

Beyond β -Carotene: Red Palm Oil for Maternal–Child Micronutrient Resilience—Provitamin A Bioefficacy, Redox–Immune Function, Food-System Delivery, and a New Clinical Evidence Agenda

Loso Judijanto

IPOSS Jakarta, Indonesia

*Corresponding Author: Loso Judijanto, IPOSS Jakarta, Indonesia. <https://orcid.org/0009-0007-7766-0647>.

Submitted: 08 October 2026

Accepted: 15 October 2026

Published: 22 October 2026

Citation: Judijanto, L. (2026). Beyond β -Carotene: Red Palm Oil for Maternal–Child Micronutrient Resilience—Provitamin A Bioefficacy, Redox–Immune Function, Food-System Delivery, and a New Clinical Evidence Agenda. *Journal of Clinical Medicine*, 1(5), 01-16.

Abstract

Vitamin A deficiency remains relevant to maternal and child health, particularly where dietary diversity, infection control, and access to micronutrient-rich foods remain inadequate. Red palm oil (RPO) is distinctive because it combines an intrinsic lipid matrix with α - and β -carotene and retains varying amounts of tocopherols, tocotrienols, phytosterols, and other minor constituents. This qualitative literature review reassesses RPO beyond the conventional question of whether it increases serum retinol. Contemporary evidence is synthesized across provitamin-A absorption and bioconversion, maternal and lactational nutrition, childhood vitamin A status, ocular health, iron–erythropoietic interactions, oxidative and immune pathways, intestinal microbiota, processing stability, food formulation, and implementation. Recent randomised trials in vitamin-A-deficient schoolchildren indicate that RPO-enriched foods can markedly increase circulating provitamin-A carotenoids and may improve iron-related and erythropoietic indicators, reduce inflammatory burden, lower helminth reinfection, alter gut-microbial ecology, and prevent incident xerophthalmia. However, effects on serum retinol are less consistently differentiated from control oils, illustrating the limitations of relying on a homeostatically regulated biomarker. Contemporary maternal RPO trials remain notably scarce. The review therefore proposes a maternal–child micronutrient-resilience framework integrating food matrix, bioavailability, inflammation-adjusted assessment, functional outcomes, existing supplementation exposure, acceptability, and food-system feasibility. RPO should be considered a context-specific complement to established micronutrient strategies rather than a universal substitute. A new generation of independently replicated maternal–infant and paediatric trials is required.

Keywords: Red Palm Oil, Red Palm Olein, Vitamin A Deficiency, β -Carotene, Maternal Nutrition, Child Nutrition, Micronutrient Resilience, Immune Function, Oxidative Stress, Food-Based Intervention.

JEL Classification: I12; I18; Q13; Q18; O33

Introduction

Maternal and Child Micronutrient Vulnerability

Micronutrient malnutrition continues to coexist with energy sufficiency, overweight, infectious disease, and dietary transition, producing the increasingly familiar phenomenon of “hidden hunger.” Vitamin A, iron, zinc, iodine, folate, and other micronutrients are particularly important during pregnancy, lactation, infancy, and childhood because these periods combine rapid tissue growth with high metabolic demand and, in many low- and

middle-income settings, recurrent infectious and inflammatory exposures. Global analyses continue to identify vitamin A deficiency (VAD) as a clinically and epidemiologically relevant condition, even though its distribution is highly heterogeneous and has changed substantially during the past several decades as supplementation and fortification programmes have expanded [1-4]. Pooled biomarker data further indicate that deficiency in at least one key micronutrient affects a large proportion of preschool-aged children and women of reproductive age world-

wide, reinforcing the need for interventions that address micronutrient quality rather than energy intake alone [5].

The concept of micronutrient vulnerability is especially important in maternal and child nutrition because deficiencies rarely occur in isolation. A woman with low vitamin A intake may simultaneously have inadequate iron, zinc, folate, or protein intake, and her physiological requirements may increase further during pregnancy and lactation. Community-based evidence from pregnant women has demonstrated the co-occurrence of iron, folate, and vitamin A deficiencies, illustrating why single-nutrient interpretations may understate the biological complexity of maternal malnutrition [6].

Similarly, a child living in a food-insecure environment can experience deficiencies alongside enteric infections, helminthiasis, systemic inflammation, and impaired intestinal function. These processes may alter nutrient absorption, transport, storage, biomarker concentrations, and biological utilisation. Consequently, an intervention should not be judged exclusively according to whether it raises one biochemical marker; it should be assessed within the nutritional, infectious, inflammatory, and food-system context in which it is delivered [7-9].

Indonesia and other tropical food systems illustrate this complexity. Food-based modelling in high-stunting districts has demonstrated that vitamin A and other nutrients can remain problematic for pregnant women and young children even where food energy is available. Such evidence supports strategies that improve not merely calorie availability but the density and bioavailability of micronutrients within habitual diets [10]. Fortification can be effective, but intervention coverage, household access, product consumption, and nutrient bioavailability determine whether theoretical nutrient delivery becomes biological benefit [11, 12].

Why Reconsider Red Palm Oil?

Red palm oil is relevant to this debate because it differs nutritionally from extensively refined palm oil. Production approaches designed to retain the natural colour of palm fruit also preserve substantially more carotenoids and vitamin-E-family compounds. RPO therefore represents not simply edible fat but a food matrix in which provitamin-A carotenoids occur within lipid, potentially facilitating intestinal solubilization and absorption. Contemporary reviews describe α -carotene and β -carotene as dominant provitamin-A constituents while also identifying tocopherols, tocotrienols, phytosterols, squalene, and other minor compounds whose concentrations depend on processing and storage conditions [13, 14].

The renewed relevance of RPO does not arise because the proposition that palm carotenoids have vitamin A activity is new. Rather, contemporary nutrition science now provides better ways to interrogate what such activity means clinically. Carotenoid bioaccessibility is influenced by food structure, oil type, emulsification, digestion, transporters, and metabolic conversion, while serum retinol is tightly homeostatically regulated

and affected by inflammation. Meanwhile, supplementation and fortification environments have changed. Populations that historically had minimal exposure to formal vitamin A programmes may now receive periodic pharmaceutical supplementation, fortified oils, micronutrient powders, or other interventions. Therefore, the policy question has shifted from “Can RPO provide β -carotene?” to “Under what biological and food-system conditions does RPO provide additional value?” [15-17].

From Vitamin A Correction to Micronutrient Resilience

This review uses micronutrient resilience as an organizing concept. Micronutrient resilience refers here to the capacity of individuals and food systems to maintain adequate micronutrient availability and function despite variation in diet quality, infection, inflammation, household resources, seasonal food access, and other stressors. Under this interpretation, RPO is potentially useful not merely if it increases a laboratory value but if it contributes to a nutritionally robust diet in ways that are bioavailable, acceptable, affordable, and compatible with existing public-health interventions.

Such framing is particularly relevant because high-dose vitamin A supplementation already has an established evidence base in populations in which deficiency remains a public-health concern. Updated Cochrane evidence indicates that vitamin A supplementation in children aged 6–59 months at risk of deficiency can reduce morbidity and mortality, although appropriate dose and delivery systems remain important [18]. At the same time, evidence that excessive or poorly targeted supplementation may not be universally beneficial emphasises the need to distinguish physiological food-based provitamin-A exposure from repeated pharmacological dosing [19].

Contemporary synthesis of food-based interventions also suggests that provitamin-A-rich foods can improve vitamin A status in some populations, although effects vary with food vehicle, baseline status, study duration, and statistical power [20]. RPO should therefore be evaluated as a possible complement within diversified intervention portfolios, not as a rhetorical replacement for interventions already supported by clinical evidence.

The Contemporary Evidence Gap

A particularly important feature of the present literature is the imbalance between new paediatric evidence and contemporary maternal evidence. Recent randomised studies in Malaysian schoolchildren with VAD have assessed RPO-enriched biscuits against comparable foods prepared with ordinary palm olein. These studies have moved beyond historical endpoints by examining retinol, retinol-binding protein, carotenoids, haematology, iron, inflammation, helminth reinfection, xerophthalmia, and gut microbiota [21-24].

In contrast, recent maternal literature is dominated by broader work on vitamin A requirements, maternal supplementation, breast-milk composition, and food-based or multiple-micronutrient interventions rather than new RPO-specific pregnancy trials. Contemporary evidence confirms that pregnancy and lac-

tation are physiologically distinct periods for vitamin A metabolism, that maternal nutrient intake can affect maternal status and breast-milk micronutrient concentrations, and that food-based interventions are increasingly relevant to maternal nutrition. Regional meta-analytic evidence also indicates that VAD remains substantial among pregnant women in some low-income settings, underscoring the continuing relevance of safe food-based strategies while also highlighting considerable geographic heterogeneity [25]. Nevertheless, direct contemporary evidence that specifies the optimal RPO dose, timing, maternal biomarker response, milk transfer, infant response, safety, and comparative effectiveness is inadequate [26-28].

The principal objective of this qualitative literature review is therefore to critically reassess RPO as a context-dependent strategy for maternal-child micronutrient resilience. The review integrates food chemistry, carotenoid bioavailability, vitamin A physiology, biomarkers, iron metabolism, immune and redox pathways, maternal-lactational nutrition, childhood functional outcomes, processing technologies, and implementation considerations. Rather than simply asking whether RPO is nutritious, the analysis asks what is sufficiently established for contemporary clinical translation, what remains biologically plausible but unproven, and what research architecture is required for the next generation of evidence.

Literature Review: Conceptual and Theoretical Foundations **RPO Composition and the Significance of Processing**

The nutritional identity of RPO depends on processing. Conventional high-temperature refining can remove much of the colour associated with natural palm carotenoids, whereas RPO processing strategies are designed to reduce undesirable components while preserving a greater fraction of carotenoids and tocopherols. This distinction is essential because clinical or public-health claims concerning RPO cannot automatically be generalised to all palm oils. Likewise, experimental results obtained using a carefully prepared red palm olein product cannot automatically be extrapolated to oils that have undergone different refining, storage, heating, or adulteration histories.

Thermal treatment is especially important because β -carotene and related pigments are susceptible to degradation and isomerisation. Studies of red palm olein under deep-fat frying, microwave heating, conventional baking, and simulated household storage indicate that meaningful quantities of carotenoids and vitamin E can persist, but retention depends on temperature, duration, oxygen, light, and repeated thermal exposure [29, 30]. Broader food-science evidence similarly shows that carotenoid concentrations and molecular forms can change across harvesting, storage, processing, cooking, and digestion, so exposure should be characterised at the point of consumption rather than inferred solely from raw-food composition [31]. In a bakery context, RPO-containing products have also demonstrated acceptable sensory performance, showing that incorporation into familiar foods is technologically possible [32].

