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GREENING THE PALM OIL INDUSTRY: PROSPECTS AND BARRIERS OF SUPERCRITICAL CO_2 EXTRACTION

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ABSTRACT

The palm oil industry, a cornerstone of global agribusiness, has faced mounting environmental and social scrutiny due to its significant contributions to deforestation, biodiversity loss and greenhouse gas (GHG) emissions. In response to these challenges, this review explores the transformative potential of supercritical carbon dioxide (SC-CO_2) extraction as a sustainable alternative for palm oil production. This review provides an in-depth examination of SC-CO_2 extraction principles, processes and its inherent advantages, including minimal environmental impact, enhanced oil quality, and improved yields. While SC-CO_2 extraction holds promise as an eco-friendly solution, it has its challenges. Technical complexities, energy requirements, and economic considerations are among the hurdles that must be addressed to facilitate its widespread adoption. Furthermore, this review offers insights into real-world case studies and scientific research, shedding light on the practical implications of SC-CO_2 extraction in the palm oil industry. It delves into the regulatory and policy frameworks shaping sustainable palm oil production, emphasising SC-CO_2 extraction's role in achieving compliance with stringent sustainability standards.

Keywords: hurdles, palm oil, prospects, supercritical carbon dioxide, sustainability.

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INTRODUCTION

The palm oil industry has long played a pivotal role in the global agribusiness landscape, supplying a versatile and ubiquitous commodity that finds its way into an array of consumer products, from food items to cosmetics, biofuels and industrial applications. Its economic significance cannot be overstated, providing livelihoods for millions, particularly in tropical regions where oil palm cultivation thrives. However, alongside its economic prosperity, the palm oil industry has garnered increasing attention.

The production of palm oil has been inextricably linked to a litany of environmental and social challenges, sparking international concern and calls for reform. The conventional extraction method for palm oil, though widely practised in the industry, presents significant drawbacks that warrant attention. Firstly, the process typically involves the use of large quantities of water. Therefore, it will produce the palm oil mill effluent (POME). POME pose environmental risks due to their potential for soil and water contamination during disposal. Moreover, their volatile nature contributes to air pollution, impacting both human health and ecosystem balance.

Furthermore, the high energy consumption associated with conventional extraction methods exacerbates environmental concerns. The need for heating and mechanical processes consumes substantial amounts of energy, often derived from non-renewable sources, leading to increased greenhouse gas (GHG) emissions and further exacerbating climate change (Siikamäki et al., 2012, Singh & Singh, 2017).

In this context, one potential solution that has gained momentum is the application of supercritical carbon dioxide (SC-CO_2) extraction for palm oil production. SC-CO_2 extraction represents a departure from traditional palm oil extraction methods, such as solvent-based and mechanical pressing, by offering a more environmentally friendly and efficient approach. The allure of SC-CO_2 extraction lies in its ability to reduce the industry's environmental footprint while enhancing oil quality and yield (Pensupa et al., 2018). This technique utilises carbon dioxide in a supercritical state where it exhibits both gas-like and liquid-like properties to extract oil from palm fruit efficiently and with fewer chemical solvents, a feature that aligns well with sustainability goals (New et al., 2022).

This review embarks on a comprehensive exploration of the prospects and hurdles associated with SC-CO_2 extraction in the context of greening the palm oil industry. It aims to provide a comprehensive overview of this innovative technology, highlighting its potential to revolutionise palm oil production by addressing key sustainability challenges. Through a critical examination of the principles, processes and advantages of SC-CO_2 extraction, this review elucidates how this method can contribute to mitigating deforestation, conserving biodiversity and reducing carbon emissions.

However, despite its promise, SC-CO_2 extraction has its challenges and limitations. This review will delve into the technical complexities, energy requirements, and economic considerations that present hurdles to its widespread adoption. This review also analyses real-world case studies and scientific research to gain insights into the practical implications of SC-CO_2 extraction within the palm oil industry. Moreover, this review explores the regulatory and policy frameworks that influence sustainable palm oil production, emphasising the role of SC-CO_2 extraction in aligning with and contributing to compliance with stringent sustainability standards and certifications.

