



# Red Palm Oil as a Source of Provitamin A Carotenoids: Bioavailability, Microencapsulation Strategies, and Therapeutic Applications in Nutritional Deficiency and Disease

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## Abstract

Red Palm Oil (RPO) is one of the richest natural dietary sources of provitamin A carotenoids, notably  $\alpha$ -carotene,  $\beta$ -carotene, and lycopene, along with vitamin E isomers and other antioxidants that support human health. These fat-soluble carotenoids are efficiently absorbed, distributed mainly to the liver and adipose tissue, and partially converted into retinol, providing a sustainable strategy to address Vitamin A Deficiency (VAD) in vulnerable populations. Randomised controlled trials and meta-analyses indicate that RPO supplementation can increase serum retinol and  $\beta$  carotene concentrations and reduce the risk of VAD in children and adults. However, carotenoids are chemically unstable, being highly susceptible to oxidation, light, and heat, which motivates the development of microencapsulation and nanoemulsion systems to preserve their stability and bioavailability. Recent systematic reviews show that spray drying and supercritical CO<sub>2</sub> based methods (SEDS) can achieve high microencapsulation efficiency and retain most carotenoid content. In contrast, RPO based nanoemulsions improve dispersibility, bioaccessibility, and functional performance in nutraceutical and pharmaceutical products. Emerging data also link RPO formulations to antioxidant, anti-inflammatory, dermatological, and gut microbiota-modulating effects, broadening its therapeutic potential beyond classical VAD programs. This mini review synthesises recent evidence (since 2020) on (i) the carotenoid composition and stability of RPO, (ii) bioavailability and intervention studies in nutritional deficiency, (iii) microencapsulation and nanoformulation strategies, and (iv) therapeutic applications and safety considerations, highlighting research gaps relevant to biomedical translation.

**Keywords:** Red palm oil, Provitamin A carotenoids, Microencapsulation, Bioavailability, Vitamin A deficiency, Nanoemulsion, Nutraceuticals, Oxidative stress, Functional foods, Gut microbiota

**JEL Classification Codes:** I12; (Health Behaviour), I15; (Health and Economic Development), I18; (Government Policy; Regulation; Public Health), L66; (Food; Beverages; Cosmetics), O13; (Economic Development: Agriculture; Natural Resources)

## Introduction

Vitamin A Deficiency (VAD) remains a major public health problem in many low- and middle-income countries, particularly

affecting preschool children and women of reproductive age. VAD contributes to preventable blindness, increased susceptibility to infection, impaired growth, and elevated child mortality, and



therefore features prominently in global nutrition and development agendas. Conventional interventions rely on high-dose vitamin A supplementation and fortification of staple foods, but these strategies face challenges with coverage, adherence, cost, and sustainability, especially in rural and food-insecure settings [1-6]. Red Palm Oil (RPO)—minimally processed oil obtained from the mesocarp of the oil palm (*Elaeis guineensis*)—is emerging as a locally available, food-based source of provitamin A carotenoids that could complement or partially replace capsule based interventions. Unlike fully refined palm oil, RPO retains high concentrations of  $\alpha$ -carotene,  $\beta$ -carotene, lycopene, and other carotenoids, conferring a characteristic deep orange-red colour and strong antioxidant capacity. These fat-soluble pigments are absorbed with dietary lipids, converted to retinol in the intestine and liver, and stored in hepatic reserves, thereby supporting vitamin A status over time [7-13].

Meta analyses of randomised controlled trials indicate that RPO consumption improves serum retinol and  $\beta$  carotene levels

and significantly reduces the risk of VAD, supporting its biological efficacy as a functional food. More recently, attention has shifted toward innovative formulations, including microencapsulated RPO powders, nanoemulsions, and functional foods (e.g., RPO enriched biscuits), to enhance stability, sensory acceptance, and bioavailability. At the same time, novel findings link RPO to antioxidant, anti-inflammatory, dermatological, and gut microbiota-modulating effects, suggesting broader biomedical utility beyond correction of VAD. *eduvest* [10,14-19]. This mini review focuses on RPO as a source of provitamin A carotenoids, emphasising (i) its carotenoid composition and stability, (ii) bioavailability and human intervention data in VAD and related conditions, (iii) microencapsulation and nanoformulation strategies, and (iv) therapeutic applications and safety profile. The goal is to provide a concise but critical synthesis relevant to biomedical researchers, nutrition scientists, and clinicians considering the incorporation of RPO based products into nutrition and health interventions [20]. An overview of RPO as a carotenoid-rich nutritional and formulation platform is presented in Figure 1.