These findings have an important translational implication: a

clinical trial cannot define its intervention simply as “red palm oil.” It should report nutrient composition at production, after storage, and preferably after the cooking or food-processing step experienced by participants. Otherwise, the nominal dose can differ materially from the biologically available dose. Microencapsulation studies reinforce this principle, demonstrating that delivery technology can alter oxidative stability and the degradation kinetics of RPO bioactives [33].

Provitamin-A Biology and the Food Matrix

Dietary vitamin A can be obtained as preformed retinoids or generated from provitamin-A carotenoids. Following ingestion, carotenoids must be released from the food matrix, incorporated into lipid droplets and mixed micelles, transported across the intestinal epithelium, and subsequently packaged or enzymatically converted. β -Carotene 15,15'-oxygenase-1 is central to cleavage of β -carotene toward retinal, which can then be reduced to retinol and esterified for transport and storage. Genetic, nutritional, and physiological factors influence the efficiency of these processes, meaning that equivalent amounts of ingested β -carotene do not necessarily yield equivalent vitamin A activity across individuals [34, 35].

The lipid nature of RPO is theoretically advantageous because carotenoids are lipophilic and require dietary lipid for efficient micellarization. A systematic review and meta-analysis of dietary-fat studies concluded that fat quantity and type influence carotenoid bioaccessibility and bioavailability, while a randomised human crossover trial subsequently demonstrated that both fat type and emulsification can materially alter postprandial carotenoid absorption [36]. These data do not establish that RPO is necessarily superior to every alternative vehicle, but they provide a mechanistic basis for viewing RPO as an integrated nutrient-delivery matrix rather than merely a carrier to which β -carotene has been added.

An important distinction is required between bioaccessibility, absorption, bioavailability, and bioconversion. In vitro gastrointestinal models may estimate the fraction of carotenoids released into a potentially absorbable micellar phase, but they cannot directly establish human tissue availability, vitamin A stores, or clinical effectiveness. Have emphasised the need to standardise these concepts because inconsistent terminology can make delivery systems appear clinically superior when only an in vitro intermediate has been measured. Encapsulation and lipid-based carrier systems can improve carotenoid stability, dispersibility, and simulated uptake, but their nutritional value still depends on release, epithelial transport, and in vivo utilization [37, 38]. Human interventions and isotope-based studies therefore remain necessary to determine whether food-technological improvements translate into nutritional benefit.

Maternal Vitamin A Physiology

Pregnancy and lactation create a distinctive nutritional context. Maternal vitamin A must support the mother's own epithelial, immune, visual, and metabolic functions while also contributing to fetal development and subsequently breast-milk nutrient

delivery. Contemporary assessment of vitamin A requirements highlights substantial uncertainty because maternal intake, liver stores, placental transfer, milk secretion, inflammation, and postpartum physiology interact in ways that are not well represented by a single circulating marker.

Lactation is particularly relevant to a food-based RPO strategy because breast milk constitutes the primary source of vitamin A for exclusively breastfed infants. Meta-analytic data demonstrate substantial variability in milk vitamin A concentrations across populations and lactation stages. Intervention evidence further indicates that maternal supplementation with fat-soluble vitamins can influence milk composition, although responses vary by dose, timing, baseline maternal status, and stage of lactation [39].

This physiology provides a strong rationale for maternal RPO research but does not itself prove maternal clinical effectiveness. The crucial unanswered question is whether sustained intake of a food-level RPO dose during pregnancy or lactation can meaningfully improve maternal vitamin A reserves and milk vitamin A without creating redundant nutrient exposure in women who already receive supplements or fortified foods. Contemporary reviews of maternal nutrition repeatedly emphasise the importance of evaluating dietary quality and supplement exposure together rather than treating them as independent systems.

Vitamin A, Epithelial Integrity and Immune Function

Vitamin A is fundamental to epithelial differentiation and immune regulation. Its metabolite retinoic acid affects gene expression through nuclear receptors and contributes to the maintenance of mucosal barriers. Current immunological literature describes roles in B-cell and T-cell function, immunoglobulin A production, epithelial antimicrobial defence, and host–microbiome interactions [40, 41]. Vitamin A deficiency can therefore be conceptualized not only as a biochemical deficiency but also as a disturbance affecting barrier tissues and immune organization.

The interaction between nutrient deficiency and infection is bidirectional. Infections can reduce food intake, impair absorption, increase nutrient losses, and alter circulating biomarkers. Deficiencies can in turn weaken epithelial and immune responses. Contemporary reviews of child nutrition emphasise that micronutrient interventions are therefore likely to exhibit different effects according to infectious burden and baseline deficiency. Evidence from skin immunity likewise demonstrates how vitamin A and retinoid signalling support epithelial host defence, illustrating mechanisms potentially relevant across mucosal tissues [42].

Oxidative Stress: Biological Plausibility versus Clinical Evidence

RPO is often described as an antioxidant food because it contains carotenoids and vitamin-E-family compounds. This description should be handled carefully. Carotenoids can interact with reactive species and singlet oxygen, while tocotrienols have been studied for potential antioxidant and anti-inflammatory effects.

However, contemporary nutrition science has moved away from treating any food rich in “antioxidants” as automatically producing clinically important reductions in oxidative damage. The activity of carotenoids varies by compound, concentration, tissue environment, redox state, and coexisting nutrients [43].

Meta-analytic evidence concerning oral carotenoids indicates possible effects on selected oxidative-stress biomarkers, but study heterogeneity and variation in compounds, populations, and outcome measures limit broad causal claims [44]. Similarly, systematic assessment of tocotrienol supplementation has produced mixed effects across inflammatory and oxidative-stress markers, and reviews of palm-derived tocotrienols emphasise that promising preclinical findings require careful clinical validation before therapeutic claims are justified [45, 46]. Therefore, RPO should not be assumed to improve maternal or child outcomes through a generic antioxidant mechanism. Future trials need prespecified biomarkers, appropriate controls, adequate statistical power, and mechanistic linkage to clinically relevant outcomes.

Vitamin A, Iron and Erythropoiesis

One of the most clinically interesting dimensions of the emerging RPO evidence is its interaction with iron status. Vitamin A and iron metabolism are connected through several pathways involving iron mobilization, erythropoiesis, inflammatory signalling, and hepcidin. Contemporary review evidence suggests that VAD can impair the mobilization of stored iron, potentially leaving iron less available for erythropoiesis even when body iron is not absolutely depleted [47].

This interaction creates both opportunity and methodological difficulty. Improvements in haemoglobin after a vitamin A intervention need not imply that RPO supplied large amounts of iron. They may instead reflect changes in iron utilisation, inflammatory status, or dietary interactions. Conversely, ferritin can increase during inflammation and therefore overstate iron stores. Iron evaluation in RPO trials should thus include a panel such as haemoglobin, ferritin, soluble transferrin receptor, transferrin saturation, and ideally hepcidin, interpreted alongside inflammatory biomarkers such as C-reactive protein (CRP) and alpha-1-acid glycoprotein (AGP) [48, 49].

Method

Review Design

This article employed a qualitative literature review (QLR) design and was explicitly not conducted as a systematic literature review or meta-analysis. The purpose was interpretive synthesis: to connect contemporary clinical, nutritional, biochemical, immunological, and food-technology evidence in order to reassess the possible role of RPO within maternal and child micronutrient strategies. The approach was selected because the central research question spans heterogeneous evidence types that cannot be meaningfully reduced to a single pooled effect estimate.

Priority was given to peer-reviewed journal literature published from 2020 through 7 October 2026. This temporal restriction

was used to ensure that the conceptual synthesis reflected contemporary understanding of vitamin A biomarkers, inflammation adjustment, maternal nutrition, food delivery technology, and recently published RPO intervention studies. Older RPO knowledge was considered indirectly were summarized by recent peer-reviewed reviews, rather than serving as the main evidentiary foundation.

Literature Identification and Evidence Domains

Literature was identified through targeted searches of biomedical and multidisciplinary academic sources using combinations of terms relating to “red palm oil,” “red palm olein,” “vitamin A,” “retinol,” “retinol-binding protein,” “ β -carotene,” “maternal nutrition,” “pregnancy,” “lactation,” “breast milk,” “child nutrition,” “xerophthalmia,” “iron,” “erythropoiesis,” “inflammation,” “immunity,” “microbiome,” “bioavailability,” “heating,” “processing,” “fortification,” and “supplementation.” Search concepts were combined iteratively to capture both direct RPO evidence and adjacent mechanistic or implementation literature needed to interpret the clinical findings.

Evidence was interpreted hierarchically but not mechanically ranked. Randomised human trials and high-quality evidence syntheses were given greatest weight for clinical claims. Human observational evidence, food-science experiments, and mechanistic reviews were used to explain biological pathways and implementation constraints. In vitro delivery studies were treated as formulation evidence rather than proof of clinical efficacy.

Thematic Analysis

The literature was organised into interacting themes: RPO composition and processing; carotenoid bioavailability; maternal–lactational nutrition; childhood vitamin A outcomes; ocular function; vitamin A–iron interactions; infection and immunity; oxidative stress; gut microbial ecology; food formulation; biomarker validity; supplementation and fortification context; and research design. Themes were interpreted comparatively so that evidence convergence, disagreement, and translational gaps could be identified across clinical, mechanistic, and food-system domains.

A deliberate distinction was made among three categories of evidence. The first comprised clinically supported RPO-specific

findings. The second comprised biologically plausible pathways supported by broader vitamin A, carotenoid, or tocotrienol literature but not adequately demonstrated for RPO. The third comprised unresolved translational propositions requiring new trials.

This interpretive separation is critical because nutritional reviews frequently move too quickly from compositional evidence to clinical claims. The present review therefore treats the presence of carotenoids or tocotrienols as a basis for mechanistic inquiry, not as automatic evidence of improved health outcomes.

Results: Thematic Findings

RPO Is More Appropriately Understood as a Food Matrix than a Single-Nutrient Supplement

The first major theme is that RPO represents an intrinsic food matrix containing provitamin-A carotenoids in lipid rather than a conventional isolated supplement. This matters because nutrient release, micellization, intestinal absorption, transport, and bioconversion depend on interactions between bioactive compounds and the surrounding matrix. Reviews of whole-food micronutrient bioavailability increasingly emphasise that the biological value of nutrients cannot always be predicted from composition tables alone [50].