As the palm oil industry stands at a crossroads, facing mounting pressure to transition toward more sustainable practices, this review aims to shed light on the potential of SC-CO_2 extraction as a transformative force. This review recognises the urgent need for innovative approaches that can address the industry's environmental and social challenges while acknowledging the complexities and considerations that must be navigated on the path to achieving a greener palm oil sector. In summary, this review sets the stage for a comprehensive exploration of SC-CO_2 extraction as a sustainable alternative in the palm oil industry. It underscores the urgency of adopting more environmentally friendly practices and the potential of SC-CO_2 extraction to play a pivotal role in reshaping the industry's future.

SC-CO_2 EXTRACTION: PRINCIPLES AND PROCESS

SC-CO_2 as a Green Extraction Method

Extraction, in the context of chemical or physical processes, involves the separation of various constituents from natural substances. This essential process plays a crucial role in a wide range of industries and applications. However, in recent times, there has been a growing global emphasis on environmental conservation and sustainable practices. This has led to the adoption of "green extraction" methodologies (Abou Elmaaty et al., 2022; Rizkiyah et al., 2023a; Uwineza & Waśkiewicz, 2020).

Green extraction methods, such as SC-CO_2 extraction, are characterised by their environmentally conscious approach. They are designed to minimise the ecological footprint of extraction processes while ensuring the production of high-quality extracts. These methods align with sustainable practices by consuming less energy, allowing for the use of alternative solvents, and making use of renewable resources. SC-CO_2 extraction, in particular, has emerged as a leading example of green extraction. It harnesses the unique properties of supercritical carbon dioxide, which is a phase of carbon dioxide that exhibits both gas-like and liquid-like characteristics under specific conditions of temperature and pressure.

SC-CO_2 extraction of palm oil can utilise various potential sources of carbon dioxide (CO_2). Firstly, industrial processes such as fermentation, combustion, and chemical manufacturing produce CO_2 as a byproduct. Capturing and purifying these emissions can provide a sustainable source for SC-CO_2 extraction. Additionally, biogas and biomass facilities generate CO_2 during the production of biogas from organic waste. This CO_2 can be captured and repurposed for SC-CO_2 extraction, contributing to a circular economy by utilising waste streams. Furthermore, advancements in carbon capture and utilisation (CCU) technologies enable the integration of CO_2 emissions captured from power plants and industrial facilities into SC-CO_2 extraction processes.

This not only reduces GHG emissions but also provides a source of CO_2 for extraction. Natural underground reservoirs, such as geological formations, also contain CO_2 that can be accessed through carbon capture and storage (CCS) technologies or naturally occurring geological formations suitable for CO_2 extraction. Moreover, CO_2 captured from renewable energy facilities powered by sources like solar or wind energy can be utilised for SC-CO_2 extraction, enhancing the sustainability of the process. By leveraging these diverse sources of CO_2, the palm oil industry can adopt environmentally friendly practices for SC-CO_2 extraction while minimising its carbon footprint and promoting sustainability. Several distinct advantages of this method is elaborated below.

Reduced environmental impact. SC-CO_2 extraction eliminates the release of potentially hazardous substances into the environment (Arsad et al., 2023).

Energy efficiency. It is energy-efficient compared to some conventional extraction techniques, contributing to reduced energy consumption and lower GHG emissions (Chemat et al., 2012).

Alternative solvents. SC-CO_2 can serve as a safe and sustainable alternative to conventional organic solvents, making it suitable for applications where chemical residues must be minimised (Putra et al., 2023a).

High-quality extracts. SC-CO_2 is highly selective, allowing for the extraction of specific compounds of interest while preserving their quality and bioactivity (Carmen et al., 2023).

Safety. It provides a safe and non-toxic extraction environment, ensuring the purity of extracted compounds (Putra et al., 2023b).

As a result of these advantages, SC-CO_2 extraction has gained recognition as an effective and environmentally friendly alternative to conventional solvent extraction techniques, particularly in the extraction of bioactive compounds from natural sources. Its adoption represents a significant step toward achieving sustainable and eco-friendly extraction processes in various industries (Abou Elmaaty et al., 2022). The schematic diagram of SC-CO_2 extraction that can be applied in palm oil extraction is shown in *Figure 1*. However, it is essential to consider the energy balance in extraction conditions, as noted by Meireles (2006). When evaluating whether the increased efficiency in extraction justifies the use of higher temperature and pressure, one must also account for the associated costs of cooling and pressurisation.

The SC-CO_2 extraction is a sophisticated method used for extracting palm oil, offering several advantages over traditional extraction techniques. The process begins with the preparation of the palm fruit, which is harvested and processed to obtain the oil-bearing fruit bunches. These bunches undergo sterilisation, threshing and pressing to extract crude palm oil. Once the crude oil is obtained, it is loaded into the extraction vessel of the SC-CO_2 extraction system.

