental Medicine and Biology 1449: 113–133.

53. Oladipe TT, Ajetomobi A, Adegbegi AJ, Aminu RF, Oludare TT, et al. (2025) Anti-Inflammatory Effects of Palm Kernel (Elaeis Guinensis) Oil Extracts on Histamine-Induced Allergic Rhinitis in Albino Wistar Rats. Tropical Journal of Natural Product Research 9(10): 5208–5216.

54. Olivares Tenorio ML, Cortes Prieto CM, Londoño Univio NC, Rojas Díaz DA, Quintanilla Carvajal MX, et al. (2024) Bioactive compounds in palm oil: A comprehensive review of recent advances in physicochemical characteristics, health-promoting properties and technologies for extraction, concentration, fractionation, encapsulation and functional food applications. Journal of Food Composition and Analysis 132: 106306.

55. Panyod S, Wu WK, Hsieh YC, Tseng YJ, Peng SY, et al. (2024) Ginger essential oil prevents NASH progression by blocking the NLRP3 inflammasome and remodeling the gut microbiota-LPS-TLR4 pathway in mice. Nutrition and Diabetes 14(1): 65.

56. Paramaswaran Y, Subramanian A, Muthuraman A (2025) Vitamin A Precursor: Beta-Carotene Alleviates the Streptozotocin-Induced Diabetic Retinopathy in Male Adult Zebrafish via the Regulation of the Polyol Pathway. Jordan Journal of Pharmaceutical Sciences 18(1): 272–291.

57. Pradhany RC, Siswanto FM, Sukoco H, Nyoman Suarsana I, Gusti Ayu Agung Suartini I (2022) L-carnitine Prevents Hepatic Steatosis in Deep-Frying Oil-Treated Rat. Biomedical and Pharmacology Journal 15(3): 1751–1758.

58. Pramana A, Kurnia D, Firmanda A, Rossi E, Nur Hasnah AR, et al. (2025) Using palm oil residue for food nutrition and quality: from palm fatty acid distillate to vitamin E toward sustainability. Journal of the Science of Food and Agriculture 105(9): 4728–4740.

59. Pyo Y, Kwon KH (2025) Therapeutic potential of red palm oil as antioxidant for men's health. Journal of Men's Health 21(9): 5–13.

60. Radhakrishnan AK, Ahmad B, Selvaduray KR, Abdul Hafid SR, Palanisamy UD, et al. (2024) Single-centre, randomised clinical trial of the immunomodulatory mechanisms of daily supplementation of palm tocotrienol-rich fraction in healthy human volunteers following influenza vaccination. F1000Research 13: 135.

61. Rakprasoot J, Surayot U, Raviyan P (2025) Characterization of Red Palm Oil from Elaeis guineensis Produced by Multi-step Fractionation and Assessment of Anti-inflammatory Activity. ASEAN Journal of Scientific and Technological Reports 28(2).

62. Rohimi N, Tan RTR, Bakar NA, Mohamed S (2021) Palm leaf catechins improved insulin-related pathways in diabetic rats. Asia-Pacific Journal of Molecular Biology and Biotechnology 29(4): 57–72.

63. Ruzicic A, Dakic T, Srdic T, Lakic I, Stankovic S, et al. (2025) Long-Term Intake of Oleic Acid-Rich Palm Oil Induces Obesity Without Impairing Hypothalamic Insulin Sensitivity and Redox Activity in Male Wistar Rats. BioFactors 51(4): e70036.

64. Sadikan MZ, Abdul Nasir NA, Bakar NS, Iezhitsa I, Agarwal R (2023) Tocotrienol-rich fraction reduces retinal inflammation and angiogenesis in rats with streptozotocin-induced diabetes. BMC Complementary Medicine and Therapies 23(1): 179.

65. Sakeh NM, Abdullah SNA, Bahari MNA, Azzeme AM, Shaharuddin NA, et al. (2021) EgJUB1 and EgERF113 transcription factors as potential master regulators of defense response in Elaeis guineensis against the hemibiotrophic Ganoderma boninense. BMC Plant Biology 21(1): 59.