Human experimental evidence supports the role of lipid context. Demonstrated that both dietary fat type and emulsification significantly affected carotenoid absorption, while broader synthesis confirms that fat is an important determinant of carotenoid bioavailability. RPO therefore has a theoretically favourable structure for provitamin-A delivery, although the magnitude of advantage relative to other carotenoid-rich foods or fortified edible oils remains context dependent.

Figure 1 conceptualises the proposed RPO Maternal–Child Micronutrient Resilience Framework, showing that nutritional effects begin before consumption with processing and nutrient retention and continue through food preparation, intestinal bioaccessibility, absorption and bioconversion, biomarker response, biological function, clinical outcomes, and implementation context. The framework highlights why food-matrix and bioavailability evidence should be interpreted together rather than as isolated stages of the intervention pathway.

Figure 1. Maternal–Child Micronutrient Vulnerability and the Role of Red Palm Oil

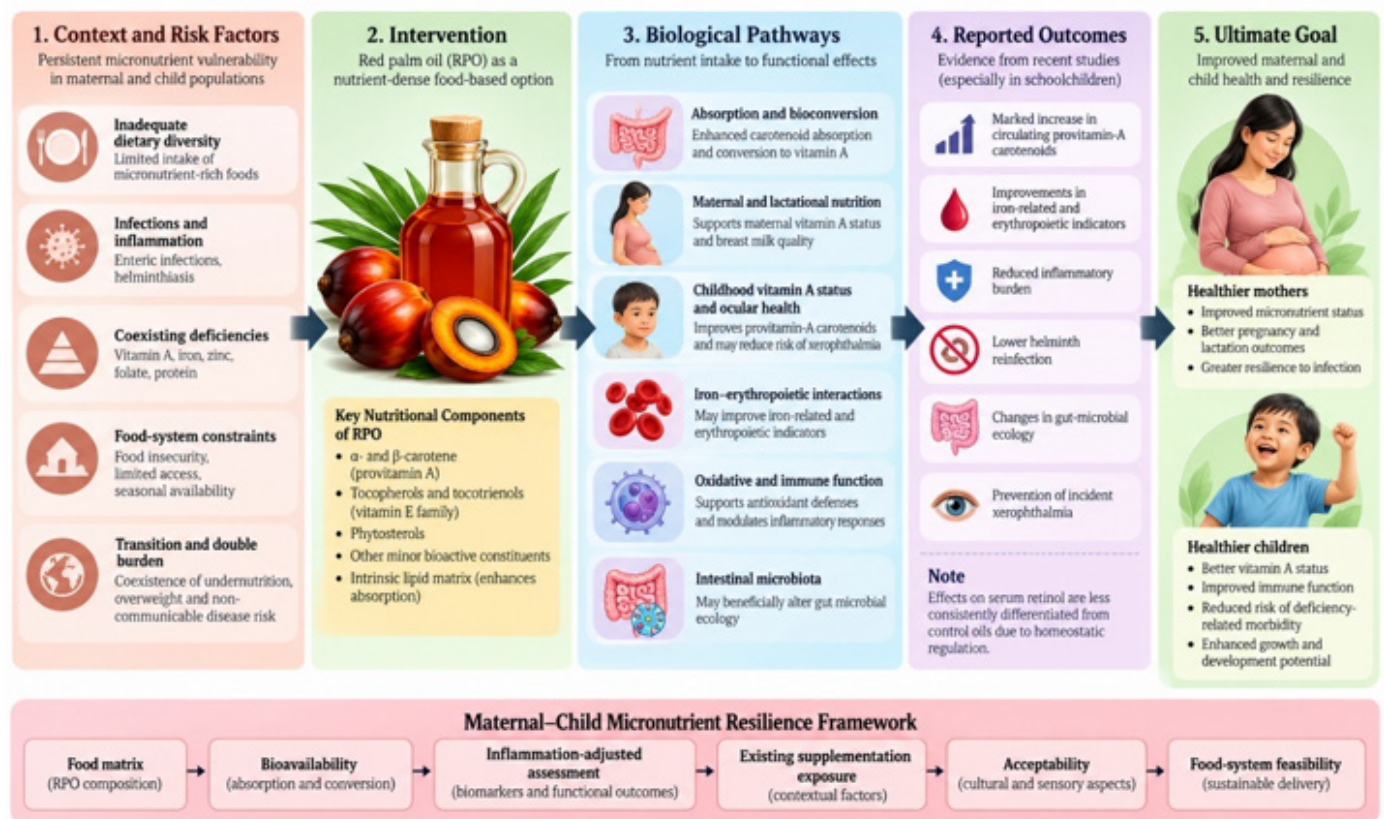


Figure 1: RPO Maternal–Child Micronutrient Resilience Framework

Figure 1 emphasises that the effect of RPO cannot be predicted from β -carotene concentration alone. The same nominal amount of RPO can generate different biological exposure depending on nutrient retention during processing, the food into which it is incorporated, household cooking, adherence, intestinal physiology, inflammation, and initial vitamin A status. This framework therefore shifts attention from a linear “RPO $\rightarrow$ retinol” model toward an intervention-system model.

Childhood Trials Demonstrate Strong Carotenoid Exposure but a More Complex Retinol Response

The most informative recent RPO evidence comes from a double-blind randomised controlled trial involving 651 vitamin-A-deficient rural Malaysian schoolchildren aged 8–12 years. Participants received either RPO-enriched biscuits or comparable palm-olein biscuits for six months. Serum retinol and RBP improved in both groups, and among children with confirmed VAD the difference in retinol improvement between groups was not statistically significant. This is important because a superficial interpretation might suggest that RPO failed to provide vitamin A benefit. Yet the same trial showed significantly greater increases in α - and β -carotene in the RPO group and more favourable changes in multiple haematological parameters and iron.

The discordance is biologically informative. Serum retinol is homeostatically regulated and does not change linearly across the

full range of liver vitamin A reserves. It can also decline during inflammatory responses independently of true depletion. Thus, a clear increase in circulating carotenoids with only modest between-group differentiation in retinol does not necessarily imply absence of biological exposure. Instead, it reveals why contemporary RPO trials need more sophisticated vitamin A assessment [51–53].

The 2025 Cochrane review of vitamin A diagnostic biomarkers is particularly relevant. Available tests have limitations in sensitivity and specificity, and evidence comparing common markers with more direct measures of stores remains incomplete. Retinol isotope-dilution research in children further shows that estimates of total liver vitamin A reserves provide information that circulating biomarkers alone cannot fully capture, particularly when inflammation is present [54]. This reinforces the argument that serum retinol should remain part of assessment but should not be the sole criterion for judging intervention effectiveness. Where feasible, future RPO trials should integrate serum retinol, RBP, CRP, AGP, carotenoids, dietary exposure, and functional or reserve-sensitive measures such as the modified relative dose-response (MRDR) test or retinol isotope dilution (RID).

The Emerging Ocular Evidence Is Clinically More Compelling than a Biomarker-Only Narrative

A subsequent cluster-randomised trial provided an important functional extension of the Malaysian evidence. In 504 schoolchildren with confirmed or marginal vitamin A status, six months

of RPO-enriched biscuit supplementation did not produce a statistically significant superiority in resolution of existing xerophthalmia, although the numerical resolution rate was higher. More importantly, the RPO group demonstrated substantially greater prevention of incident xerophthalmia and conjunctival xerosis, and children receiving RPO were reported to be considerably less likely to develop xerophthalmia than controls.

This distinction between treatment and prevention deserves attention. Reversal of established epithelial pathology may require a different vitamin A dose, duration, or clinical management strategy than prevention of new disease. A modest food-based provitamin-A intervention may therefore be more suited to maintaining functional adequacy than rapidly treating advanced deficiency. If independently replicated, this would support positioning RPO as a preventive dietary strategy in selected high-risk populations rather than as a replacement for therapeutic vitamin A.

These ocular findings also illustrate why next-generation nutrition trials should incorporate clinically meaningful endpoints. Serum retinol can be influenced by inflammation and homeostasis, whereas development of xerophthalmia represents a functional consequence more closely connected to tissue-level vitamin A inadequacy. Functional outcomes cannot replace biomarkers, but triangulating biochemical, dietary, and clinical data can provide a more persuasive assessment of benefit.

RPO, Iron and Erythropoiesis: An Underappreciated Signal

The 2024 Malaysian RCT also reported greater improvements in haemoglobin, packed cell volume, mean corpuscular volume, mean corpuscular haemoglobin, and iron in the RPO group, together with a reduction in microcytic anaemia that was observed in the experimental group. These findings raise the possibility that correcting provitamin-A inadequacy may influence erythropoiesis and iron utilisation even when RPO is not primarily an iron supplement.

Such a mechanism is compatible with broader evidence on vitamin A–iron interactions. Vitamin A deficiency may impair iron mobilization and contribute to iron sequestration, while infection and inflammatory cytokines can increase hepcidin and further reduce iron availability for erythropoiesis. Iron status must therefore be interpreted through a multidimensional framework rather than haemoglobin alone.

However, the RPO findings should not yet be generalised to all children or interpreted as proof that RPO treats anaemia. Anaemia is heterogeneous; iron deficiency, inflammation, malaria, helminths, haemoglobin disorders, folate and vitamin B12 insufficiency, and other causes may coexist. Future trials should incorporate ferritin, soluble transferrin receptor, CRP, AGP, transferrin saturation, and preferably hepcidin, with prespecified mediation analysis to determine whether improvements result from iron absorption, redistribution, reduced inflammation, improved erythropoiesis, or multiple pathways.

Infection and Immune Outcomes: Promising but Not Yet Definitive

A related study reported lower *Ascaris lumbricoides* reinfection after anthelmintic treatment among VAD schoolchildren receiving RPO-enriched biscuits. The finding is biologically plausible because vitamin A and retinoic-acid signalling influence epithelial integrity and immune regulation, including mucosal immunity. Nevertheless, helminth reinfection is determined by environmental sanitation, exposure, treatment efficacy, behaviour, and host immunity, making causal attribution to RPO alone challenging.

Consequently, the helminth finding should be treated as a signal requiring replication rather than evidence that RPO functions as an anti-infective intervention. A stronger future design would combine nutritional assessment with immune phenotyping, exposure measurement, sanitation variables, and longitudinal infection surveillance.

The broader mechanistic literature supports continued investigation. Retinoic acid contributes to mucosal immune organization and IgA biology, while vitamin A is increasingly recognised as an important coordinator of nutrient–host–microbiome interactions. Such evidence provides a plausible biological pathway through which improved vitamin A status might alter susceptibility to infection, but it does not establish that every RPO-derived change is mediated through this mechanism.