In the SC-CO_2 extraction system, the crude palm oil is subjected to high pressure and temperature conditions to achieve supercritical state conditions for the CO_2. Typically, SC-CO_2 extraction occurs at temperatures around 31°C and pressures of approximately 73 atm (Putra et al., 2020, 2023d). At these conditions, CO_2 behaves as a solvent, penetrating the oil matrix and selectively extracting desired components, such as triglycerides, which are the primary constituents of palm oil. This selective extraction process ensures that only the desired compounds are extracted, leaving behind unwanted substances.

After the extraction process, the SC-CO_2 containing the dissolved palm oil components is depressurised and passed into a separator. The pressure is reduced, causing the SC-CO_2 to revert to its gaseous state, leaving behind the extracted palm oil. The CO_2 is then recycled for reuse in the extraction process, making the method environmentally friendly and sustainable. The extracted palm oil may undergo further purification steps, such as filtration or refining, to remove any remaining impurities and improve its quality. The final product is high-quality palm oil ready for use in various applications, including food, cosmetics, and biofuels.

In summary, SC-CO_2 extraction offers an efficient and environmentally friendly alternative to conventional palm oil extraction methods. By utilising SC-CO_2 as solvent, this method ensures the extraction of high-quality palm oil while minimising environmental impact and maintaining food safety standards.

SC-CO_2 as a Solvent for Palm Oil Extraction

Indeed, CO_2 has a long history of use as a supercritical fluid, and its selection is primarily based on its remarkable properties. One of the key advantages of SC-CO_2 extraction is its unique combination of characteristics, which make