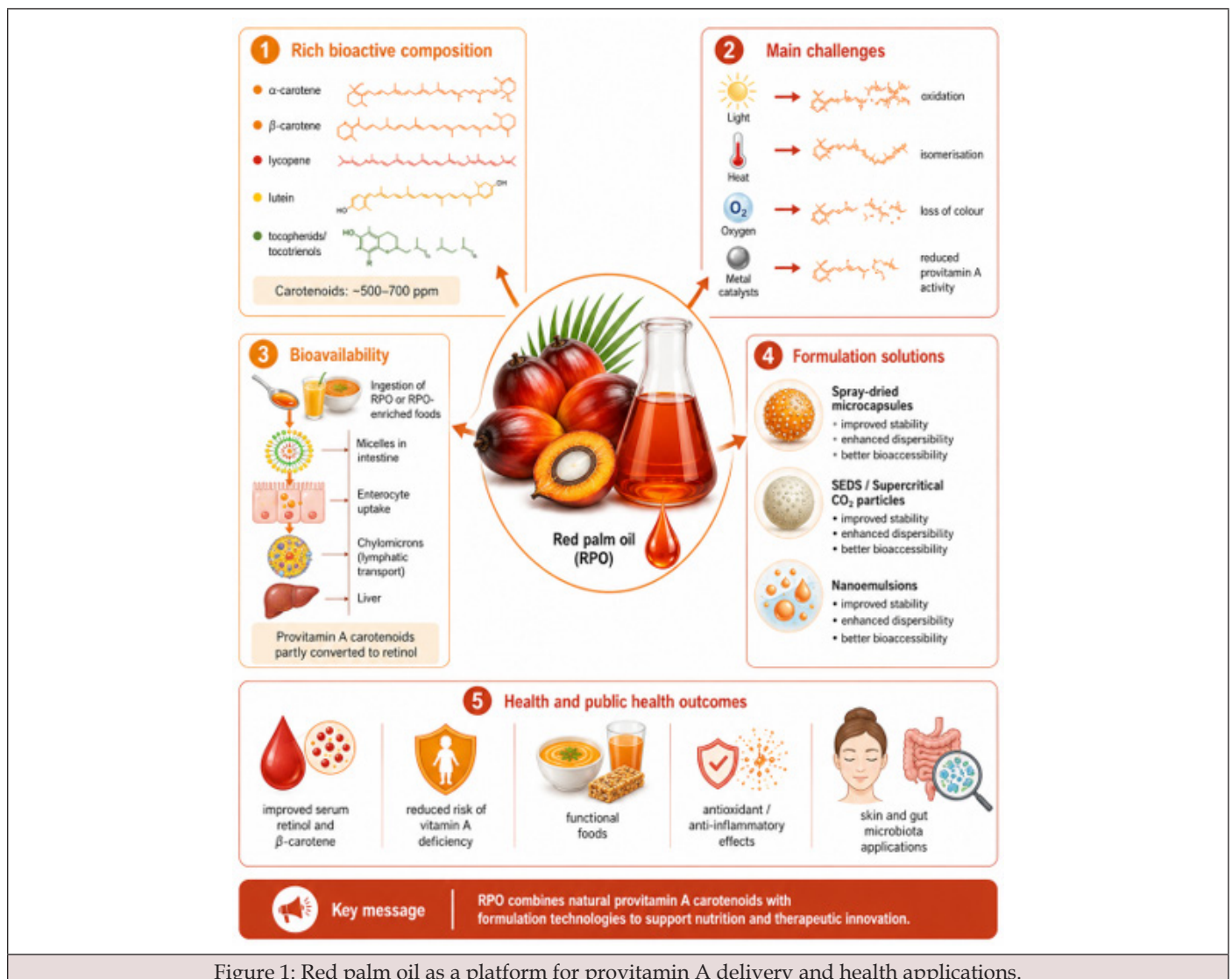


Figure 1: Red palm oil as a platform for provitamin A delivery and health applications.

Red palm oil is positioned in this review as a multifunctional nutritional platform because it combines a naturally rich provitamin A carotenoid profile with lipid-soluble antioxidant compounds and formulation potential. Figure 1 summarises the central logic of the review: RPO contains  $\alpha$ -carotene,  $\beta$ -carotene, lycopene, lutein, tocopherols, and tocotrienols; these bioactives support vitamin A status and antioxidant activity, but they are vulnerable to degradation during processing and storage. The Figure also introduces microencapsulation and nanoemulsion strategies as technological solutions that improve stability, dispersibility, bioaccessibility, and practical use in functional foods and nutraceutical products.

## Carotenoid Composition and Stability in Red Palm Oil

### Factors Affecting Carotenoid Degradation

### Carotenoid Profile and Antioxidant Matrix

RPO is distinguished from other edible oils by its exceptionally high carotenoid content, typically in the range of 500–700 ppm, which is several folds higher than that of commonly consumed fruits and vegetables such as papaya, mango, sweet potato, pumpkin, and carrot on a per fat basis. The major carotenoids include  $\alpha$ -carotene and  $\beta$ -carotene, both with provitamin A activity, and non-provitamin A carotenoids such as lycopene and lutein, which contribute additional antioxidant and photoprotective functions. Recent compositional analyses confirm that minimally processed RPO retains a balanced profile of saturated and unsaturated fatty acids together with tocopherols and tocotrienols, creating a synergistic antioxidant matrix that supports carotenoid stability and biological activity [7,14,21-24].