Gut Microbiome Findings Expand the Biological Hypothesis

In 2025, an RCT analysis of 328 vitamin-A-deficient Malaysian schoolchildren reported that RPO-enriched biscuit supplementation altered gut microbial composition and network characteristics over six months. The RPO group showed changes in alpha-diversity indices and enrichment of several taxa interpreted as potentially beneficial; some microbial changes correlated with carotenoid, α -tocopherol, and haematological improvements.

These findings are novel but require restrained interpretation. Higher microbial diversity is not universally beneficial, lower diversity is not automatically harmful, and taxonomy alone does not establish metabolic function. Furthermore, correlations between bacterial taxa and micronutrient biomarkers cannot establish directionality. Improved nutrient exposure may alter intestinal ecology, but baseline microbial ecology may also influence nutrient metabolism and absorption.

The more defensible conclusion is that the microbiome represents a plausible mediator or modifier of RPO response and should be incorporated into selected future mechanistic trials. Metagenomics, microbial metabolomics, intestinal inflammatory markers, and dietary assessment could help determine whether the observed microbial shifts contribute to biological benefit or merely accompany altered dietary exposure.

Figure 2 integrates the multiple pathways linking RPO intake with functional outcomes and highlights the bidirectional roles of inflammation and intestinal ecology. It distinguishes the ret-

inoid pathway from parallel carotenoid and vitamin-E-family pathways while showing where ocular, immune, erythropoietic, and microbiome-related functions may converge

Figure 2. Biological Pathways from RPO Consumption to Maternal and Child Outcomes

Mechanistic pathways, converging functions, and major effect modifiers

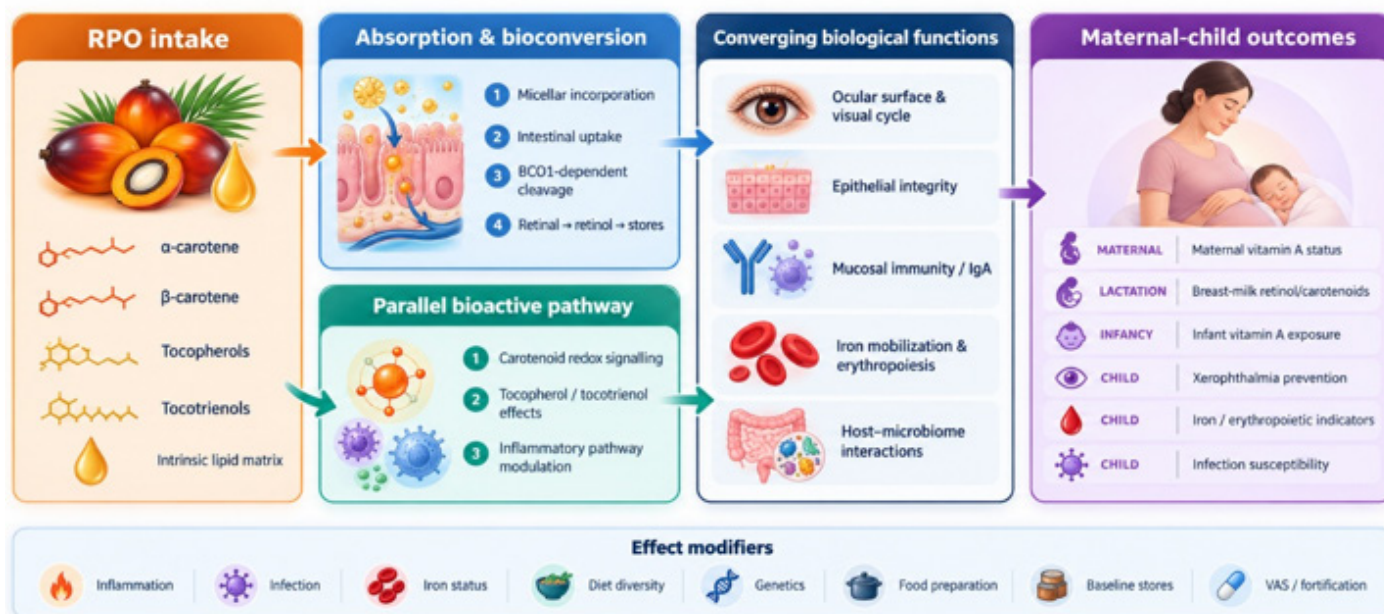


Figure 2: Biological Pathways from RPO Consumption to Maternal and Child Outcomes

The figure demonstrates why an RPO intervention may produce biological responses that cannot be captured by serum retinol alone. It also illustrates that the causal chain remains incompletely demonstrated: several arrows represent plausible mechanisms supported by broader nutrient biology but still require RPO-specific confirmation.

Maternal and Lactational Evidence Remains the Most Important Translational Gap

The maternal–child framing of RPO is scientifically attractive but presently ahead of direct contemporary evidence. Vitamin A requirements change during pregnancy and lactation, and maternal nutrition influences both maternal status and infant nutrient exposure. Yet recent RPO-specific intervention research has concentrated on school-aged children rather than pregnant women, lactating mothers, neonates, or young infants.

This gap is particularly important because pregnancy requires a different safety and efficacy framework from childhood supplementation. Preformed vitamin A can be harmful at excessive doses during pregnancy, whereas provitamin-A carotenoids are regulated through conversion pathways. Even so, a food-based product should not be presumed automatically appropriate for every pregnant population. Total vitamin A exposure from diet, supplements, fortified foods, and RPO must be quantified.

Human-milk evidence further argues for direct trials. Maternal supplementation can change concentrations of some vitamins in milk, especially fat-soluble vitamins, but the magnitude and

persistence of response vary markedly. Human milk itself shows substantial variation in vitamin A content across lactation and populations.

Thus, a maternal RPO study should assess maternal carotenoids, retinol, RBP, CRP and AGP; breast-milk retinol and carotenoids; maternal dietary intake; infant intake; and infant status longitudinally.

Maternal dietary interventions should also be evaluated within the broader nutrition package. Reviews of pregnancy supplementation show that multiple micronutrients can improve selected maternal and child outcomes, while food-based perinatal interventions are increasingly being investigated as pragmatic approaches to undernutrition [55]. RPO therefore competes not with “no nutrition” but with an evolving portfolio of antenatal supplements, balanced-energy protein products, fortified foods, and diversified diets.

Processing, Heating and Storage Are Clinical Variables, Not Merely Food-Science Details

A recurring weakness in nutrition translation is treating food preparation as separate from efficacy. RPO illustrates why this separation is artificial. Carotenoids may be reduced through prolonged thermal processing, oxidative exposure, or inappropriate storage, meaning that a nutritionally promising oil at manufacture may deliver substantially different doses in a household kitchen.

The existing food-science literature suggests that RPO can retain meaningful carotenoids and vitamin E across common processing conditions, but degradation is exposure dependent. Storage under lower temperature and protection from light can improve stability, while product formulation can also affect sensory acceptance and nutrient retention.

Encapsulation and emulsion technologies provide an additional pathway. Demonstrated that microencapsulation can increase oxidative stability and modify carotenoid and vitamin-E degradation during storage. Reported that a pectin-stabilized RPO Pickering emulsion produced markedly higher in vitro β -carotene bioaccessibility than unformulated RPO [56]. The result is technologically promising but remains a measure of simulated gastrointestinal bioaccessibility rather than demonstrated human benefit.

More recent nanoemulsion research has expanded potential delivery options for RPO in functional foods [57]. Yet formulation science should progress in parallel with safety, regulatory, sensory, cost, and clinical research. A technologically optimized RPO delivery vehicle is only useful for public nutrition if it remains affordable, acceptable, scalable, and biologically effective.

Acceptability and Adherence Determine Biological Effectiveness

Food-based interventions depend on behaviour. RPO has a characteristic colour, aroma, and flavour profile that can be advantageous in some cuisines and challenging in others. Product design therefore matters. Bakery studies demonstrate that acceptable foods can be formulated using red palm olein, and school-based trials have successfully delivered RPO through biscuits over multiple months.

A study among preschool children in the Eastern Cape of South Africa likewise illustrates the feasibility of incorporating RPO into a biscuit-based intervention, though population, design, and outcome differences prevent simple comparison with the Malaysian trials [58]. Together, these studies suggest that familiar food vehicles can support repeated delivery, but feasibility evidence should not be conflated with proof of long-term effectiveness.

However, biscuits should not become the assumed universal delivery vehicle. A school snack can support adherence during a controlled study, but household programmes may need cooking oil, spreads, complementary foods, blended products, or other culturally appropriate vehicles. Long-term effectiveness should therefore be evaluated under normal household conditions rather than inferred solely from supervised feeding.

Discussion and Analysis

Moving Beyond “Does RPO Raise Serum Retinol?”

The central interpretation emerging from this review is that the classic serum-retinol question is no longer sufficient. Contemporary RPO trials have provided an instructive example: strong increases in provitamin-A carotenoids and improvements in selected functional or haematological outcomes can occur without

a proportionately distinctive serum-retinol response relative to the control group.

This finding is consistent with modern understanding of vitamin A assessment. Serum retinol and RBP are influenced by homeostatic control and inflammation. BRINDA methodology demonstrates why inflammation markers such as CRP and AGP should be incorporated when interpreting micronutrient biomarkers. In Ghanaian children and women, inflammation adjustment improved some aspects of classification while introducing other sensitivity limitations relative to MRDR, showing that statistical correction is valuable but cannot transform serum retinol into a perfect indicator of liver stores.

Future RPO trials should therefore use triangulated vitamin A assessment. At minimum, this should combine circulating retinol or RBP, α - and β -carotene, CRP, AGP, dietary assessment, and clinical endpoints. In mechanistic substudies, MRDR or retinol isotope dilution should be considered. The objective is not to abandon serum retinol but to prevent it from acting as the sole gatekeeper of nutritional effectiveness.

Does the RPO Matrix Offer a Meaningful Advantage?

The intrinsic combination of provitamin-A carotenoids and lipid is one of the strongest theoretical arguments for RPO. A lipid matrix facilitates carotenoid solubilization, and controlled human evidence demonstrates that dietary fat characteristics and emulsification affect carotenoid absorption. Food delivery may also offer advantages in regularity, cultural integration, and lower risk of acute pharmacological dosing.

Nevertheless, “food-based” should not be equated with “superior.” Synthetic fortification can provide accurately standardised doses at large scale. Micronutrient powders can address multiple deficiencies simultaneously. Pharmaceutical vitamin A can rapidly deliver therapeutic doses. Diversified diets can provide wider nutritional benefits than a single oil. Each strategy addresses a different part of the nutritional problem [59].