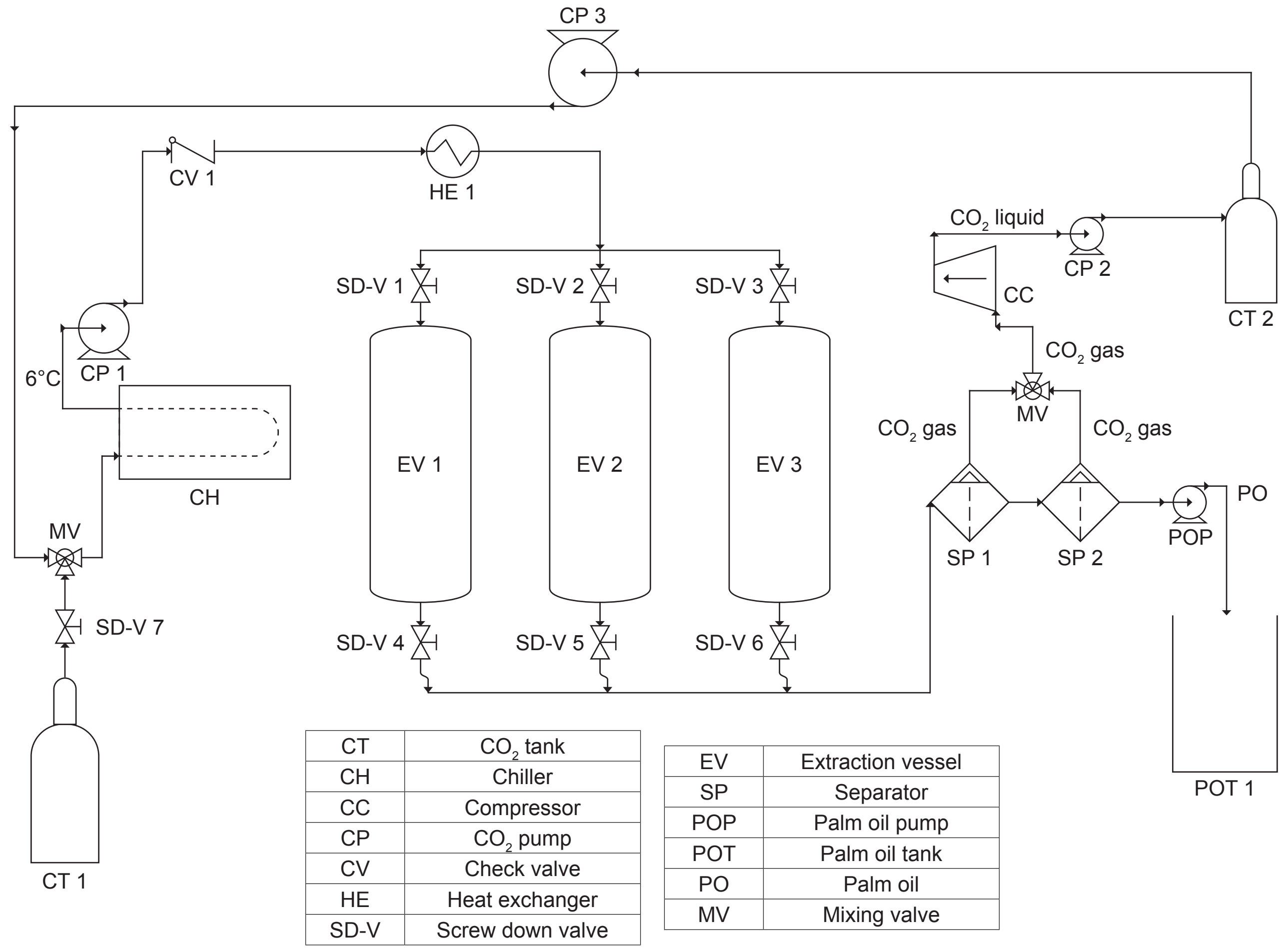

Figure 1. Schematic diagram of SC-CO_2 extraction (closed loop system) for the palm oil industry.

it particularly well-suited for a wide range of applications. One of the standout features of CO_2 is its relatively low critical temperature, which is a defining property for supercritical fluids. The critical temperature of CO_2 is around 31°C (87.8°F) under typical atmospheric pressure conditions (Daud et al., 2022). This relatively low critical temperature is significant for several reason.

Moderate operating temperatures. Because CO_2 becomes supercritical at relatively low temperatures, SC-CO_2 extraction can be conducted at moderate temperature levels (Honda et al., 2022). This is advantageous for processes involving heat-sensitive compounds. Operating at lower temperatures helps prevent substance degradation due to heat induction, ensuring the preservation of the compound's quality and integrity.

Selective extraction. The moderate temperature range of SC-CO_2 allows for selective extraction (Idham et al., 2020). Different compounds have varying solubilities in SC-CO_2 depending on temperature and pressure. By adjusting these parameters, it's possible to extract specific compounds while leaving others behind selectively. This selectivity is a valuable feature in applications where the isolation of particular components is desired.

Safety and compatibility. The use of moderate temperatures enhances the safety of SC-CO_2 extraction processes (Temelli, 2009). It reduces the risk of thermal degradation or unwanted chemical reactions that can occur at higher temperatures. Additionally, SC-CO_2 is compatible with a wide range of materials, making it suitable for various extraction equipment and materials construction.

In summary, the low critical temperature of carbon dioxide makes it an exceptionally versatile and advantageous supercritical fluid, especially in SC-CO_2 extraction processes. Its ability to operate at moderate temperatures prevents substance degradation, ensures selectivity in extraction and enhances the overall safety and compatibility of the process. These characteristics contribute to the widespread use of SC-CO_2 extraction in industries where the preservation of compound quality and environmental sustainability are paramount.

Parameter Effects on SC-CO_2 Extraction

Optimising the conditions for SC-CO_2 extraction is a critical initial step in the procedure, aiming to achieve the efficient extraction of bioactive compounds while minimising the extraction of undesired components. This optimisation of operational parameters is fundamental in the development of SC-CO_2 technology, given the multitude of process factors that can influence extraction efficiency. Various parameters associated with supercritical fluid extraction (SFE) need careful adjustment to ensure the successful extraction of bioactive components from plant materials. *Table 1* shows the optimal conditions for extracting palm oil.

Several factors have been identified as having significant effects on the efficiency of SC-CO_2 extraction. These factors include the type of sample being processed, the choice of supercritical fluid, operating pressure, flow rate, temperature and extraction time. As previously reported (Reverchon, 1997), all of these parameters can influence the rate and success of the extraction process. However, it's worth noting that the primary parameters that play a pivotal role in determining extraction performance are pressure and temperature. These parameters are typically fine-tuned to achieve the desired outcomes in terms of both yield and selectivity.

Additionally, factors such as the moisture content in the sample matrix, the size of the sample and its particles and the flow rate of the solvent can also have a substantial impact on the overall extraction performance. Therefore, comprehensive optimisation of these parameters is essential to achieve the most efficient and effective SC-CO_2 extraction process, ensuring that the desired bioactive compounds are extracted while minimising the unwanted components.

