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E-B
Environment - Behaviour
Proceedings Journal

ISSTM-TEd 2024

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e-IPH
e-International
Publishing House Ltd.,
United Kingdom

International Symposium on Strategy & Transformation Management For Tertiary Education
Virtual Symposium
14 - 16 Oct 2024

Main Organiser: Universiti Teknologi MARA (UiTM)
Co-Organiser: East Kazakhstan Technical University (EKTU)

Sustainable Green Extraction Techniques for Carotenoids from Palm Oil and its By-products

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Abstract
This review emphasised the extraction methods of carotenoids using solvent extraction, supercritical fluid extraction, adsorption extraction, ultrasonic-assisted extraction, pressurised liquid extraction, and enzymatic assisted extraction of crude palm oil (CPO) and its by-products, namely palm pressed fiber oil (PPFO), oil palm empty fruit bunch (OPEFB) and palm oil mill effluent (POME). The importance of green extraction technology and the effect of pre-treatment and the extraction process on the yield of carotenoids are also discussed. The utilization of palm oil by-products can be significantly increased by extracting carotenes and utilising them as value-added products.

Keywords: Carotenoids; palm oil; palm oil by-products; extraction methods

DOI: https://doi.org/10.21834/e-bpj.v10iSI34.7480

1.0 Introduction

Carotenoids are naturally produced by photosynthetic organisms, non-photosynthetic bacteria, fungi, algae, and particular species of aphids (Maoka, 2020). It primarily consist of 40-carbon terpenoids composed of eight isoprenoid units at their core structural level. Carotenoids, classified as carotenes or xanthophylls, owe their yellow to purple colours to a conjugated system of irregular single and double bonds (Kultys & Kurek, 2022). Carotenoids play biological and functional roles in plants, humans, and animals. It serves as a Vitamin A precursor, possesses antioxidant capacity, protects against UV radiation, and prevents several types of diseases (Polyakov et al., 2023). Anshori et al. (2022) reported palm oil as one of the richest and popular sources of carotenoids, dominated by β-carotene and α-carotene. Throughout the palm oil milling operation, several by-products are generated, including oil palm empty fruit bunches (OPEFB), palm pressed fibre (PPF), and palm oil mill effluent (POME). Research on adding value to palm oil by-products is essential to showcase their potential, increase utilization and reduce waste generation. Diverse extraction technologies have been employed to

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DOI: https://doi.org/10.21834/e-bpj.v10iSI34.7480

retrieve carotenoids from these feedstock. Several reviews have been published, covering various aspects of carotenoid extraction from palm oil. Although many studies exist on carotenoid extraction from palm oil, few assess the operational effectiveness or pre-treatment strategies, highlighting the need for this review.

Therefore, this review aims to consolidate and evaluate the latest advancements in carotenoid extraction from palm oil and its by-products, with a particular focus on green, sustainable, and high-efficiency technologies. Specifically, the objectives of this review are to: (i) summarise the current understanding of carotenoid composition in crude palm oil and its major by-products, (ii) compare the performance and operational principles of conventional and emerging extraction techniques, and (iii) highlight recent innovations, challenges, and research gaps that can guide future development of environmentally responsible carotenoid recovery strategies.

2.0 Literature Search Strategy

This review synthesised information from peer-reviewed articles, scholarly reviews, and technical reports related to carotenoid extraction from palm oil and its by-products. The literature search was primarily conducted using major academic databases, including Scopus, Web of Science, and Google Scholar. The search focused on publications from the past two decades up to the submission date of this manuscript (2025), though key foundational papers, regardless of age, were included to establish context. The search terms were strategically selected based on the review's scope and the defined objectives, including combinations of keywords such as: "Carotenoids", "palm oil", "palm oil by-products" (e.g., PPFO, OPEFB, POME), "extraction methods" (e.g., SFE, PLE, UAE, EAE), and "green extraction techniques". The identified literature was then screened to cover the current understanding of carotenoid composition, the performance of conventional and emerging extraction techniques, and recent innovations and challenges, in line with the overall review objectives.