Accordingly, the strongest case for RPO is not that it replaces these strategies but that it may fill particular gaps. Populations with habitual oil use, local access to palm products, persistent provitamin-A inadequacy, limited dietary diversity, and incomplete reach of other interventions could be promising targets. By contrast, populations already consuming adequate vitamin A through diverse diets, fortified foods, and supplements may derive little incremental benefit.

RPO as a Component of Precision Public Nutrition

The concept of precision public nutrition is useful because nutritional interventions have heterogeneous treatment effects. Baseline deficiency is an obvious modifier: a participant with low vitamin A stores has greater biological potential to benefit than an individual who is already replete. Infection, inflammation, iron status, intestinal health, age, pregnancy, genetics, and concurrent supplementation can further modify response.

This implies that trials should be designed to detect heterogeneity rather than averaging it away. Participants should be characterised by baseline retinol/RBP, inflammation, carotenoid intake, anaemia, iron indices, dietary diversity, supplementation history, and fortification exposure. Predefined subgroup analysis can then ask whether RPO is most effective in confirmed VAD, marginal status, high inflammation, iron deficiency, low dietary diversity, or particular combinations.

This approach would also prevent inappropriate public-health generalization. A favourable trial in rural VAD schoolchildren should not automatically justify universal RPO supplementation for urban children, pregnant women, or populations with low prevalence of deficiency. Public-health nutrition is increasingly moving from universal assumptions toward context-specific portfolios, and RPO should be evaluated within that transition.

Reinterpreting the Oxidative-Stress Claim

Oxidative stress provides a plausible but frequently overstated rationale for RPO. The oil contains carotenoids and vitamin E forms, but the literature does not justify presenting RPO as a proven clinical antioxidant therapy in mothers or children. Meta-analyses of carotenoids and tocotrienols show heterogeneity, and biological antioxidant capacity measured experimentally does not automatically translate into improved patient-important outcomes.

The appropriate next step is mechanistic clinical research. Trials could measure F2-isoprostanes, oxidised lipids, antioxidant enzyme activity, inflammatory cytokines, and other prespecified biomarkers alongside vitamin A status and functional outcomes. Mediation models could then examine whether RPO-related improvements in clinical outcomes are actually associated with changes in redox biology. Until such evidence develops, redox modulation should be described as a plausible secondary pathway rather than a confirmed primary mechanism.

Reinterpreting Immune and Microbiome Findings

The RPO-immune hypothesis is stronger than a generic antioxidant narrative because vitamin A has established roles in mucosal immunity. Retinoic-acid signalling is involved in IgA production, lymphocyte programming, epithelial regulation, and host-microbiome interactions.

The Malaysian helminth and microbiome studies therefore create a coherent hypothesis: improving provitamin-A exposure could contribute to a mucosal environment that alters host-pathogen or host-microbiome relationships. Nevertheless, the available

RPO-specific evidence remains insufficient for causal certainty. Reinfection can be shaped by exposure, and microbiome composition can shift for multiple nutritional reasons.

A strong next-generation study would integrate clinical infection surveillance, mucosal or systemic immune biomarkers, stool metagenomics, microbial metabolites, and dietary intake. Such integration would allow researchers to move from an association between RPO and microbial taxa toward a mechanistic model connecting nutrient exposure, immune function, microbial activity, and clinical outcomes.

Maternal-Infant Dyads Should Become the Priority Research Population

The most significant evidence gap identified in this review concerns pregnancy and lactation. Contemporary maternal nutrition science clearly establishes the importance of vitamin A requirements and breast-milk transfer, yet modern RPO intervention trials in mother-infant dyads are scarce.

A high-quality maternal trial should recruit women based on baseline vitamin A and dietary status and randomize them to a standardised RPO-containing food, an isoenergetic control oil, or an ethically appropriate comparator consistent with local care. Investigators should document antenatal vitamin use and fortified-food exposure to prevent hidden co-intervention.

Maternal outcomes should include dietary intake, circulating α - and β -carotene, retinol, RBP, CRP, AGP, iron indices, and adverse events. Lactation assessments should include breast-milk retinol and carotenoids at standardised postpartum times. Infant outcomes should include growth, morbidity, vitamin A status, and where feasible reserve-sensitive markers.

Such studies would answer a substantially more clinically relevant question than whether pregnant women can absorb RPO carotenoids. They would determine whether a realistic food-based dose produces a meaningful mother-infant benefit on top of the modern standard of care.

Figure 3 shows the asymmetry in evidence maturity across populations and outcomes. It indicates that contemporary paediatric evidence has advanced from biochemical exposure measures toward functional and microbiome outcomes, whereas direct evidence in pregnant women, lactating mothers, and infants remains comparatively limited.

Figure 3. Contemporary Evidence-Maturity Map for RPO in Maternal-Child Nutrition

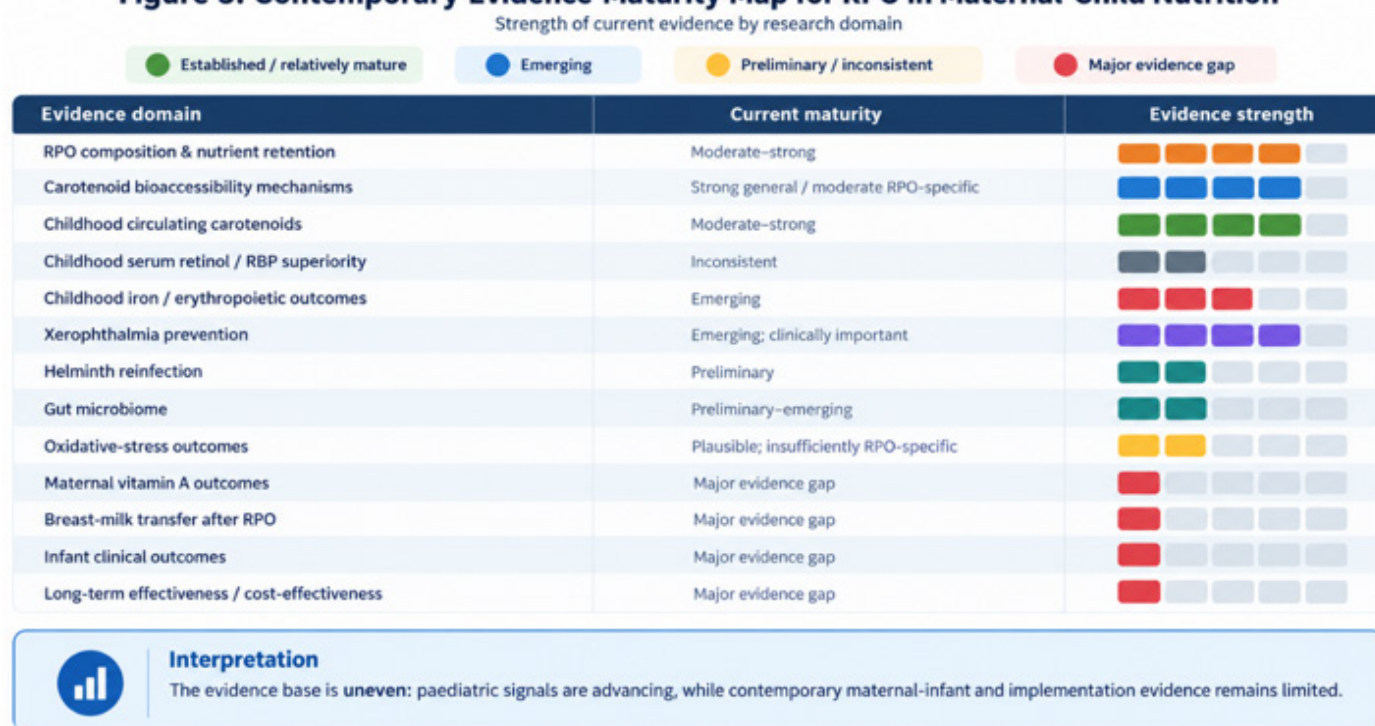


Figure 3: Contemporary Evidence-Maturity Map for RPO in Maternal-Child Nutrition

Figure 3 illustrates that RPO research should not be described either as an evidence-free field or as a mature intervention science. The most defensible description is an uneven evidence base: composition and bioavailability mechanisms are well developed, contemporary paediatric trials provide meaningful signals, but maternal-infant and long-term implementation evidence remain insufficient.

RPO Versus Vitamin A Supplementation and Fortification

It is neither scientifically necessary nor ethically desirable to construct RPO and established vitamin A interventions as competitors. High-dose supplementation has evidence for reducing morbidity and mortality among young children at risk of deficiency. Fortification can improve population micronutrient exposure where appropriate vehicles, industry coverage, and regulatory enforcement exist. Multiple micronutrient powders can simultaneously address several deficiencies in young children.

RPO potentially occupies a different niche. It can be incorporated into meals, locally produced foods, or institutional feeding; it simultaneously provides dietary energy; and its provitamin A is embedded in a lipid matrix. These properties may support repeated physiological exposure rather than intermittent pharmacological dosing.

However, food-based provitamin A also has disadvantages. Composition can vary. Cooking may change carotenoid retention. Dietary compliance may be inconsistent. Sensory preference can affect intake. Precise dosing is more difficult than with capsules, and the intervention adds dietary fat. These charac-

teristics mean that RPO programmes should be compared not simply on efficacy but on net nutritional value, adherence, cost, cultural fit, supply reliability, and opportunity cost.

Safety and Communication

Public communication surrounding RPO needs to avoid two opposite errors. The first is dismissing RPO because it is a fat and therefore treating its micronutrient profile as irrelevant. The second is promoting RPO as a near-universal remedy because it contains carotenoids and tocotrienols.

The appropriate message is conditional. RPO is a nutrient-dense edible oil with demonstrable provitamin-A delivery potential, but clinical value depends on dose, preparation, baseline status, dietary context, and existing interventions. Excessive total energy intake remains relevant, and no edible oil should be presented as a substitute for dietary diversity.

The distinction between provitamin-A carotenoids and preformed vitamin A is also important. β -Carotene conversion is regulated, while pharmacological retinol exposure raises different safety considerations. Nevertheless, programmes should quantify total vitamin A exposure to avoid unnecessary or redundant intervention, particularly in populations already covered by supplements and fortified staples.

Next-Generation Clinical Evidence Agenda

The field now needs trials designed around the limitations revealed by existing evidence rather than repetitions of old biomarker studies. A stronger research programme should connect

exposure verification, multidimensional biomarker assessment, functional outcomes, and implementation measures from the outset.