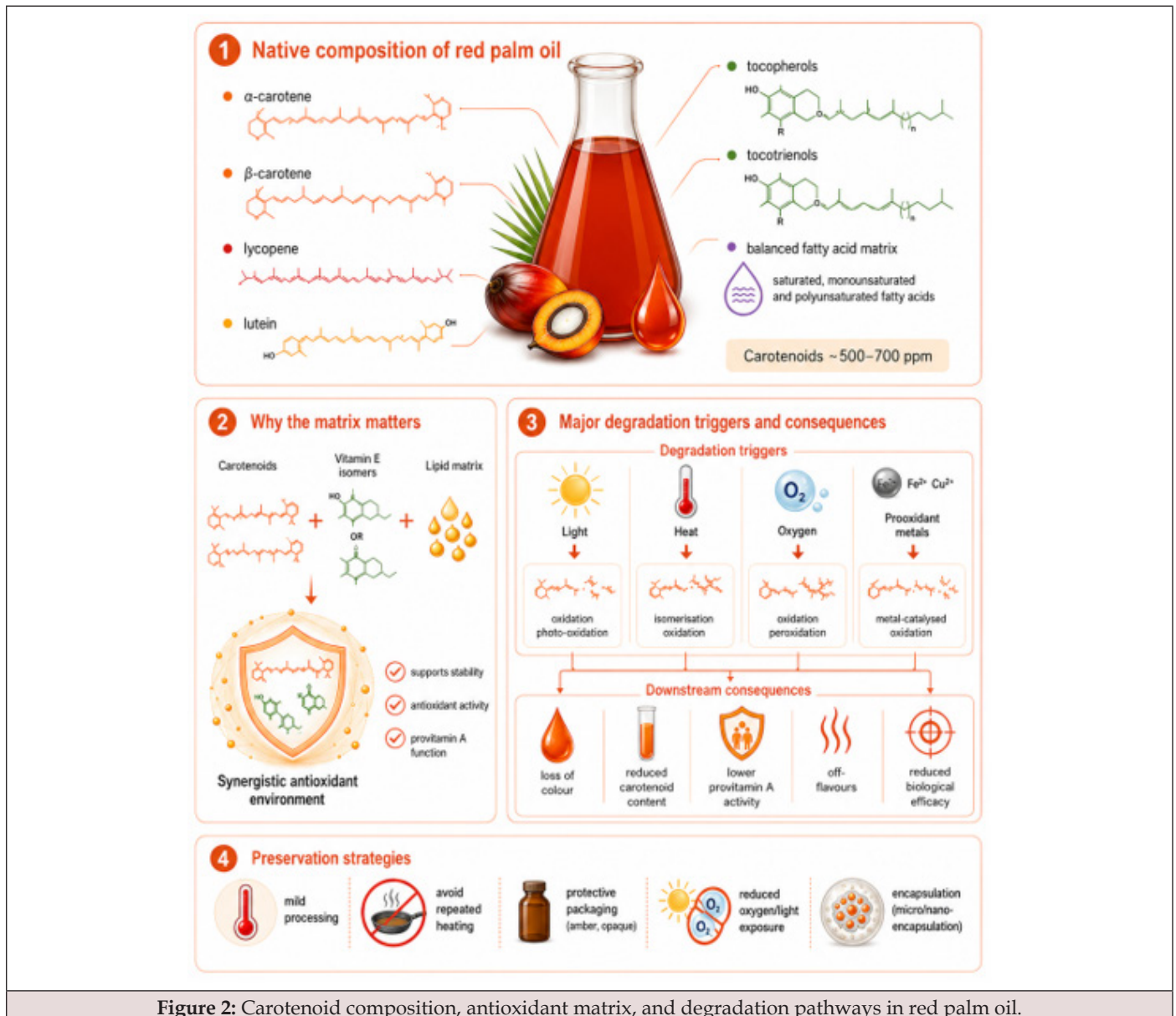


Figure 2: Carotenoid composition, antioxidant matrix, and degradation pathways in red palm oil.

Despite its rich carotenoid content, RPO is highly susceptible to oxidative degradation, especially under light exposure, elevated temperatures, oxygen, and prooxidant metals, leading to loss of colour and bioactivity. The conjugated double bond system of carotenoids makes them prone to isomerisation and oxidation, which can decrease provitamin A activity and generate off-flavours. Processing conditions such as deodorisation, repeated heating, and long storage significantly reduce carotenoid levels, whereas mild refining and appropriate packaging help preserve them [7,16,25-28]. Microencapsulation and formulation studies demonstrate that process parameters—including inlet air temperature, feed flow rate, and wall material composition for spray drying; pressure and co solvent conditions for supercritical CO<sub>2</sub> methods; and emulsifier type and droplet size in emulsions—strongly influence carotenoid retention and oxidative stability. Integrating RPO into stable microcapsules or nanoemulsions\*\* thus, represents a key

strategy to protect carotenoids during processing, storage, and gastrointestinal transit [19,29-33]. The relationship between RPO composition, antioxidant protection, degradation triggers, and preservation strategies is summarised in Figure 2. Figure 2 illustrates the compositional and stability basis for the biological value of RPO. It shows that RPO contains provitamin A carotenoids, non-provitamin A carotenoids, vitamin E isomers, and a lipid matrix that together create a synergistic antioxidant environment. At the same time, the figure highlights the major degradation triggers—light, heat, oxygen, and prooxidant metals—that promote oxidation, isomerisation, colour loss, lower carotenoid content, reduced provitamin A activity, and off-flavour formation. The preservation strategies shown in the figure support the need for mild processing, protective packaging, reduced oxygen/light exposure, and encapsulation.