3.0 Production of Palm oil and The Generated By-Products

Producing palm oil starts with harvesting the fully matured oil palm fresh fruit bunches (FFB), as illustrated in Figure 1. The harvested FFB is brought to the palm oil mill to extract the crude palm oil (CPO) and palm kernel (PK). The palm oil milling process involves several basic operations, including (i) FFB reception and grading, (ii) FFB sterilisation; (iii) FFB stripping and threshing; (iv) digestion of fruitlets; (iv) pressing the digested mashes for extracting crude oil; (v) screening of crude oil; (vi) clarification and purification of oil; (vii) vacuum drying of the oil, (viii) storage, and (viiii) dispatch (Hoe et al., 2020).

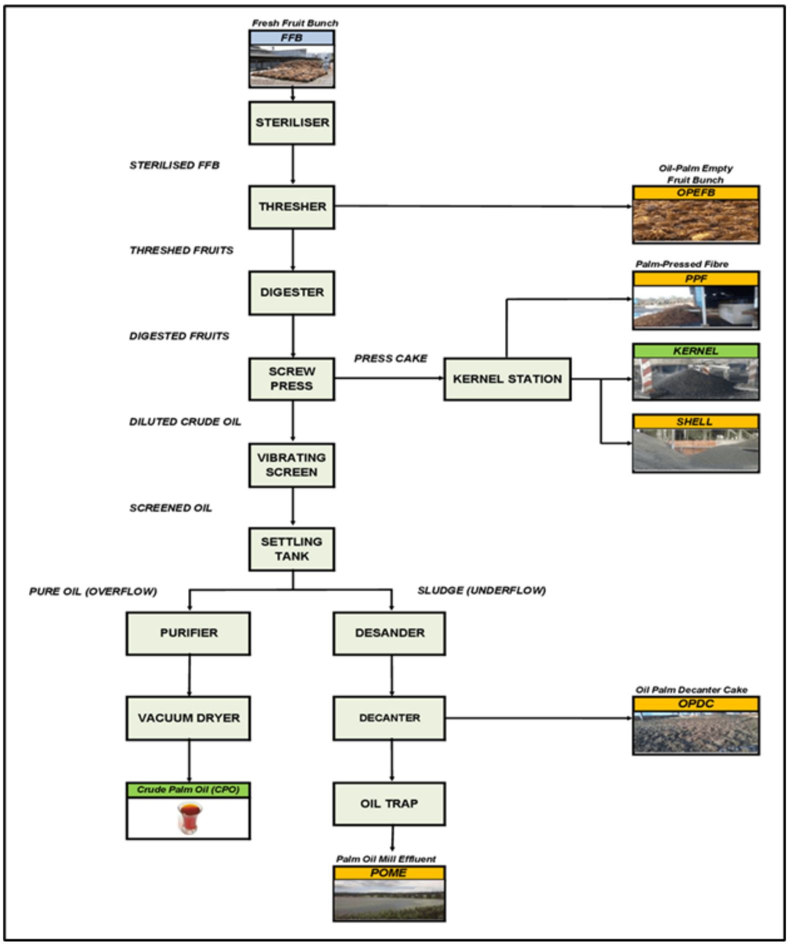

Fig. 1: Production of palm oil and its by-products

Figure 1 shows that the first by-product generated from the palm oil milling process is OPEFB, the empty bunches generated from the stripping process of sterilised FFB during the threshing process. PPF is the fibrous residue left after removing the endocarp during screw pressing of palm fruits. As the final liquid discharge of palm oil milling processing, the POME is a brownish eluent composed of water, residual oil, suspended solids, and organic matter. These palm oil by-products are considered potential carotenoid sources from palm oil processing (Kupan et al., 2016). The overall process generates several types of by-products including PPF, OPEFB, shell, oil palm decanter cake (OPDC) and POME, which can be categorised into i) product-specific by-products (solid form), and ii) process-specific by-products (aqueous form). The product-specific by-products are high in organic content and are highly valuable for producing particle boards, adsorbents, briquettes, and various cellulosic materials. The residual oil from PPF has been reported to contain high phytonutrient content suitable for nutraceuticals, pharmaceuticals, and cosmeceuticals. At the same time, POME, which is available in aqueous form, is produced in considerable amounts and is beneficial for fertiliser, animal feed, and phenolic antioxidants (Hoe et al., 2020).