First: Maternal–infant dyad trials should become a priority. Pregnancy and lactation studies should integrate maternal biomarkers, breast milk, infant status, and clinically meaningful follow-up.

Second: Future child trials should stratify confirmed deficiency, marginal status, and vitamin-A adequacy. This would clarify whether treatment effects are driven primarily by deficiency correction.

Third: Comparators should become more informative. RPO should be compared with ordinary oil, an appropriately fortified oil, standard supplementation where relevant, or dietary strategies matched for energy and food vehicle.

Fourth: Interventions should report actual carotenoid and tocotrienol exposure after processing and storage rather than relying only on formulation targets.

Fifth: Biomarker panels should integrate retinol, RBP, carotenoids, CRP, AGP, iron indices and, where feasible, MRDR or isotope-dilution methods so that changes in circulating exposure can be interpreted against nutrient stores and inflammatory status.

Sixth: Clinically meaningful outcomes should be prespecified. These can include xerophthalmia, morbidity, infection, growth, anaemia phenotype, maternal outcomes, infant status, and ad-

herence.

Seventh: Mechanistic substudies should link oxidative, inflammatory, immune, microbiome, and iron pathways rather than measuring them independently.

Eighth: Interventions should be tested under real-world preparation conditions because household cooking and storage may be more important to effectiveness than nutrient content measured at the factory.

Ninth: Economic and implementation outcomes should be embedded within effectiveness trials, including cost per adequately nourished child, supply-chain reliability, acceptability, household use, and displacement of other foods.

Tenth: Independent replication is essential because some of the most important contemporary RPO evidence comes from a relatively concentrated research programme. This concentration does not invalidate the findings, but confidence in generalisability will increase substantially when different research groups reproduce key results across populations, food vehicles, and health systems.

Figure 4 translates these priorities into a proposed next-generation trial architecture. The sequence links baseline population characterisation, randomisation, verified nutrient exposure, multidimensional biological assessment, functional outcomes, mechanistic modules, implementation outcomes, and long-term replication within one coherent research design.

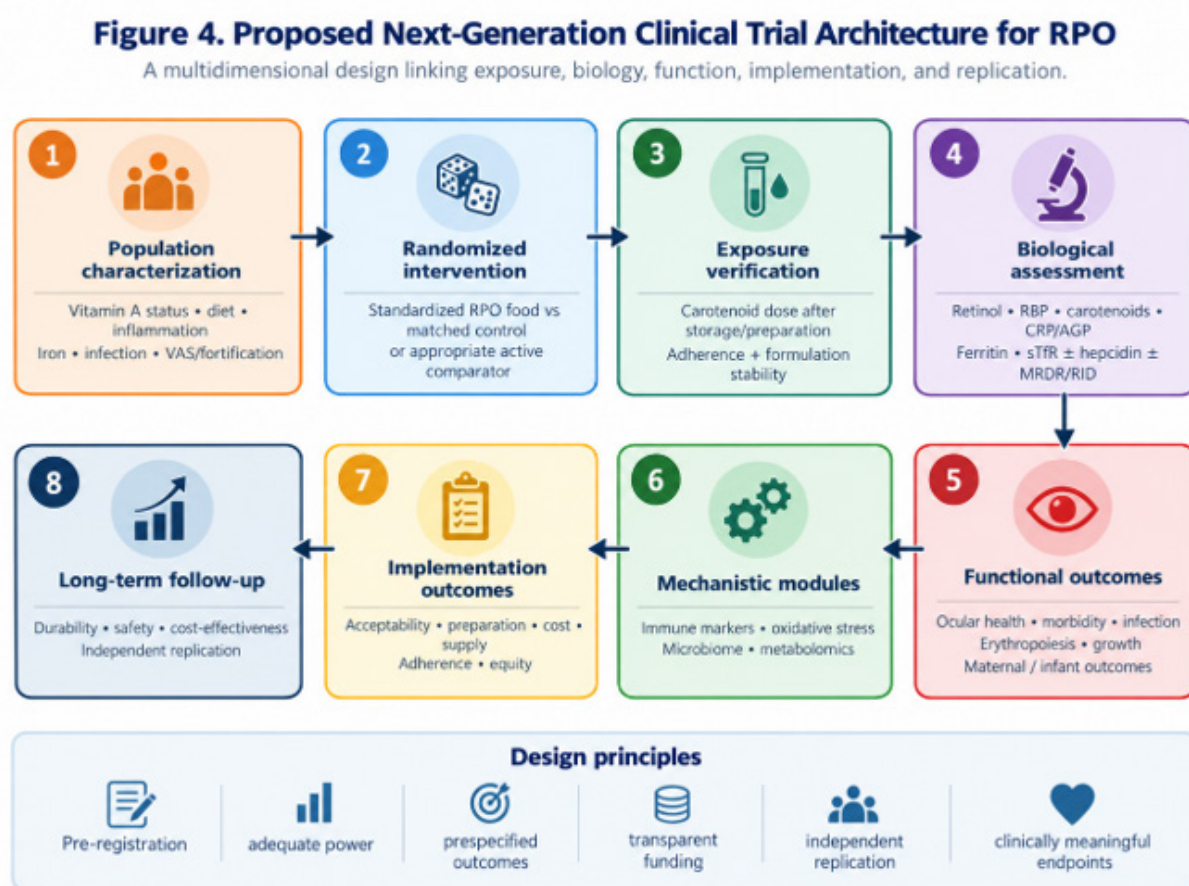


Figure 4: Proposed Next-Generation Clinical Trial Architecture for RPO

Figure 4 reflects the central methodological recommendation of this review: RPO should be evaluated as a complex nutritional intervention operating within a biological and food-system environment. Trials restricted to a single circulating biomarker are unlikely to resolve the remaining questions.

Broader Implications for Food-Based Micronutrient Resilience

The contemporary nutrition environment increasingly challenges the simple distinction between supplementation and food. Fortified blended foods, lipid-based nutrient supplements, multiple micronutrient powders, biofortified crops, commercial fortification, and naturally nutrient-dense foods form a continuum of interventions. The relevant policy question is not which category is ideologically preferable, but which combination delivers adequate nutrients safely, consistently, affordably, and equitably.

RPO may have particular value where edible palm oil is already culturally and economically embedded in the food system. In such contexts, preserving naturally occurring carotenoids during processing could represent a food-system strategy rather than creating an entirely new distribution programme. Conversely, in settings where palm oil is not culturally accepted, locally available, or economically competitive, importing RPO specifically as a vitamin A intervention might offer little advantage over established fortification or supplementation.

Food technology can strengthen this proposition by improving stability, palatability, and carotenoid bioaccessibility. Microencapsulation, Pickering emulsions, and nanoemulsions demonstrate what is technically possible. Yet the most advanced formulation is not necessarily the best public-health product. A simple oil that families reliably consume may outperform a sophisticated nanoformulation that is expensive, unfamiliar, or difficult to manufacture.

This distinction reinforces the meaning of micronutrient resilience. Resilience is not maximised by the highest laboratory bioaccessibility; it emerges when nutrient quality, biological utilisation, food practices, and delivery systems work together. RPO could contribute to such resilience where the full system is favourable.

The same reasoning applies to maternal nutrition. A pregnancy intervention cannot be designed around RPO alone if women remain deficient in iron, folate, zinc, iodine, or protein. Reviews of maternal supplementation and fortified-food programmes indicate that nutritional needs are multidimensional. RPO should therefore be tested as part of a nutritional portfolio, with analyses examining whether its contribution is additive, redundant, or synergistic.

At the child level, micronutrient powders and high-dose supplementation likewise remain relevant. RPO may offer repeated dietary exposure and perhaps additional advantages related to food matrix and carotenoid delivery, but these hypotheses should be assessed through comparative effectiveness research rather than assumed from composition.

Finally, contemporary discussions of hidden hunger should acknowledge that food insecurity and micronutrient inadequacy are increasingly intertwined with climate, food prices, dietary transition, and inequity. Nutrient-dense strategies that can be embedded in local food systems may therefore have value beyond conventional supplementation programmes, provided they are nutritionally justified and sustainably delivered.

Limitations of the Current Evidence and of This Review

Several limitations constrain interpretation. First, contemporary RPO clinical studies remain few compared with the much larger literature on vitamin A supplementation and fortification. The most detailed recent paediatric findings arise from a limited number of interconnected trials, and therefore independent replication is necessary.

Second, available trials differ in baseline vitamin A status, intervention vehicle, population age, and outcomes. An RPO biscuit study cannot automatically be generalised to household cooking oil, pregnant women, infants, or other ethnic and dietary groups.

Third, many proposed RPO mechanisms are inferred from broader vitamin A, carotenoid, tocotrienol, or food-matrix literature. Biological plausibility is valuable for developing hypotheses but is not equivalent to demonstration of RPO-specific clinical effects.

Fourth, vitamin A biomarkers themselves create uncertainty. Serum retinol and RBP are convenient but imperfect, especially during inflammation, whereas advanced methods such as isotope dilution are more resource intensive. This limits direct comparison among studies.

Fifth, oxidative and immune claims remain especially vulnerable to overinterpretation. Changes in individual laboratory markers may not translate into clinically meaningful protection. The same concern applies to microbiome studies, where taxonomic shifts should not be equated automatically with improved health.

Sixth, this article was deliberately designed as a qualitative literature review rather than a systematic review. It therefore emphasises interpretive integration and contemporary conceptual development rather than exhaustive enumeration, formal risk-of-bias scoring, or meta-analysis. This design is appropriate to the broad translational question but does not produce pooled estimates of RPO efficacy.

Conclusion and Future Directions

Red palm oil deserves renewed attention in maternal and child nutrition, but the reason is more sophisticated than its high β -carotene content. RPO combines provitamin-A carotenoids with an intrinsic lipid matrix and additional bioactive compounds, creating a plausible food-based platform for improving micronutrient exposure. Contemporary paediatric trials have substantially strengthened the evidence base by moving beyond simple compositional claims. They demonstrate robust increases in provitamin-A carotenoids and emerging signals involving erythropoiesis, iron status, inflammation, helminth reinfection,

gut microbial ecology, and prevention of xerophthalmia.

At the same time, these studies reveal why serum retinol alone is an inadequate endpoint for the next generation of research. Homeostatic control, infection, and inflammation complicate its interpretation, while clinically meaningful outcomes may change even when between-group serum-retinol differences are small.