## Bioavailability of Carotenoids from Red Palm Oil

### Absorption and Metabolism

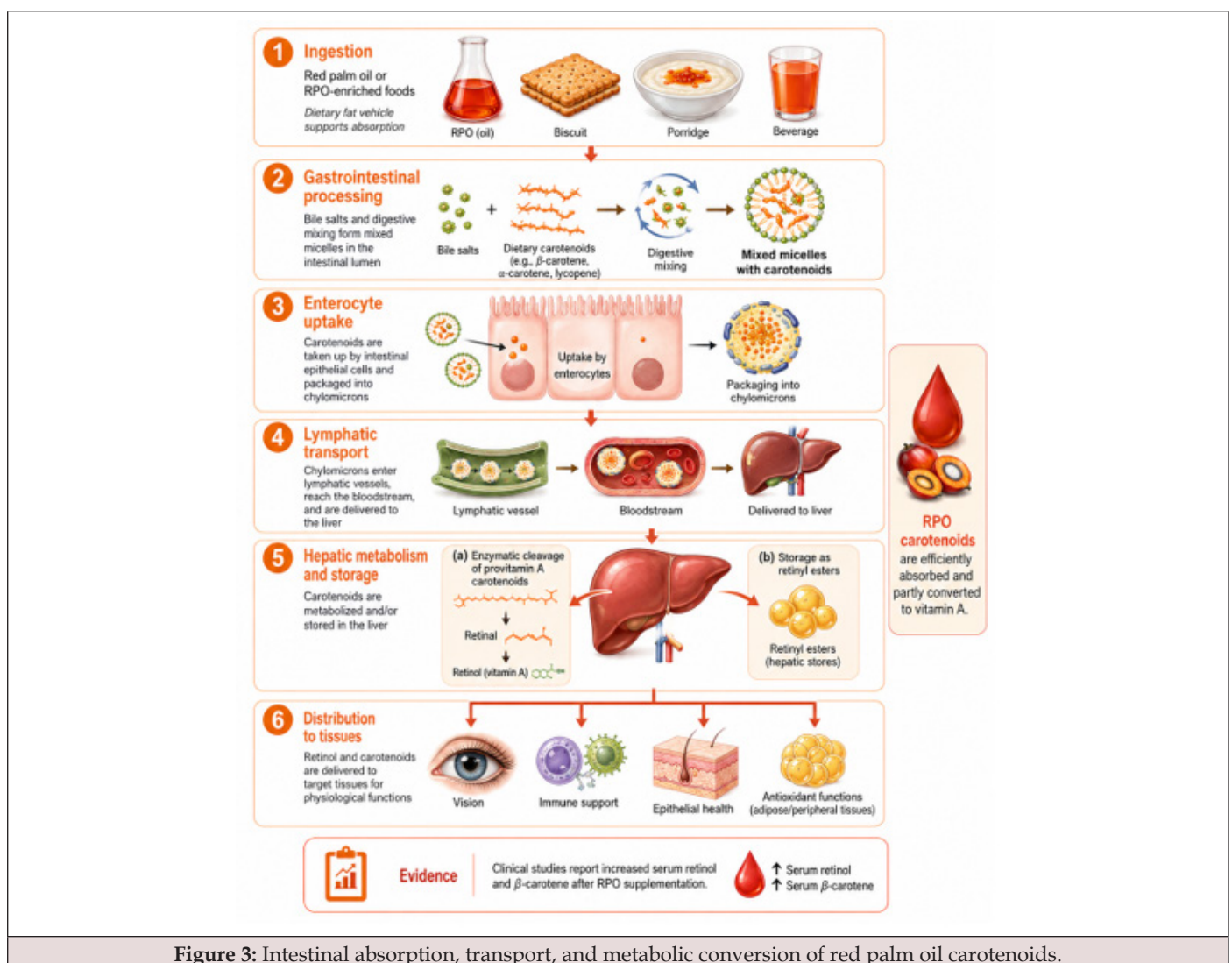


Figure 3: Intestinal absorption, transport, and metabolic conversion of red palm oil carotenoids.

Carotenoids in RPO are fat soluble, and their gastrointestinal absorption follows the general pathway of dietary lipids: incorporation into mixed micelles with bile salts and dietary fat, uptake by enterocytes, incorporation into chylomicrons, and transport via the lymphatic system to the liver and peripheral tissues. Controlled studies indicate that a minimum of ~5 g of dietary fat is required for optimal carotenoid absorption, a criterion naturally fulfilled by oil-based vehicles such as RPO. Once in the liver, provitamin A carotenoids are enzymatically cleaved to retinal and reduced to retinol, which is stored mainly as retinyl esters, while a fraction of unmetabolized carotenoids is redistributed to other tissues [34-39]. Earlier pharmacokinetic experiments, conducted before 2020, showed that RPO-derived  $\alpha$  and  $\beta$ -carotene are efficiently absorbed and converted to vitamin A, with plasma carotene and retinol levels increasing after supplementation. More recent comprehensive reviews reaffirm that fat soluble carotenoids in RPO exhibit favourable ADME/ADMET characteristics, including good oral absorption, tissue distribution, and metabolic conversion to retinol, while maintaining antioxidant functions in target tissues [7,40-42]. The absorption, transport, hepatic conversion, storage, and tissue distribution of RPO carotenoids are depicted in Figure 3.