Effect of Pressure at Constant Temperature in SC-CO_2 Extraction for Palm Oil

Pressure plays a pivotal role in the SC-CO_2 extraction process, exerting a significant influence on various aspects of the extraction procedure. Several studies, including those by Li et al. (2023) and Putra et al. (2023e), have underscored the importance of pressure in SC-CO_2 extraction. One of the primary effects of pressure in SC-CO_2 extraction is its impact on the solubility of compounds and the diffusivity of the solvent within the matrix. By utilising a back pressure regulator to maintain the desired pressure level, precise control over the SC-CO_2 process can be achieved. At a fixed temperature, increasing the pressure is known to enhance the solubility of bioactive compounds and subsequently increase the extraction yield (Sodeifian et al., 2022). This occurs because elevated pressure boosts the solvent power and extraction efficiency of SC-CO_2. Additionally, higher pressure leads to an increase in the density of the SC-CO_2, further improving its solubilising capabilities, which is especially relevant in the recovery of compounds like carotene and tocopherol (Arsad et al., 2023).

However, it is important to note that raising the pressure above a certain point may have diminishing returns. Excessive pressure can potentially lead to reduced solvent diffusivity, meaning that the SC-CO_2 may have more difficulty penetrating the pores of the raw material, resulting in decreased solute dissolution (Putra et al., 2023b). Furthermore, excessively high-pressure conditions are not universally recommended for all target compounds, as they may cause compression of the raw material, potentially decreasing the overall extraction yield (Putra et al., 2018).

The effect of pressure on SC-CO_2 extraction is closely associated with changes in solvent power, which are influenced by the density of the solvent and the strengthening of intermolecular physical interactions. These factors collectively contribute to the complex relationship between pressure and extraction efficiency in SC-CO_2 processes (Farobie & Hartulistiyoso, 2021). In summary, pressure control is a crucial parameter in extraction, impacting the solubility of compounds, solvent diffusivity, and the overall extraction yield. Achieving the optimal pressure conditions is essential to maximise the efficiency and selectivity of SC-CO_2 extraction processes for specific target compounds and raw materials.

TABLE 1. THE CRITICAL PARAMETERS IN THE SC-CO_2 EXTRACTION IN THE PALM OIL RECOVERY

Parameter	The optimal range	References
Temperature	40°C-70°C	Bezerra, et al. (2018), Ooi et al. (1996), Tan et al. (2017)
Pressure	10-30 MPa	
Co-solvent	Ethanol (10%)	
Time	Less than 3 hr	
Flow rate	1-3 mL/min	
Particle size	0.25 dp < 1.80 mm	

Effect of Temperature at Constant Pressure in SC-CO_2 Extraction for Palm Oil

Temperature is a critical parameter in SC-CO_2 extraction, and its effects are multifaceted, especially when maintained at constant pressure. Temperature exerts dual influences on the SC-CO_2 extraction process, which are essential to consider in optimising the conditions.

Density and solvating capacity. As temperature increases, one of the primary effects is a reduction in the density of CO_2. This decrease in density can lead to a decrease in the solvating capacity of SC-CO_2. In other words, higher temperatures can reduce the ability of SC-CO_2 to dissolve and carry compounds from the sample matrix (Sodeifian et al., 2016).

Solubility and extraction yield. On the other hand, raising the temperature has a positive impact on the solubility of target compounds and, consequently, on the overall extraction yield. This increase in solubility is attributed to the rise in the vapour pressure of the target compounds, making them more amenable to extraction by SC-CO_2. However, this can also lead to a phenomenon known as "retrogradation," where the isotherms cross. In simpler terms, higher temperatures may result in lower yields, while lower temperatures can lead to higher yields, depending on the specific compounds and conditions (Putra et al., 2023c; Sodeifian & Usefi, 2023).

Competing influences. The inversion of yield isotherms is a consequence of the competing influences of temperature on the extraction process. The dominant factor at play depends on the pressure conditions. Below a certain crossover pressure, the density effect tends to dominate, whereas, at higher pressures, it is the solute vapour pressure that controls the extraction process (Cockrell et al., 2020).