Evidence in pregnant and lactating women remains the most important gap. Modern mother–infant dyad trials are needed to determine whether realistic RPO intake can improve maternal vitamin A reserves, breast-milk vitamin A and carotenoid concentrations, infant status, and functional outcomes within contemporary supplementation and fortification environments.

RPO should therefore not be framed as a universal substitute for pharmaceutical vitamin A, synthetic fortification, micronutrient powders, or dietary diversification. Its more defensible role is as a context-dependent complementary food strategy whose value depends on deficiency prevalence, habitual diet, existing intervention coverage, food preparation, acceptability, affordability, local supply, and verified nutrient retention.

The research priority is no longer to prove repeatedly that red palm oil contains β -carotene. The priority is to establish where, for whom, at what dose, in which food vehicle, and alongside which existing interventions RPO generates meaningful maternal and child health benefit. Answering those questions would move RPO research from nutrient composition toward precision public nutrition and genuine micronutrient resilience.

References

1. Bang, Y.-J. (2023). Vitamin A: A key coordinator of host–microbe interactions in the intestine. *BMB Reports*, 56(3), 133–139. <https://doi.org/10.5483/BMBRep.2023-0005>
2. Bezerra, D. S. (2022). Breast milk retinol levels after vitamin A supplementation at different postpartum amounts and intervals. *Nutrients*, 14(17), Article 3570. <https://doi.org/10.3390/nu14173570>
3. Bos, A., van Egmond, M., Mebius, R. (2022). The role of retinoic acid in the production of immunoglobulin A. *Mucosal Immunology*, 15, 562–572. <https://doi.org/10.1038/s41385-022-00509-8>
4. Carretero-Krug, A., Montero-Bravo, A., Morais-Moreno, C., Puga, A. M., Samaniego-Vaesken, M. d. L., Partearroyo, T., & Varela-Moreiras, G. (2024). Nutritional status of breastfeeding mothers and impact of diet and dietary supplementation: A narrative review. *Nutrients*, 16(2), Article 301. <https://doi.org/10.3390/nu16020301>
5. Dewi, N. U., Mahmudiono, T. (2021). Effectiveness of food fortification in improving nutritional status of mothers and children in Indonesia. *International Journal of Environmental Research and Public Health*, 18(4), Article 2133. <https://doi.org/10.3390/ijerph18042133>
6. Eyeberu, A., Getachew, T., Tiruye, G., Balis, B., Tamiru, D., Bekele, H., Abdurke, M., Alemu, A., Dessie, Y., Shiferaw, K., & Debela, A. (2023). Vitamin A deficiency among pregnant women in Ethiopia: A systematic review and meta-analysis. *International Health*, 15(6), 630–643. <https://doi.org/10.1093/inthealth/ihad038>
7. Fahmida, U., Pramesthi, I. L., Kusuma, S., Wurjandaru, G., Izwardy, D. (2022). Problem nutrients and food-based recommendations for pregnant women and under-five children in high-stunting districts in Indonesia. *Current Developments in Nutrition*, 6(5), Article nzac028. <https://doi.org/10.1093/cdn/nzac028>
8. Fite, M. B. (2023). Co-occurrence of iron, folate, and vitamin A deficiency among pregnant women in eastern Ethiopia: A community-based study. *BMC Nutrition*, 9, Article 72. <https://doi.org/10.1186/s40795-023-00724-x>
9. Gannon, B. M., Jones, C., Mehta, S. (2020). Vitamin A requirements in pregnancy and lactation. *Current Developments in Nutrition*, 4(10), Article nzaa142. <https://doi.org/10.1093/cdn/nzaa142>
10. Gannon, B. M., Huey, S. L., Mehta, N. H., Shrestha, N., Lopez-Perez, L., Martinez, R. X., Rogers, L. M., Garcia-Casal, M. N., & Mehta, S. (2025). Selected laboratory-based biomarkers for assessing vitamin A deficiency in at-risk individuals. *Cochrane Database of Systematic Reviews*, 2025(5), Article CD013742. <https://doi.org/10.1002/14651858.CD013742.pub2>
11. Geng, T., Bao, S., Sun, X., Ma, D., Zhang, H., Ge, Q., Liu, X., & Ma, T. (2023). A clarification of concepts related to the digestion and absorption of carotenoids and a new standardized carotenoids bioavailability evaluation system. *Food Chemistry*, 400, Article 134060. <https://doi.org/10.1016/j.foodchem.2022.134060>
12. Guo, Z., Liu, Y., Luo, Y. (2024). Mechanisms of carotenoid intestinal absorption and the regulation of dietary lipids: Lipid transporter-mediated transintestinal epithelial pathways. *Critical Reviews in Food Science and Nutrition*, 64(7), 1791–1816. <https://doi.org/10.1080/10408398.2022.2119204>
13. Imdad, A., Mayo-Wilson, E., Haykal, M. R., Regan, A., Sidhu, J., Smith, A., & Bhutta, Z. A. (2022). Vitamin A supplementation for preventing morbidity and mortality in children from six months to five years of age. *Cochrane Database of Systematic Reviews*, 2022(3), Article CD008524. <https://doi.org/10.1002/14651858.CD008524.pub4>
14. Keats, E. C., Oh, C., Chau, T., Khalifa, D. S., Imdad, A., & Bhutta, Z. A. (2021). Effects of vitamin and mineral supplementation during pregnancy on maternal, birth, child health and development outcomes in low- and middle-income countries: A systematic review. *Campbell Systematic Reviews*, 17(2), Article e1127. <https://doi.org/10.1002/cl2.1127>
15. Keikha, M., Shayan-Moghadam, R., Bahreynian, M., Keshladi, R. (2021). Nutritional supplements and mother's milk composition: A systematic review of interventional studies. *International Breastfeeding Journal*, 16, Article 1. <https://doi.org/10.1186/s13006-020-00354-0>
16. Khor, B.-H., Tiong, H.-C., Tan, S. C., Wong, S. K., Chin, K.-Y., Karupiah, T., Ima-Nirwana, S., & Abdul Gafor, A. H. (2021). Effects of tocotrienols supplementation on markers of inflammation and oxidative stress: A systematic review and meta-analysis of randomized controlled trials. *PLOS ONE*, 16(7), Article e0255205. <https://doi.org/10.1371/journal.pone.0255205>
17. Lee, W. J., Tan, C. P., Sulaiman, R., Hee, Y. Y., Chong, G. H. (2020). Storage stability and degradation kinetics of bioactive compounds in red palm oil microcapsules produced

- with solution-enhanced dispersion by supercritical carbon dioxide: A comparison with the spray-drying method. *Food Chemistry*, 304, Article 125427. <https://doi.org/10.1016/j.foodchem.2019.125427>.
18. Liu, Y., Liu, Y. (2024). Construction of lipid-biomacromolecular compounds for loading and delivery of carotenoids: Preparation methods, structural properties, and absorption-enhancing mechanisms. *Critical Reviews in Food Science and Nutrition*, 64(6), 1653-1676. <https://doi.org/10.1080/10408398.2022.2118229>.
 19. Loganathan, R., Ahmad Tarmizi, A. H., Vethakkan, S. R., Teng, K.-T. (2020a). Retention of carotenes and vitamin E, and physico-chemical changes occurring upon heating red palm olein using deep-fat fryer, microwave oven and conventional oven. *Journal of Oleo Science*, 69(3), 167–183. <https://doi.org/10.5650/jos.ess19209>
 20. Loganathan, R., Ahmad Tarmizi, A. H., Vethakkan, S. R., Teng, K.-T. (2020b). Storage stability assessment of red palm olein in comparison to palm olein. *Journal of Oleo Science*, 69(10), 1163–1179. <https://doi.org/10.5650/jos.ess20036>.
 21. Loganathan, R., Ahmad Tarmizi, A. H., Vethakkan, S. R., & Teng, K.-T. (2020c). Thermal stability and sensory acceptance of cupcakes containing red palm olein. *Journal of Oleo Science*, 69(7), 671–676. <https://doi.org/10.5650/jos.ess19253>.
 22. Lowe, N. M. (2021). The global challenge of hidden hunger: Perspectives from the field. *Proceedings of the Nutrition Society*, 80(3), 283–289. <https://doi.org/10.1017/S0029665121000902>.
 23. Luo, H., Geng, J., Zeiler, M., Nieckula, E., Sandalinas, F., Williams, A., Young, M. F., & Suchdev, P. S. (2023). A practical guide to adjust micronutrient biomarkers for inflammation using the BRINDA method. *The Journal of Nutrition*, 153(4), 1265-1272. <https://doi.org/10.1016/j.tjnut.2023.02.016>.
 24. 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), Article 4402. <https://doi.org/10.3390/molecules30224402>.
 25. Maurya, V. K., Shakya, A., Aggarwal, M., Gothandam, K. M., Bohn, T., & Pareek, S. (2021). Fate of β -carotene within loaded delivery systems in food: State of knowledge. *Antioxidants*, 10(3), Article 426. <https://doi.org/10.3390/antiox10030426>.
 26. McDonald, C. M., Wessells, K. R., Stewart, C. P., Dewey, K. G., de Pee, S., Rana, R., Hafeez-Ur-Rehman, H., Mwangi, M. N., & Hess, S. Y. (2024). Perinatal intervention strategies providing food with micronutrients to pregnant and breastfeeding women in low- and middle-income countries : A scoping review. *Maternal & Child Nutrition*, 20(4), Article e13681. <https://doi.org/10.1111/mcn.13681>.
 27. Mejia, L. A., Erdman, J. W., Jr. (2025). Impact of vitamin A deficiency on iron metabolism and anemia: A historical perspective and research advances. *Nutrition Reviews*, 83(3), 577–585. <https://doi.org/10.1093/nutrit/nuae183>.
 28. Meléndez-Martínez, A. J. (2022). A comprehensive review on carotenoids in foods and feeds: Status quo, applications, patents, and research needs. *Critical Reviews in Food Science and Nutrition*, 62(8), 1999–2049. <https://doi.org/10.1080/10408398.2020.1867959>.
 29. Melse-Boonstra, A. (2020). Bioavailability of micronutrients from nutrient-dense whole foods: Zooming in on dairy, vegetables, and fruits. *Frontiers in Nutrition*, 7, Article 101. <https://doi.org/10.3389/fnut.2020.00101>.
 30. Mohan, K., Makebe, C. W., Jayamurthy, P., & Nisha, P. (2022). Red palm oil Pickering emulsion with pectin yields improved in vitro beta carotene bioaccessibility and oil stability. *Journal of Food Processing and Preservation*, 46, Article e16930. <https://doi.org/10.1111/jfpp.16930>.
 31. Namaste, S. M. L., Ou, J., Williams, A. M., Young, M. F., Yu, E. X., & Suchdev, P. S. (2020). Adjusting iron and vitamin A status in settings of inflammation: A sensitivity analysis of the Biomarkers Reflecting Inflammation and Nutritional Determinants of Anemia (BRINDA) approach. *The American Journal of Clinical Nutrition*, 112(Suppl. 1), 458S–467S. <https://doi.org/10.1093/ajcn/nqaa141>.
 32. Nankumbi, J., Grant, F., Sibeko, L., Mercado, E., O’Neil, K., & Cordeiro, L. S. (2023). Effects of food-based approaches on vitamin A status of women and children: A systematic review. *Advances in Nutrition*, 14(6), 1436–1452. <https://doi.org/10.1016/j.advnut.2023.08.009>.
 33. Ohanenye, I. C., Emenike, C. U., Mensi, A., Medina-Godoy, S., Jin, J., Ahmed, T., Sun, X., & Udenigwe, C. C. (2021). Food fortification technologies: Influence on iron, zinc and vitamin A bioavailability and potential implications on micronutrient deficiency in sub-Saharan Africa. *Scientific African*, 11, Article e00667. <https://doi.org/10.1016/j.sciaf.2020.e00667>.
 34. Opperman, M., Olivier, L. (2023). Nutritional status assessment and intervention with a red palm oil biscuit among preschool children attending informal crèches, in the Eastern Cape, South Africa. *African Journal of Food, Agriculture, Nutrition and Development*, 23(4), 23099–23119. <https://doi.org/10.18697/ajfand.119.21685>.
 35. Palmer, A. C., Bedsaul-Fryer, J. R., Stephensen, C. B. (2024). Interactions of nutrition and infection: The role of micronutrient deficiencies in the immune response to pathogens and implications for child health. *Annual Review of Nutrition*, 44, 99–124. <https://doi.org/10.1146/annurev-nutr-062122-014910>.
 36. Piskin, E., Cianciosi, D., Gulec, S., Tomas, M., Capanoglu, E. (2022). Iron absorption: Factors, limitations, and improvement methods. *ACS Omega*, 7(24), 20441–20456. <https://doi.org/10.1021/acsomega.2c01833>.
 37. Roche, F. C., Harris-Tryon, T. A. (2021). Illuminating the role of vitamin A in skin innate immunity and the skin microbiome: A narrative review. *Nutrients*, 13(2), Article 302. <https://doi.org/10.3390/nu13020302>.
 38. Stevens, G. A., Beal, T., Mbuya, M. N. N., Luo, H., Neufeld, L. M. (2022). Micronutrient deficiencies among preschool-aged children and women of reproductive age worldwide: A pooled analysis of individual-level data from population-representative surveys. *The Lancet Global Health*, 10(11), e1590–e1599. [https://doi.org/10.1016/S2214-109X\(22\)00367-9](https://doi.org/10.1016/S2214-109X(22)00367-9).
 39. Suchdev, P. S., Jefferds, M. E. D., Ota, E., da Silva Lopes, K., & De-Regil, L. M. (2020). Home fortification of foods with multiple micronutrient powders for health and nutrition in children under two years of age. *Cochrane Database of Systematic Reviews*, 2020(2), Article CD008959. <https://doi.org/10.1002/14651858.CD008959.pub3>.
 40. Suri, D. J., Wirth, J. P., Adu-Afarwuah, S., Petry, N., Rohner,