Figure 3 explains the biological pathway through which RPO carotenoids become nutritionally active. After ingestion, the lipid matrix of RPO supports the incorporation of carotenoids into mixed micelles during gastrointestinal digestion. These micelles facilitate uptake by enterocytes, packaging into chylomicrons, and lymphatic transport to the bloodstream and liver. In the liver, provitamin A carotenoids may be cleaved to retinal and converted to retinol, stored as retinyl esters, or distributed to peripheral tissues where they contribute to vision, immune support, epithelial health, and antioxidant functions.

### Human Intervention Studies and VAD Outcomes

A key body of evidence comes from Randomised Controlled Trials (RCTs) and meta-analyses evaluating RPO for the prevention and treatment of VAD. A meta-analysis including nine RCTs reported that RPO significantly reduces the risk of VAD (relative risk  $\approx 0.55$ ) and increases serum retinol and  $\beta$  carotene concentrations in both children and adults, confirming biological efficacy. The analysis also noted substantial heterogeneity in dosage, duration, and baseline nutritional status, highlighting the need for standardised protocols [10,17,42-45]. More recently, a double blind, randomised controlled trial in vitamin A deficient Malaysian schoolchildren evaluated 6-month supplementation with red palm olein (RPO)-enriched biscuits versus palm olein-enriched biscuits as control. Beyond improving vitamin A status, the RPO biscuits significantly modulated gut microbiota composition, increasing the abundance of potentially beneficial taxa and shifting microbial metabolic pathways associated with vitamin A metabolism and immune function, suggesting interactions between carotenoid intake and the gut ecosystem. These findings expand the potential benefits of RPO from micronutrient repletion to microbiota mediated health

effects [17,46].

### Bioavailability in Microencapsulated and Nanoemulsion Forms

Systematic reviews of palm oil carotenoid microencapsulation indicate that, despite processing stresses, microencapsulated RPO can maintain high carotenoid content and favourable bioavailability. A recent literature review concluded that various microencapsulation methods—spray drying, complex coacervation, and supercritical CO<sub>2</sub> based techniques—achieve good encapsulation efficiency and preserve carotenoid content within standard ranges, supporting their use in functional foods. The supercritical CO<sub>2</sub> (SEDS) method often yields the best microcapsule quality, whereas spray drying is considered the most practical for commercial production, despite slightly lower carotenoid retention [20,31,47-52]. Parallel developments in RPO nanoemulsion systems show that reducing droplet size to the nanoscale enhances the dispersibility, physical stability, and *in vitro* bioaccessibility of carotenoids and can potentiate antioxidant and anti-inflammatory effects in biological models. Recent work on RPO Nanoemulsions (RPO NEs) demonstrates improved aqueous dispersion, increased simulated intestinal bioaccessibility, and greater antioxidant capacity compared with coarse emulsions or bulk oil, underscoring the potential of nanoformulations for oral delivery of carotenoids [53-58].

### Microencapsulation and Formulation Technologies

#### Spray Drying and Wall Materials

Spray drying is currently the most widely used technique for producing RPO microcapsules suitable for incorporation into powdered foods, beverages, and supplements. Common wall materials include gum arabic, maltodextrin, modified starches, and proteins, which form a protective matrix around RPO droplets. Studies report microencapsulation efficiencies typically between ~60–85%, with carotenoid retention remaining high (e.g., about 2775  $\mu\text{g/g}$  oil retained from an initial 2910  $\mu\text{g/g}$  after spray drying under optimised conditions). Process optimisation focusing on solids content, inlet air temperature, feed rate, and emulsifier concentration is essential to maximise encapsulation efficiency and colour retention while limiting oxidation and off-flavours [19,29,31,59-61].

#### Supercritical CO<sub>2</sub> Based Seds Technique

The solution enhanced dispersion by supercritical CO<sub>2</sub> (SEDS) technique has attracted interest for high value RPO formulations. In this process, an RPO-wall material solution is atomised into a chamber containing supercritical CO<sub>2</sub>, promoting rapid solvent removal and particle formation. Comparative studies show that SEDS produced microcapsules can achieve microencapsulation efficiencies >90%, with enhanced carotene retention and improved

particle morphology compared with conventional spray drying. However, SEDS requires specialised equipment and a higher capital investment, which may limit its application to pharmaceutical or high-value nutraceutical products rather than mass-market staples [20,50,51,62,63].

### Nanoemulsions and Advanced Delivery Systems

Oil in water nanoemulsions, prepared using high pressure homogenization, ultrasonication, or spontaneous emulsification, offer another versatile platform for delivering RPO carotenoids. Recent reviews describe RPO based nanoemulsion systems with droplet sizes below 200 nm that exhibit excellent physical stability, improved bioavailability, and enhanced antioxidant and anti-inflammatory properties compared with conventional emulsions.

Such systems can be incorporated into functional beverages, enteral nutrition formulas, and topical preparations, or further processed into spray dried powders [14,58,64,65].

A 2025 review of pharmaceutical formulation strategies from RPO emphasises that nanoemulsions, self-emulsifying drug delivery systems, and solid lipid carriers based on RPO can improve the solubility, permeability, and controlled release of lipophilic bioactives, including carotenoids and co-formulated drugs. These approaches align RPO with broader trends in lipid-based drug delivery, expanding potential applications into dermatology, ophthalmology, and chronic disease management [53]. The major encapsulation and nanoformulation strategies for improving RPO carotenoid stability and delivery are compared in Figure 4.