Impact on heat-sensitive compounds. It's essential to recognise that while raising the temperature can enhance extraction efficiency, it may not be suitable for all compounds, particularly those that are heat-sensitive. Many bioactive compounds can break down or undergo oxidation at elevated extraction temperatures, leading to a loss of their biological activity (Dhakane-Lad & Kar, 2021). Therefore, temperature conditions must be carefully adjusted, especially for thermolabile compounds like carotene and tocopherol, which are typically extracted at temperatures ranging from 35°C-70°C (Mustapa et al., 2011).

Temperature-pressure relationship. The effects of temperature and pressure are interconnected. An increase in temperature at constant pressure will decrease the density of the solvent (SC-CO_2) and its solvation power. Conversely, higher temperatures will increase the vapour pressure of the solute, enhancing the solubility of the solute in SC-CO_2 (Kamaruddin et al., 2022).

In summary, temperature control is a vital aspect of SC-CO_2 extraction, with its impact on density, solvating capacity, solubility and extraction yield. Optimising temperature conditions is essential to balance the competing influences and achieve efficient extraction while preserving the integrity of heat-sensitive compounds when necessary. Additionally, understanding the interplay between temperature and pressure is key to fine-tuning the SC-CO_2 extraction process for specific applications.

Effect of Co-solvent/modifier in SC-CO_2 Extraction for Palm Oil

Co-solvents, organic solvents that can be mixed with SC-CO_2 at various ratios, are instrumental in the extraction processes, mainly when targeting hydrophilic or polar compounds. SC-CO_2, by its nature, is a nonpolar solvent and excels in extracting nonpolar compounds. However, it needs to extract hydrophilic substances efficiently. Co-solvents are introduced to modify the polarity of SC-CO_2, enhancing its ability to dissolve and interact with hydrophilic molecules. This addition expands the versatility of SC-CO_2 extraction, allowing for the effective extraction of a broader range of compounds (Marcus, 2018). Co-solvents bring about a crucial enhancement in solvent power through their intrinsic polarity, facilitating interactions like hydrogen bonding and dipole-dipole interactions with the target compounds. These interactions substantially elevate extraction yields, making SC-CO_2 an effective method for a wide array of compounds (Pimentel-Moral et al., 2019).

The choice of co-solvent depends on several factors, including the nature of the material being extracted, the specific compounds of interest, and the outcomes of preparatory tests. Commonly used co-solvents in SC-CO_2 extraction processes include ethanol and methanol, with ethanol often recommended for use in food-related applications due to its safety credentials according to the Food and Drug Administration (FDA) in the United States (Rizkiyah et al., 2023b). Nonetheless, the use of methanol is limited in food or oil manufacturing due to its toxicity concerns. In summary, co-solvents play a pivotal role in SC-CO_2 extraction, allowing for the efficient extraction of hydrophilic and polar compounds that would be challenging to extract using pure SC-CO_2. The choice of co-solvent is made based on the specific extraction requirements, safety considerations, and regulatory guidelines for the intended application.

Effect of Particle Size in SC-CO_2 Extraction for Palm Oil

Particle size is a crucial factor that significantly influences the success of SC-CO_2 extraction. The size and form of particles in the sample matrix have direct implications for the extraction process, especially regarding mass transfer kinetics and the interaction between SC-CO_2 and soluble compounds. Smaller particle sizes play a pivotal role in enhancing extraction efficiency and mass transfer kinetics. When the sample matrix has a small physical morphology, the diffusion path lengths for the extracted solutes to move into the fluid phase become shorter. This results in higher extraction efficiencies and increased mass transfer surface area, as noted by Putra et al. (2023c). The particle size typically varies depending on the nature of the natural product being extracted, falling within the range of 0.25-1.80 mm. However, it's essential to evaluate the optimal particle size on case-to-case basis.

Particle form is another crucial consideration. During the grinding process, particles can take on various shapes, including spherical, flaky, plate-like or irregular forms. These different forms can impact the diffusivity of the solvent as it penetrates the raw material. For instance, smaller particle sizes have been observed to increase the diffusivity coefficient of extracts (Kim & Lim, 2020). However, there is a limit to how small the particles should be, as the smallest sizes, such as 0.2 mm, can lead to reduced diffusivity coefficients (0.72×10^{-13} m/s^2). This reduction is often attributed to compaction and channelling within the particle bed, which can hinder mass transfer. Fine particle sizes may also lead to bed caking and the formation of preferential SC-CO_2 flow paths, further reducing mass transfer efficiency.