66. Sarada PM, Okosodo EF (2026) Indigenous wild vegetables and native fruits for the treatment of tropical disease in Ilaro for sustainable tourism in south west Nigeria. Boletin Latinoamericano y Del Caribe de Plantas Medicinales y Aromaticas 25(4): 487–502.

67. Shaikh SA, Varatharajan R, Muthuraman A (2022) Palm Oil Derived Tocotrienol-Rich Fraction Attenuates Vascular Dementia in Type 2 Diabetic Rats. International Journal of Molecular Sciences 23(21): 13531.

68. Shamsuddin NAM, Zulfakar MH (2023) Nanostructured Lipid Carriers for the Delivery of Natural Bioactive Compounds. Current Drug Delivery 20(2): 127–143.

69. Shang H, Li P, Zhang X, Xu X, Gong J, et al. (2022) The Gain-of-Function Mutation, OsSpl26, Positively Regulates Plant Immunity in Rice. International Journal of Molecular Sciences 23(22): 14168.

70. Shekhar N, Tyagi S, Rani S, Thakur AK (2023) Potential of Capric Acid in Neurological Disorders: An Overview. Neurochemical Research 48(3): 697–712.

71. Syarifah Noratiqah SB, Zulfarina MS, Ahmad SU, Fairus S, NainaMohamed I (2019) The pharmacological potential of oil palm phenolics (OPP) individual components. International Journal of Medical Sciences 16(5): 711–719.

72. Tan SW, bin Israf Ali DA, Khaza'ai H, Wong JW, Vidyadaran S (2020) Cellular uptake and anti-inflammatory effects of palm oil-derived delta (δ)-tocotrienol in microglia. Cellular Immunology 357: 104200.

73. Venmathi Maran BA, Iqbal M, Gangadaran P, Ahn BC, Rao PV, et al. (2022) Hepatoprotective Potential of Malaysian Medicinal Plants: A Review on Phytochemicals, Oxidative Stress, and Antioxidant Mechanisms. Molecules 27(5): 1533.

74. Viola I, Coppa M, Lussiana C, Gullì CG, Malfatto V, et al. (2026) Hazelnut skin supplementation during ewes' peripartum period increases immune-related serum proteins in lambs without affecting their growth. Italian Journal of Animal Science 25(1): 405–412.

75. Wang X, Zhang C, Bao N (2023) Molecular mechanism of palmitic acid and its derivatives in tumor progression. Frontiers in Oncology 13: 1224125.

76. Wu X, Xu M, Geng M, Chen S, Little PJ, et al. (2023) Targeting protein modifications in metabolic diseases: molecular mechanisms and targeted therapies. Signal Transduction and Targeted Therapy 8(1): 220.

77. Yang CT, Cole RM, Colombo E, Angelotti A, Ni A, et al. (2026) Foods Fortified with Soybean or Palm Oil Show No Effect on Inflammation or Oxidized Low-Density Lipoprotein in Adults with Overweight or Obesity: A Secondary Analysis of a Randomized Placebo-Controlled Crossover Trial. Current Developments in Nutrition 10(2): 107635.

78. Yang L, Yang C, Chu C, Wan M, Xu D, et al. (2022) Beneficial effects of monounsaturated fatty acid-rich blended oils with an appropriate polyunsaturated/saturated fatty acid ratio and a low n-6/n-3 fatty acid ratio on the health of rats. Journal of the Science of Food and Agriculture 102(15): 7172–7185.

79. Yeganehjoo H, Zamani N, Chitkara S, Shah AK (2024) The Potential Role of Tocotrienols Against Cardiovascular Diseases. In Advances in Biochemistry in Health and Disease 28: 149–161.

80. Zhang N, Zhang S, Dong X (2024) Plant-derived bioactive compounds and their novel role in central nervous system disorder treatment via ATF4 targeting: A systematic literature review. Biomedicine and Pharmacotherapy 176: 116811.

81. Zio S, Tarnagda B, Sankara S, Tapsoba F, Zongo C, et al. (2025) Nutritional and therapeutic interest of most widely produced and consumed plant oils by human: A review. Applied Food Research 5(2): 101093.