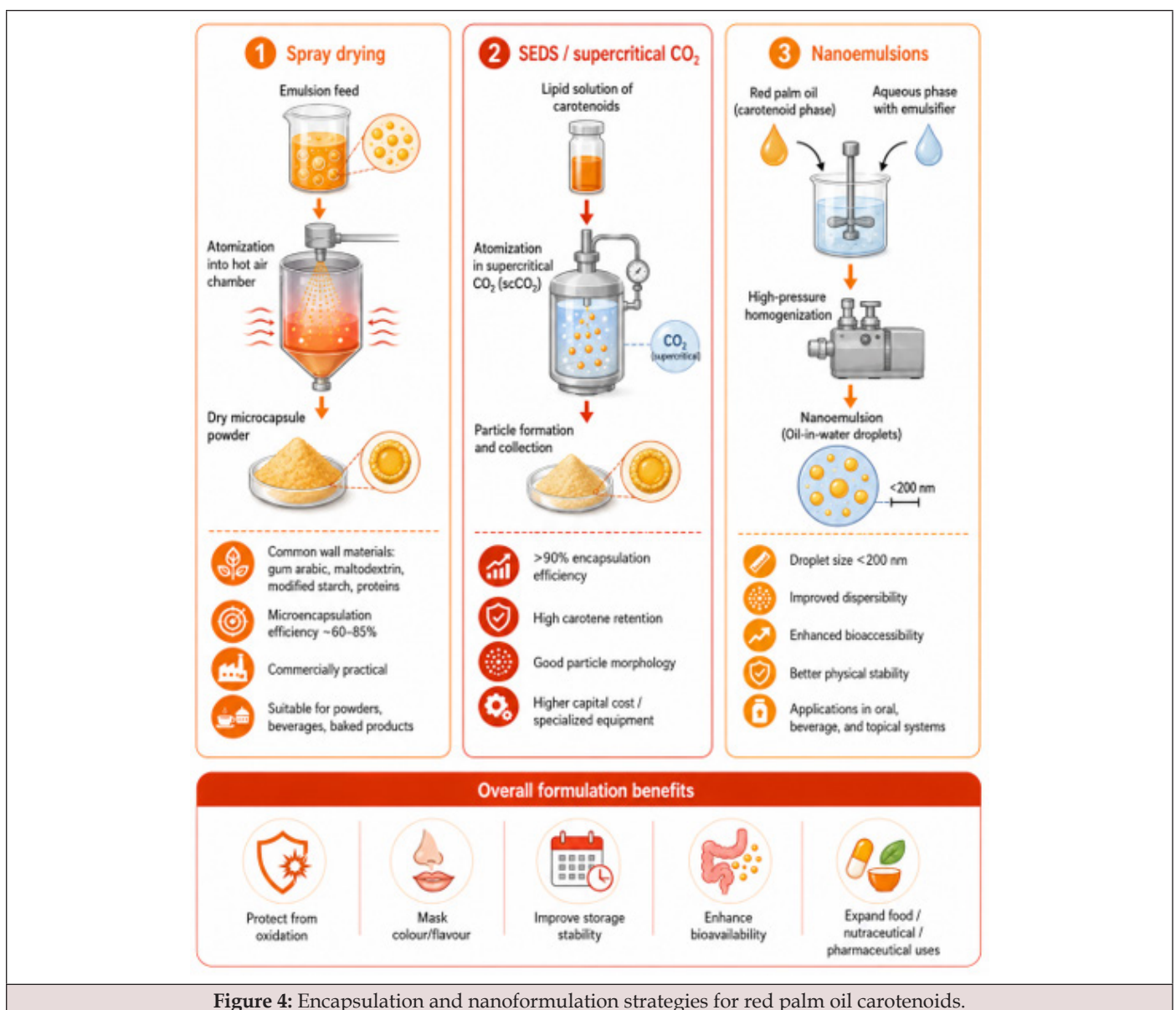


Figure 4: Encapsulation and nanoformulation strategies for red palm oil carotenoids.

Figure 4 compares the main formulation technologies used to protect and deliver RPO carotenoids. Spray drying is presented as a commercially practical approach for producing microcapsule powders suitable for foods, beverages, and supplements, although encapsulation efficiency is generally lower than that reported for SEDS. The SEDS/supercritical CO<sub>2</sub> method is shown as a higher-efficiency technology with strong carotene retention and favourable particle morphology, but greater equipment and cost requirements. Nanoemulsions are presented as a delivery platform that improves dispersibility, physical stability, bioaccessibility, and applicability in oral, beverage, and topical systems.

## Therapeutic and Nutraceutical Applications

### Vitamin A Deficiency and Public Health Nutrition

The most established application of RPO is in VAD prevention programs. Evidence from RCTs and programmatic evaluations indicates that RPO fortification of commonly consumed foods (e.g., porridges, biscuits, and cooking oil blends) can improve vitamin A status and lower VAD prevalence in at risk populations, offering a food based alternative or complement to high dose capsule supplementation. The meta-analysis of nine RCTs demonstrated a ~45% reduction in VAD, alongside significant increases in serum retinol and  $\beta$ -carotene in both children and adults [17,43,46]. RPO enriched functional foods may be especially useful in school-based feeding programs, where they can be integrated into locally acceptable products such as biscuits or baked goods, as illustrated by the Malaysian schoolchildren trial. In addition to improving vitamin A status, the RPO biscuits modulated gut microbiota, suggesting potential downstream impacts on immunity and metabolism that warrant further study [17,46].