In the realm of palm oil extraction using SC-CO_2, an important consideration is the particle size of the palm oil material. The particle size plays a crucial role in the efficiency and effectiveness of the extraction process. If the particle size becomes too small, it can lead to issues such as clogging in the extraction equipment and difficulty in handling the material during the extraction process.

To address these concerns, Putra et al. (2020) have suggested an optimal particle size for palm oil extraction using SC-CO_2. Their research recommends that the average particle size should be around 1 cm. This size ensures that the palm oil material is large enough to prevent clogging while still being small enough to facilitate efficient extraction by SC-CO_2. By maintaining an average particle size of 1 cm, several benefits can be realised. Firstly, it helps to prevent clogging in the extraction equipment, ensuring smooth operation and minimising downtime. Additionally, it allows for easier handling of the palm oil material during the extraction process, reducing the risk of material loss or inefficiencies.

Moreover, optimising the particle size for SC-CO_2 extraction contributes to the overall effectiveness of the process. It promotes better contact between the CO_2 solvent and the palm oil material, enhancing the extraction efficiency and maximising the yield of high-quality palm oil. In summary, controlling the particle size of the palm oil material is crucial for successful extraction using SC-CO_2. By adhering to the recommended average particle size of 1 cm, operators can mitigate potential challenges such as clogging and ensure optimal extraction performance, leading to improved efficiency and yield in the palm oil extraction process.

In summary, particle size and form are critical considerations in SC-CO_2 extraction processes. While smaller particle sizes generally enhance extraction efficiency and mass transfer, an optimal size must be determined based on the specific material and compounds being targeted. The form of the particles also influences diffusivity and should be taken into account to maximise extraction yields while avoiding compaction and channelling issues that can hinder the process.

Effect of Flow Rate in SC-CO_2 Extraction for Palm Oil

The flow rate of carbon dioxide (CO_2) plays a pivotal role in SC-CO_2 extraction experiments, significantly influencing the efficiency of the process. A higher CO_2 flow rate effectively reduces the residence time of CO_2 within the extraction vessel, facilitating increased interactions between CO_2 and the target compounds, such as carotene and tocopherol in palm oil. This enhanced contact leads to improved extraction efficiency, as observed by Peng et al. (2020). Furthermore, the SC-CO_2 flow rate has a profound impact on the mass transfer during extraction, encompassing the solubility-controlled and diffusion-controlled phases. Lowering the solvent flow rate, specifically CO_2, can optimise the efficiency of the extraction process, particularly within the solubility-controlled zone. In this phase, the rate of solute dissolution in CO_2 governs the process, and lower flow rates can be advantageous. They not only enhance efficiency but also reduce the overall volume of solvent needed to extract a specific quantity of target compounds.

The production of compounds of interest, such as carotene and tocopherol in palm oil, is intricately linked to the quantity of CO_2 required for extraction within the solubility-controlled zone, particularly at lower pressures. Controlling the CO_2 flow rate provides a means to fine-tune the extraction process, achieving the desired yield of bioactive compounds, as noted by Idham et al. (2020). In summary, the CO_2 flow rate is a critical parameter in SC-CO_2 extraction, impacting residence time, mass transfer, and overall process efficiency. By carefully adjusting the flow rate, researchers can optimise interactions between CO_2 and target compounds, improve solubility-controlled extraction phases, and minimise solvent usage while achieving the desired yields of bioactive compounds in the extraction processes.

Recent Studies on Palm Oil Extraction by SC-CO_2

A wealth of research has been devoted to exploring various techniques for palm oil recovery, with a particular focus on methods like SC-CO_2 extraction. The parameters governing SC-CO_2 extraction have been extensively studied, aiming to optimise the extraction of valuable compounds such as carotenes and tocopherols as shown in *Table 2*. These results have yielded valuable insights for improving palm oil processing. Ooi et al. (1996) conducted experiments involving the continuous SC-CO_2 processing of crude palm oil, revealing its effectiveness in reducing levels of free fatty acids, monoglycerides, diglycerides, specific triglycerides and certain carotenes. The resulting refined palm oil exhibited reduced free fatty acid content and elevated carotene levels. The study highlighted how increasing extraction pressure enhanced the solvent power of the supercritical fluid.

Tan and Zhao (2017) introduced a unique approach combining SC-CO_2 and n-hexane to extract palm oil and enrich natural β-carotene. This two-step procedure effectively preconcentrated β-carotene using SC-CO_2, followed by solvent extraction, significantly increasing β-carotene concentrations. Bezerra et al. (2018) investigated palm fibre oil extraction using SC-CO_2, showing that oil yields reached a maximum at specific temperature and pressure conditions. Notably, SC-CO_2 extraction resulted in oils with higher saturation levels and lower carotenoid content compared to traditional solvent-based extraction.