4.0 Carotenoids in Palm Oil and By-Products

Although around 50 carotenoids are present in the human diet, 16 common types are found in palm oil and its by-products, with carotene being the dominant one. Table 1 summarises carotenoid and carotene yields from various extraction techniques towards CPO, PPFO, OPEFB, and POME. The CPO recorded carotenoid concentrations ranging from 500 ppm to over 201,000 ppm. The low value of carotenoids recorded, as reported by May (1994) and Mohd Setapar et al. (2014), represents the carotenoid value of natural CPO, which only undergoes a physical separation process. On the other hand, the transition from molecular distillation to Supercritical Fluid Extraction (SFE) showed a notable effect, increasing from over 80,000 ppm (May, 1994) to 201,000 ppm (Puah et al., 2008).

Table 1. Comparison of carotenoid yield in palm oil, its by-products, and waste using different extraction technologies

Palm oil and by-products	Extraction Technology			Yield	References
	Pre-treatment	Extraction Parameter/ Operating Conditions	Extraction Process	Carotenoids (A) β- carotene (B) (concentration, ppm)	
Crude Palm Oil (CPO)	N/A	N/A	N/A	A* (500-4,592)	(May, 1994)
	N/A	N/A	Esterification & Adsorption	A (5,000 - 9,000)	
	N/A	N/A	Vacuum Distillation	A (> 20,784)	
	N/A	N/A	Molecular Distillation	A (>80,000)	
	N/A	N/A	Adsorption	A (3,700 - 5,600)	
	N/A	HP-20 adsorbent; 50 °C incubation; 70 rpm; IPA	Adsorption	B (31.44)	(Chan et al., 2000)
	1. Silica gel activation: (120 °C; 2 hrs) 2. Immersion of CPO in a water bath (50-60 °C) 3. Column pre-treated with hexane	Silica gel adsorbent; Polypropylene filtration column fitted with polyethylene; 10-20 mmHg Vacuum pump; CPO:silica gel at 1:10	Adsorption Chromatography (Vacuum Column Chromatography)	N/A	(Ping, 2007)
	1. FFA: Esterification (Acid catalysis) 2. TAG: Transesterification (KOH, Methanol)	10 MPa; 40°C; SC-CO_2	SFE	A (201,000)	(Puah et al., 2008)
	1. Adsorbent Activation: Mix IPA-HP-20, filtration & drying 2. 6 g CPO:50 mL IPA	1. Adsorption: 1:4 (CPO:HP-20); 1 hr; 40-45°C 2. Soxhlet Extraction: IPA; 1 hr & hexane; 3 hrs	Adsorption & Soxhlet Extraction	B (3,790)	(Kupan et al., 2016)
	N/A	N/A	N/A	A* (500 – 700)	(Mohd Setapar et al., 2014)