### Antioxidant and Anti-Inflammatory Effects

Beyond VAD, RPO's carotenoids, tocopherols, and tocotrienols exhibit strong antioxidant activity, scavenging Reactive Oxygen Species (ROS) and protecting cellular lipids and membranes from peroxidation. In vitro and in vivo studies show that RPO and its formulations can reduce oxidative stress markers, improve plasma antioxidant capacity, and attenuate inflammatory pathways, including NF- $\kappa$ B signalling. RPO nanoemulsions, in particular, have been reported to enhance antioxidant and anti-inflammatory responses relative to bulk oil, likely due to improved dispersion and cellular uptake of carotenoids [22,66-68]. These properties underpin exploratory applications of RPO in conditions where oxidative stress and inflammation are central, such as cardiometabolic disorders, skin ageing, and inflammatory bowel conditions, although robust clinical evidence in these domains is still limited [22,69-71].

### Dermatological and Cosmetic Applications

Given its intense colour and antioxidant content, RPO is increasingly investigated for dermatological and cosmetic

applications, including skin photoprotection, support for barrier function, and anti-ageing formulations. Carotenoids such as  $\beta$  carotene and lycopene accumulate in the skin, where they can quench singlet oxygen and reduce UV induced oxidative damage. At the same time, vitamin E isomers modulate lipid peroxidation and inflammatory responses. A recent comprehensive review describes RPO as a promising ingredient for cosmeceutical products, with benefits related to skin elasticity, hydration, and protection against environmental stressors, particularly when delivered in nanoemulsion or encapsulated forms that improve stability and reduce greasiness [7,14,22,72].

### Gut Microbiota and Systemic Health

The randomised controlled trial of RPO enriched biscuits in vitamin A deficient schoolchildren provides the first robust evidence that long term RPO intake can alter gut microbiota composition, increase certain beneficial bacterial taxa and modulate metabolic pathways associated with vitamin A and bile acid metabolism. These findings suggest bidirectional interactions between carotenoid rich diets and the gut microbiome, with potential implications for immune function, metabolic health, and intestinal integrity. While causal mechanisms require further exploration, this line of research positions RPO as a candidate for microbiota targeted nutritional interventions [17,46,73,74].

## Safety, Challenges, and Future Directions

### 1.1. Safety Profile and Regulatory Status

RPO is consumed traditionally in many regions and is generally recognized as safe when used as a dietary fat within recommended energy intakes. Safety concerns primarily relate to overall fat intake and cardiovascular risk, as well as to oxidation products that can form when RPO is repeatedly heated or poorly stored. Recent reviews indicate that minimally processed, non-oxidized RPO used in moderate amounts does not appear to pose specific toxicological concerns, and that its carotenoids and vitamin E isomers may confer protective effects against oxidative stress-related diseases. Nonetheless, regulatory frameworks for RPO based nutraceuticals and fortified foods differ between jurisdictions, particularly regarding labelling of carotenoid content, colour additives, and health claims [75-79].

### Sensory and Formulation Constraints

A major challenge in RPO utilization is its intense colour, characteristic flavour, and susceptibility to oxidation, which can limit consumer acceptability and complicate incorporation into light colored foods. Microencapsulation, nanoemulsion formation, and blending with other oils are promising strategies to mask sensory attributes, improve oxidative stability, and allow controlled modulation of colour. However, these technologies add cost and complexity, and may be difficult to implement in resource limited settings without local manufacturing capacity [19,43,80-82].

### Research Gaps and Future Directions

Several research gaps remain. First, there is a need for well-designed, adequately powered RCTs that compare different RPO formulations (bulk oil, microencapsulated, nanoemulsion) head-to-head in terms of bioavailability, clinical efficacy, and safety across diverse populations, including pregnant women, infants, and individuals with chronic diseases. Second, long term observational and intervention studies are warranted to clarify the cardiometabolic impact of RPO based interventions, given its saturated fat content but high antioxidant load. Third, the molecular mechanisms linking RPO intake to gut microbiota, immune function, and systemic health

should be investigated using multi omics approaches and systems biology frameworks [20]. From a technological perspective, future work should focus on scalable, cost-effective encapsulation and nanoformulation techniques that can be implemented in producer countries and integrated into local food systems, while maintaining high carotenoid retention and bioavailability. Sustainability aspects, including the environmental and social footprint of palm oil production, also need to be considered to ensure that RPO based health interventions align with broader sustainable development goals [21]. The established clinical evidence, emerging therapeutic applications, remaining challenges, and future research directions for RPO are synthesised in Figure 5.