- F., Sheftel, J., & Tanumihardjo, S. A. (2021). Inflammation adjustments to serum retinol and retinol-binding protein improve specificity but reduce sensitivity when estimating vitamin A deficiency compared with the modified relative dose-response test in Ghanaian children. *Current Developments in Nutrition*, 5(8), Article nzab098. 41–59. <https://doi.org/10.1093/cdn/nzab098>.
41. Suri, D. J. (2023). Association between biomarkers of inflammation and total liver vitamin A reserves estimated by 13C-retinol isotope dilution among preschool children in 5 African countries. *The Journal of Nutrition*, 153(3), 622–635. <https://doi.org/10.1016/j.tjnut.2022.10.012>.
 42. Tan, C.-H., et al. (2026). Recent advancements in red palm oil nanoemulsion systems: A comprehensive review of formulations, characterization, and functional applications. *Journal of the Science of Food and Agriculture*, 106(9), 5112–5124. <https://doi.org/10.1002/jsfa.70387>.
 43. Tan, P. Y., Loganathan, R., Teng, K.-T., Lee, S. C., Mohd Johari, S. N., Selvaduray, K. R., Ngui, R., & Lim, Y. A.-L. (2023). Red palm olein-enriched biscuit supplementation lowers *Ascaris lumbricoides* reinfection at 6-month after anthelmintic treatment among schoolchildren with vitamin A deficiency. *Acta Tropica*, 240, Article 106860. <https://doi.org/10.1016/j.actatropica.2023.106860>.
 44. Tan, P. Y., Loganathan, R., Teng, K.-T., Mohd Johari, S. N., Lee, S. C., Selvaduray, K. R., Ngui, R., & Lim, Y. A.-L. (2024). Supplementation of red palm olein-enriched biscuits improves levels of provitamin A carotenes, iron, and erythropoiesis in vitamin A-deficient primary schoolchildren: A double-blinded randomised controlled trial. *European Journal of Nutrition*, 63(3), 905–918. <https://doi.org/10.1007/s00394-023-03314-6>.
 45. Tan, P. Y., Lim, C. C., Seng, K. B. H., Loganathan, R., Lim, Y. A.-L., Teng, K.-T., Mohd Johari, S. N., Selvaduray, K. R., & Ramli, N. (2025a). Red palm olein supplementation as a potential preventive solution for xerophthalmia among vitamin A-deficient primary schoolchildren: A cluster randomized controlled trial. *European Journal of Clinical Nutrition*, 79, 928–936. <https://doi.org/10.1038/s41430-025-01620-2>.
 46. Tan, P. Y., Loganathan, R., Lee, S. C., Mohd Johari, S. N., Teng, K.-T., Selvaduray, K. R., et al. (2025b). Red palm olein biscuit supplementation modulates gut microbiota in vitamin A deficient rural Malaysian schoolchildren: A randomised controlled trial. *Nature Communications*, 16, Article 9341. <https://doi.org/10.1038/s41467-025-64395-x>.
 47. Terao, J. (2023). Revisiting carotenoids as dietary antioxidants for human health and disease prevention. *Food & Function*, 14(17), 7799–7824. <https://doi.org/10.1039/D3FO02330C>.
 48. Wali, N., Agho, K., & Renzaho, A. M. N. (2022). Hidden hunger and child undernutrition in South Asia: A meta-ethnographic systematic review. *Asia Pacific Journal of Clinical Nutrition*, 31(4), 713–739. [https://doi.org/10.6133/apjcn.202212_31\(4\).0014](https://doi.org/10.6133/apjcn.202212_31(4).0014).
 49. Wang, Y., Yang, F., Liu, T., Zhao, C., Gu, F., Du, H., Wang, F., Zheng, J., & Xiao, H. (2024). Carotenoid fates in plant foods: Chemical changes from farm to table and nutrition. *Critical Reviews in Food Science and Nutrition*, 64(5), 1237–1255. <https://doi.org/10.1080/10408398.2022.2115002>.
 50. Weffort, V. R. S., & Lamounier, J. A. (2024). Hidden hunger—A narrative review. *Jornal de Pediatria*, 100(Suppl. 1), S10–S17. <https://doi.org/10.1016/j.jped.2023.08.009>.
 51. Widjaja-Adhi, M. A. K., & Golczak, M. (2020). The molecular aspects of absorption and metabolism of carotenoids and retinoids in vertebrates. *Biochimica et Biophysica Acta—Molecular and Cell Biology of Lipids*, 1865(11), Article 158571. <https://doi.org/10.1016/j.bbalip.2019.158571>.
 52. Yao, C. H., Lee, C. J., Tan, S. N., Poon, D. T. S., Chong, C. Y. E., & Pui, L. P. (2021). Red palm oil: A review on processing, health benefits and its application in food. *Journal of Oleo Science*, 70(9), 1201–1210. <https://doi.org/10.5650/jos.ess21108>.
 53. Yao, Y., Tan, P., & Kim, J. E. (2022). Effects of dietary fats on the bioaccessibility and bioavailability of carotenoids: A systematic review and meta-analysis of in vitro studies and randomized controlled trials. *Nutrition Reviews*, 80(4), 741–761. <https://doi.org/10.1093/nutrit/nuab098>.
 54. Yao, Y., Yang, Z., Yin, B., Goh, H. M., Toh, D. W. K., & Kim, J. E. (2023). Effects of dietary fat type and emulsification on carotenoid absorption: A randomized crossover trial. *The American Journal of Clinical Nutrition*, 117(5), 1017–1025. <https://doi.org/10.1016/j.ajcnut.2023.03.011>.
 55. Zainal, Z., Khaza'ai, H., Radhakrishnan, A. K., & Chang, S. K. (2022). Therapeutic potential of palm oil vitamin E-derived tocotrienols in inflammation and chronic diseases: Evidence from preclinical and clinical studies. *Food Research International*, 156, Article 111175. <https://doi.org/10.1016/j.foodres.2022.111175>.
 56. Zhang, H., Ren, X., Yang, Z., & Lai, J. (2022). Vitamin A concentration in human milk: A meta-analysis. *Nutrients*, 14(22), Article 4844. <https://doi.org/10.3390/nu14224844>.
 57. Zhang, Y., Lu, Y., Wang, S., Yang, L., Xia, H., & Sun, G. (2021). Excessive vitamin A supplementation increased the incidence of acute respiratory tract infections: A systematic review and meta-analysis. *Nutrients*, 13(12), Article 4251. <https://doi.org/10.3390/nu13124251>.
 58. Zhao, T. (2022). Global burden of vitamin A deficiency in 204 countries and territories from 1990–2019. *Nutrients*, 14(5), Article 950. <https://doi.org/10.3390/nu14050950>.
 59. Zhuang, C., Yuan, J., Du, Y., Zeng, J., Sun, Y., Wu, Y., Gao, X.-H., & Chen, H.-D. (2022). Effects of oral carotenoids on oxidative stress : A systematic review and meta-analysis of studies in the recent 20 years. *Frontiers in Nutrition*, 9, Article 754707. <https://doi.org/10.3389/fnut.2022.754707>.

Copyright: ©2026 Loso Judijanto. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.