Palm Pressed Fiber Oil (PPFO)	N/A	hexane; 10 & 12 hrs; 68°C	Soxhlet Extraction	B (SFE[b], 2,076.96 > SFE[a] > SE)	(Putra et al., 2020)
		50°C; 30 MPa; SC-CO_2; ethanol as co-solvent[b]	SFE[a]		
			SFE with co-solvent[b]		
	N/A	40 °C & 0 °C; 15, 30 and 45 MPa; SC-CO_2	SFE	A (5.32-26.11)	(Bezerra et al., 2018)
	1. Adsorbent Activation: Mix IPA-HP-20, filtration & drying 2. 6 g CPO:50 mL IPA	1. Adsorption: 1:4 (CPO:HP-20); 1hr; 40-45°C 2. Soxhlet Extraction: IPA; 1hr & hexane; 3 hrs	Adsorption & Soxhlet Extraction	B (1,414)	(Kupan et al., 2016)
	N/A	N/A	N/A	A* (1,800-2,400)	(May, 1994)
Oil palm empty fruit bunch (OPEFB)	Cutting off OPEFB	1. Solvents: n-hexane; ethanol; isopropyl alcohol 2. OPEFB Forms: stalk, spikelet 3. OPEFB: Solvent (1:60, w/v) 4. Optimum condition: n-hexane; 5-cm OPEFB spikelets	Soxhlet Extraction	B (2.32 ± 0.01)	(Anshori et al., 2022)
	1. Adsorbent Activation: Mix IPA-HP-20, filtration & drying 2. 6 g CPO:50 mL IPA	1. Adsorption: 1: 4 (CPO: HP-20); 1hr; 40-45 °C 2. Soxhlet: IPA; 1 hr; & hexane; 3 hrs	Adsorption & Soxhlet Extraction	B (702)	(Kupan et al., 2016)
	N/A	Maceration	N/A	A* (915)	(Anshori et al., 2022)
Palm oil mill effluent (POME)	1. Extraction of POME residual oil (Solvent Extraction in flocculator): POME:Solvents (n-hexane & pet. ether), 1:1 (gradual increment of solvent); 10 mins; 150 rpm 2. Sample dilution (10g extracted oil dissolved with 30 mL n-hexane)	1. Solvent Extraction: n-hexane:POME (0.6:1.0) 2. Adsorption Column Chromatography: 63-200 µm silica gel adsorbent; 200 mm length & 20 mm internal diameter column; initial solvent (170 mL n-hexane) & Second solvent (100 mL ethanol/ n-hexane)	Adsorption Column Chromatography	B1. POME-residual oil: 417.9 (petroleum ether); 394.8 (n-hexane) B2. Carotene extracts from POME-residual oil: 1450 (4 times of original concentration)	(Ahmad et al., 2009)
	Extraction of POME-residual oil (Solvent Extraction in flocculator): POME: n-hexane (1:0.6); 10 mins; 30 rpm	1. Adsorbent: Silica Gel 63-200 µm 2. Operating condition: Extracted oil: silica gel (1:6); 40 °C Column; initial solvent (n-hexane) & second solvent (Ethanol)	Adsorption Column Chromatography	B1. 453, carotene content of POME-residual oil B2. 32,052 Carotene extract of POME-residual oil using column adsorption (pet. ether)	(Ahmad et al., 2009)

Notes: *No information provided about the extraction techniques applied to the sample

By incorporating heat up to 40 degrees Celsius during adsorption column chromatography, the carotenoid yield in POME has increased to a range of 417.9-32,052 ppm (Ahmad et al., 2009). Overall, employing diverse extraction techniques from palm oil and its by-products can significantly boost the recovery of valuable carotenoids, supporting the sustainability and economic viability of the palm oil industry.

5.0 Extraction of Carotenoids from Palm Oil and By-Products

5.1 Pre-Treatment

The pre-treatment phase in the extraction of carotenoids from palm oil is a process designed to modify the oil's properties, thereby favoring extraction. The cell walls form a barrier that hinders solvent penetration into the cell. Additionally, the linkage between carotenoids and other large molecules like proteins and fatty acids impedes the movement of carotenoids during extraction (Hoe et al., 2020). Therefore, in the initial extraction stage, various methods, such as physical, chemical, enzymatic, or biological approaches, are employed to overcome these obstacles and enhance the efficient extraction of carotenoids. The selection of appropriate techniques for cell disruption is mainly determined by the specific properties of the cellular matrix and cell wall (Saini & Keum, 2018). Several pre-treatment strategies, such as deacidification, neutralisation, transesterification, and saponification, can be incorporated into extraction methods (Hoe et al., 2020).