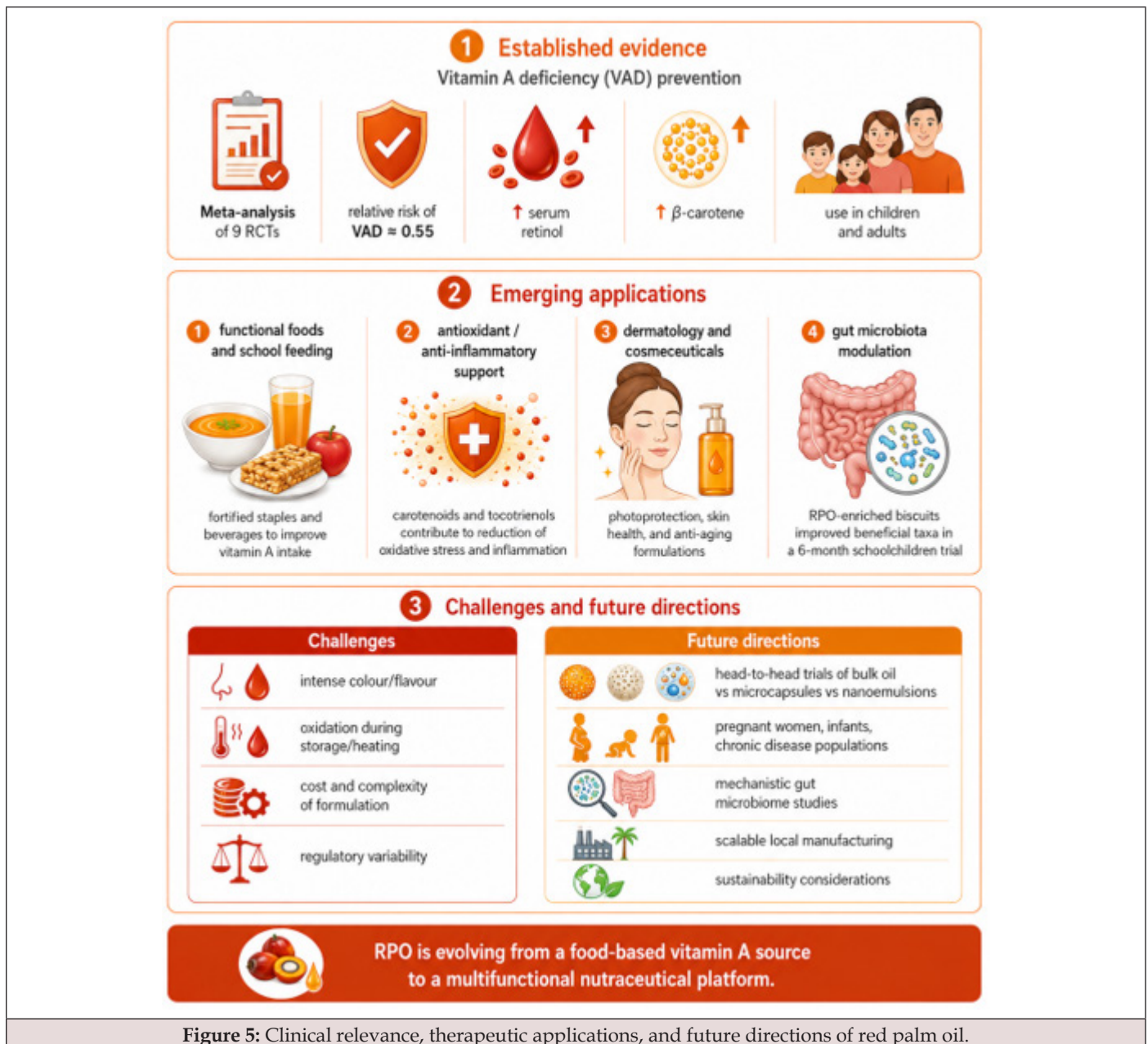


Figure 5: Clinical relevance, therapeutic applications, and future directions of red palm oil.

Figure 5 integrates the clinical and translational implications of RPO discussed throughout the review. It highlights the strongest evidence base, including RCT and meta-analytic findings showing improved serum retinol and  $\beta$ -carotene and reduced risk of vitamin A deficiency. It also summarises emerging applications in functional foods, antioxidant and anti-inflammatory support, dermatology, cosmeceuticals, and gut microbiota modulation. Finally, the figure identifies major implementation challenges, including sensory constraints, oxidation, formulation cost, regulatory variability, and the need for future head-to-head trials, mechanistic microbiome studies, scalable manufacturing, and sustainability assessment.

## Conclusion

RPO is a unique functional lipid that combines high levels of provitamin A carotenoids with vitamin E isomers and other antioxidants, offering a food-based strategy to combat vitamin A deficiency and potentially modulate broader health outcomes. Evidence from randomised trials and meta-analyses shows that RPO fortification and supplementation can increase serum retinol and  $\beta$  carotene concentrations and reduce VAD risk, particularly in children and women. Advances in microencapsulation and nanoemulsion technologies have significantly improved the stability, sensory attributes, and bioavailability of RPO carotenoids, facilitating their incorporation into a wide range of nutraceutical, functional food, and potentially pharmaceutical formulations. Emerging research highlights additional antioxidant, anti-inflammatory, dermatological, and gut microbiota-modulating effects of RPO and its formulations, although more robust clinical data are needed to substantiate therapeutic claims beyond VAD. Overall, RPO represents a promising biomedical resource at the interface of nutrition and health, but its optimal deployment will require careful attention to formulation science, safety evaluation, sensory acceptability, and the sustainability of palm oil supply chains.

## Acknowledgement

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## Conflict of Interest

None.

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