5.2 Extraction Methods

5.2.1 Solvent Extraction (SE)

Solvent extraction is a technique for extracting both oil and bioactive compounds using a specific solvent. While organic solvents such as chloroform, hexane, isopropanol, methylene chloride, or diethyl ether are frequently used for the extraction of carotenoids from palm oil (Saini & Keum, 2018), these substances may pose environmental and health hazards (Latip et al., 2000). The traditional technique employed is maceration, in which the sample is soaked in a suitable solvent to allow the desired compounds to dissolve into the liquid phase over time. The process will lead to cell disruption, which will further facilitate solvent entry to solubilise intracellular carotenoids. It can be performed by physical, chemical, or mechanical means, depending on the suitability and availability of the equipment and/or reagents (Saini & Keum, 2018). Maceration is one of the favourable techniques due to its simplicity. It involves a low-temperature process that eliminates the need for sophisticated instruments while still achieving a good carotene yield. Latip *et al.* (2000) successfully used a solvent extraction method to extract carotene from CPO. The study used hexane to extract carotene from a synthetic porous resin (SP 850) pre-treated with a CPO-IPA mixture. On the other hand, Cardenas-Toro *et al.* (2015) have successfully conducted a low-pressure solvent extraction (LPSE) to extract carotene from PPF, where both ethanol and hexane were used as extraction solvents. Though the study reported that the carotene yield obtained using ethanol and hexane was statistically similar for both solvents, ethanol is seen as a better solvent option for the carotene extraction technique from PPF due to higher global extraction yield and similarity values of carotenoid extracts.

5.2.2 Supercritical Fluid Extraction (SFE)

Supercritical fluid extraction (SFE) is a widely practiced method that involves employing solvents at temperatures and pressures above their critical points. SFE is a rapid, effective, and green technique for extracting natural compounds from various substances. The SFE technique is known as one of the green extraction methods used for carotenoid recovery from fruits and vegetable by-products (Ewelina Kultys & Marcin Andrzej Kurek, 2022). Lau *et al*. (2008) was among the studies that successfully used SFE to extract β-carotene from PPFO. The bioactive compounds obtained using SFE from plants have various chemical structures comprising a broad spectrum of polarities. There are several types of supercritical fluids which can be used in SFE, including carbon dioxide, propane, ethane, nitrous oxide, 1,1,1,2-Tetrafluooroethane (R-134a), ammonia, n-pentane, propane, water, fluoroform, and sulfur hexafluoride (Mohd Setapar et al., 2014). Due to its low polarity, carbon dioxide (CO_2) is commonly used to extract nonpolar bioactive compounds. Approximately 90% of supercritical fluid extraction is executed using CO_2 and is considered a clean technology for several practical reasons, including minimum thermal degradation, easy solvent separation, being non-toxic, the absence of secondary products, and environmentally hazardous waste Mohd Setapar *et al.* (2014). Temperature and pressure are two most significant operational parameters of SFE. They were reported to affect the properties of supercritical fluids for dissolving the target phytonutrients and manipulating the selectivity of compounds in the extracted fluid, respectively. Anshori et al (2022) reported a combination of 60 °C and a pressure range between 14 and 30 MPa as optimum processing conditions for SFE since the condition is able to deliver excellent extraction performance while maintaining minimum phytonutrient degradation. Additionally, extra pre-treatment processes such as sample grinding and moisture removal contribute to effective extraction.

5.2.3 Adsorption Extraction (AE)

The adsorption technique is a procedure involving the capture (adsorption) and release (desorption) of specific substances, determined by their interaction with the adsorbent surface and the solvent properties. The concept of adsorption-desorption serves as a strategy for separation, concentrating target components into a distinct fraction. During the process, the components within the oil mixture attach to the adsorbent and are subsequently released in the desorption process under reversed conditions (Phoon et al., 2018). Since adsorption can be conducted at atmospheric pressure and room temperature, this extraction method is suitable for heat-sensitive compounds and effectively minimises energy consumption. Additional benefits of this adsorption technique include ease of operation, lenient requirements for feedstock pre-treatment, low capital costs for adsorbents, and the ability to reuse spent adsorbents through a regeneration step. Adsorption plays a crucial role in the palm oil processing industry, contributing to the purification, concentration, and extraction of phytonutrients from palm oil (Hoe et al., 2020). Batch adsorption techniques utilising synthetic adsorbents, followed by solvent extraction, have proven successful in achieving substantial recovery of concentrated carotene from CPO. It also effectively increased the carotene concentration to 15,000 ppm, approximately 25 times the original concentration in CPO (Latip et al., 2000).

5.2.4 Ultrasonic-Assisted Extraction (UAE)

Ultrasound-Assisted Extraction (UAE) is an innovative technique that utilises ultrasound energy in conjunction with solvents to efficiently extract specific compounds from a variety of plant matrices (Kumar et al., 2021). One of the key benefit of UAE is its ability to yield concentrated green extracts devoid of residual solvents and impurities (Bitwell et al., 2023). In the context of palm oil extraction, UAE proves particularly effective for extracting carotenoids, which are valued for their antioxidant properties and as precursors to Vitamin A. The application enhances the efficiency of carotenoid released by breaking down cell walls, enabling a more effective extraction process. It does not only shorten extraction time and lowers the necessary temperature (Saini & Keum, 2018), it also helps to preserve the integrity of biologically active compounds. The extraction process is based on cavitation whereby the rapid conversion of liquid to gas under reduced pressure resulting from high-frequency sound waves. This phenomenon leads to the formation, growth, and collapse of microbubbles within the liquid, creating violent molecular collisions and generating regions of extremely high temperature (up to 5500 °C) and pressure (up to 50 MPa) for brief periods (9–10 seconds) (Huang et al., 2022). Such conditions significantly damage cell walls, enhancing solvent penetration and facilitating the leaching of carotenoids. Optimised cavitation conditions can increase extraction efficiency by up to tenfold. However, the method does have drawbacks, including the potential for sudden temperature fluctuations caused by the cavitation phenomenon, which can lead to undesirable reactions such as thermo-oxidation and volatilisation of low-volatility compounds. Hence, careful optimisation of cavitation parameters is essential to mitigate the risk. In summary, UAE represents a sustainable and efficient approach for carotenoid extraction from palm oil, offering advantages in yield, speed, and environmental impact.

5.2.5 Pressurised Liquid Extraction (PLE)

Pressurised Liquid Extraction (PLE), also known as Accelerated Solvent Extraction (ASE), is a sustainable and efficient green extraction technique increasingly used for carotenoid extraction from palm oil and its by-products. This method utilises liquid solvents under elevated temperatures and pressures to enhance extraction efficiency by improving cell membrane permeability, thereby facilitating the recovery of bioactive compounds like carotenoids (Ewelina Kultys & Marcin Andrzej Kurek, 2022). PLE is considered an environmentally friendly methods since it minimise the use of organic solvents while achieving comparable extraction efficiencies (Saini & Keum, 2018). A previous study demonstrated the potential of PLE for extracting carotenoids from compressed palm fiber using heated ethanol as the solvent. The key advantage of PLE lies in its ability to operate at high temperatures (20–200 °C) and pressures (35–200 bar), which increases solvent solubility and diffusion, allowing for faster and more efficient extraction (Barp et al., 2023). Unlike the LPSE method, PLE uses elevated conditions to decrease solvent viscosity, enabling better penetration into solid. The high-pressure conditions also help to preserve thermolabile compounds, reducing degradation and enhancing carotenoid yield materials (Barp et al., 2023). Various solvents have been tested for carotenoid extraction in PLE, including ethanol, methanol, acetone, and hexane. While hexane is frequently used, combinations of ethanol and hexane have also shown extraction effectiveness. The choice of solvent and its combination is critical, as it affects extraction efficiency, selectivity, and sustainability (Alara et al., 2021). PLE can be conducted in either dynamic or static modes. The dynamic method continuously supplies solvents through pumps, while the static method involves multiple extraction cycles with solvent replacement between each cycle. Both modes offer flexibility depending on the solubility of the analyte in the chosen solvent. PLE offers advantages in scalability and speed, making it more suitable for industrial applications. PLE's ability to operate at higher temperatures makes it especially effective for extracting heat-stable compounds, which is advantageous when processing large quantities of material (Ewelina Kultys & Marcin Andrzej Kurek, 2022). In summary, PLE stands out as a highly efficient and sustainable method for carotenoid extraction, offering reduced solvent usage, faster processing times, and the ability to protect bioactive compounds.

5.2.6 Enzymatic Assisted Extraction (EAE)

Enzyme-Assisted Extraction (EAE) has emerged as an effective and sustainable method for extracting carotenoids and other bioactive compounds from palm oil and its by-products. Enzymes act as ideal catalysts that facilitate the degradation of cell walls and membranes, significantly enhancing the release and availability of bioactive components. EAE typically employs enzymes like proteases, pectinases, cellulases, tannases, and carbohydrates, which can selectively target and break down plant cell structures to release valuable compounds, ensuring high extraction yields while maintaining the integrity of thermolabile compounds like carotenoids. Compared to other methods, EAE operates under milder conditions, preserving the extracted carotenoids' quality and purity and making it safer for the environment. Using low heat during extraction reduces the risk of compound degradation, ensuring the stability of the bioactive constituents. Moreover, the process is characterised by its rapidity, high efficiency, and selectivity, making it suitable for obtaining high-purity extracts with minimal environmental impact (Nadar et al., 2018). The high cost of enzymes and the sensitivity of enzymes to environmental factors such as pH and temperature are real challenges of the EAE technique (Picot-Allain et al., 2021), which limit its application in large-scale industrial processes. However, EAE remains a valuable and eco-friendly method for sustainable carotenoid extraction, particularly when applied to palm oil processing, where it ensures the preservation of key phytonutrients while minimising environmental impact.

5.3 Analytical Insights and Broader Implications

Recent advancements in carotenoid extraction must be interpreted not only through technical performance but also through broader frameworks of green chemistry, sustainable resource utilisation, and circular economy principles. These perspectives emphasise minimising solvent use, reducing energy demand, and increasing value recovery from agro-industrial by-products key issues currently faced by the palm oil sector. From this standpoint, solvent extraction, although widely reported and effective in early studies, contradicts several sustainability principles due to its reliance on hazardous organic solvents and significant waste generation. In contrast, SFE aligns more closely with green chemistry theory as it uses CO_2 as a clean, recyclable solvent and reduces thermal degradation of carotenoids. Literature reporting high carotenoid yields from SFE supports the theoretical expectation that supercritical fluids enhance mass transfer and solubilisation of non-polar compounds. Similarly, PLE and UAE address limitations found in conventional techniques by improving diffusion, reducing solvent volumes, and shortening processing time. These improvements reflect current industry needs to transition towards energy-efficient and eco-friendly extraction platforms. However, UAE's cavitation-induced localised heating introduces concerns regarding thermo-oxidation, demonstrating an important trade-off between extraction efficiency and compound stability. Adsorption-based methods fit within the context of circular resource utilisation due to reusability of adsorbents and low operational energy demand. This aligns with palm oil industry priorities of valorising waste streams while maintaining low processing costs. Meanwhile, EAE demonstrates strong theoretical relevance due to its mild operating conditions and selectivity, although industrial application remains constrained by enzyme cost and sensitivity.

It is also essential to consider the broader implications of carotenoid extraction advancements beyond the immediate scope of palm oil processing. The increasing global demand for natural antioxidants and nutraceutical ingredients positions palm-based carotenoids as high-value compounds with potential applications in functional foods, pharmaceuticals, and cosmeceuticals. Sustainable extraction technologies such as SFE, PLE, and EAE also align with international sustainability goals, particularly the UN Sustainable Development Goals (SDGs) related to responsible production, climate action, and waste reduction. By enabling cleaner and more resource-efficient valorisation of palm by-products, these technologies can contribute to reducing the environmental footprint of the palm oil industry while supporting circular economy initiatives in producing countries. Furthermore, the optimisation of green extraction technologies has implications for policy development, industry standards, and commercial investment. As global markets shift towards environmentally responsible sourcing, industries adopting green extraction techniques are better positioned to meet regulatory expectations and consumer preferences. At the same time, advancements in these technologies create opportunities for technology transfer, new business models for by-product valorisation, and interdisciplinary collaborations between academia and industry.

Overall, the reviewed findings indicate that while multiple extraction technologies are viable, each is influenced by theoretical, economic, and environmental considerations. SFE and PLE emerge as the most consistent with global green-extraction trends. However, selecting an optimal method depends on balancing yield performance, sustainability goals, cost implications, and the physicochemical properties of palm-based matrices. These insights highlight the need for future research to integrate techno-economic analysis, life cycle assessment, and optimisation models to support scalable, industry-ready carotenoid recovery systems. The new direction for further research should focus on developing and validating integrated techno-economic analysis and optimisation models to support the design of scalable, industry-ready recovery systems. Beyond extraction yield, research must also investigate the stability and bioavailability of the carotenoid extracts in target downstream applications. Efforts should align with circular economy principles by exploring the valorisation of the spent/extracted palm oil by-product matrix after carotenoid recovery to ensure minimal waste and maximize resource utilisation

6.0 Conclusions

The review successfully consolidated and evaluated the latest advancements in carotenoid extraction from CPO and its by-products, including PPFO, OPEFB, and POME. The various techniques reviewed such as SE, SFE, AE, UAE, PLE, and EAE offer diverse paths for recovery. The optimal technique is indicated by achieving the highest possible yield with minimum processing costs. The ideal extraction condition for this statement is a combination of adsorption and solvent extraction using an appropriate solvent ratio. This strategy aligns with modern trends in green extraction, particularly with the utilisation of eco-friendly solvents. The environmental benefits of these methods are the reduction of hazardous waste, lowering the carbon footprint and scalable, making them viable options for large-scale production. Several limitations were identified in this study. Most studies primarily focus on maximizing yield, but a complete comparison of techniques is hindered by the lack of integrated techno-economic analysis and Life Cycle Assessment (LCA), which limits the ability to ascertain the true industrial sustainability of methods like SFE (which has high capital costs) versus AE (which has low operational energy demand). Despite their theoretical promise, the industrial-scale up of techniques like EAE is limited by enzyme costs and sensitivity, while UAE poses risks of thermo-oxidation due to cavitation-induced localised heating. The effectiveness of the extraction conditions (solvent, temperature, pressure) is also highly matrix-specific, varying widely between CPO and the different by-products, highlighting the challenge of developing a universal, robust protocol. To address these limitations and improve research findings, future work should prioritize the development and optimisation of hybrid extraction systems for example, combining a mild pre-treatment (like enzymatic hydrolysis) to disrupt the cell matrix with an efficient, clean recovery step using SFE or PLE. A reporting framework that includes solvent-use efficiency, energy consumption per gram of carotenoid extracted, and a comprehensive economic analysis should also be considered to enable meaningful, evidence-based comparisons across diverse technologies. Increased investigation into novel, eco-friendly solvents, such as Deep Eutectic Solvents (DESs), within PLE should also be a priority to replace hazardous organic solvents used in conventional SE. These efforts are essential to support scalable, industry-ready carotenoid recovery systems.

Acknowledgements

The authors acknowledge the support of Universiti Teknologi MARA (UiTM), Malaysia, and Universitas Andalas (UNAND), Indonesia, through the Strategic Research Partnership Grant [100-RMC 5/3/SRP INT (043/2023)], which jointly funded this study.

Paper Contribution to Related Field of Study

This paper contributes to the understanding of green extraction technologies and sustainable resource utilisation by reviewing various carotenoid extraction methods from palm oil and its by-products. It emphasises the impact of pre-treatment and extraction techniques on carotenoid yield and highlights the potential for valorising palm oil by-products into high-value compounds.

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