TABLE 2. PREVIOUS STUDIES OF PALM OIL EXTRACTION BY SC-CO_2

Authors	Objective	Findings
Ooi et al. (1996)	Investigate the effectiveness of continuous SC-CO_2 processing for refining crude palm oil.	- Reduction of free fatty acids, monoglycerides, diglycerides, specific triglycerides, and carotenes in palm oil. - Refined palm oil with less than 0.1% free fatty acid content. Introduction of a co-solvent, ethanol, notably lowered free fatty acid levels to below 0.1%. - Adjusting parameters like pressure, temperature, and solvent-to-feed ratio is feasible for refining palm oil with SC-CO_2.
Tan and Zhao (2017)	Combine SC-CO_2 extraction and n-hexane to extract and enrich natural β-carotene from palm oil.	- β-carotene concentration increased from 10 g/100 g to 16.7 g/100 g. - Combination with n-hexane solvent further increased β-carotene concentration to 58.7 g/100 g. - SC-CO_2 selectively removed contaminants, allowing purification of β-carotene through hexane extraction.
Bezerra et al. (2018)	Investigate SC-CO_2 extraction of palm pressed-fibre oil at various temperatures and pressures.	- Oil yields reached a maximum of 6.09% at 40°C and 450 bar. - Oils obtained exhibited high saturation levels but relatively low carotenoid content.
De França and Meireles (2000)	Explore the kinetics of carotene and lipid extraction from crushed palm fibres using SC-CO_2.	- Extract from pressed palm fibres exhibited varying concentrations of free fatty acids and carotenoids. - Carotenoid concentrations increased while free fatty acid concentrations decreased over time. - Mathematical model effectively quantified the entire extraction curve, providing valuable insights into the extraction process.
Putra et al. (2020)	Investigate the impact of operational parameters on oil production, total tocopherol compounds, and total carotene compounds during SC-CO_2 extraction.	- The highest oil yield reached 18.49% under specific conditions. - Total tocopherol compounds measured 2020.09 mg/kg. - Total carotene compounds reached 2076.96 mg/kg under specific conditions. - High-pressure conditions were ideal for extracting palm fibre oil due to increased extraction rates, diffusivity, and solubility. - Increased pressure led to higher CO_2 density, enhancing solvent-solute interactions.

De França and Meireles (2000) explored the kinetics of carotene and lipid extraction from crushed palm fibres using SC-CO_2, developing a mathematical model for mass transfer. This model effectively quantified the extraction process, offering insights into the dynamics of the extract composition. Putra et al. (2020) conducted a comprehensive investigation into the SC-CO_2 impact of extraction on oil production, total tocopherol compounds, and total carotene compounds. They used semi-empirical models to determine extraction rates and solubility, revealing that high-pressure conditions were ideal for extracting palm fibre oil due to enhanced extraction rates and solubility.

In summary, these studies collectively provide valuable insights into optimising and improving palm oil recovery through SC-CO_2 extraction methods. The results show the significance of parameter adjustments, co-solvent utilisation, and pretreatment processes to enhance the extraction of valuable compounds from palm-derived materials, contributing to more efficient and sustainable palm oil production.

ADVANTAGES OF SC-CO_2 EXTRACTION FOR PALM OIL EXTRACTION

SC-CO_2 extraction stands at the forefront of innovative technologies that hold immense promise for the palm oil industry. This advanced extraction method has garnered attention for its ability to provide numerous distinct advantages, ranging from environmental sustainability to improved product quality and economic viability. SC-CO_2 extraction offers several distinct advantages for the palm oil industry, as shown below.

Environmental Benefits

The environmental benefits of SC-CO_2 extraction are significant and make it an environmentally friendly choice for various industries, including the palm oil industry. One of the primary environmental benefits of SC-CO_2 extraction is that it utilises CO_2 as the solvent. CO_2 is non-toxic and non-flammable, making it inherently safer for both workers and the environment compared to traditional organic solvents often used in extraction processes (Abdul Aziz et al., 2022). This reduces the risk of accidents, spills and harmful exposure to chemicals in the workplace.

Traditional solvent-based extraction methods can leave behind residues of organic solvents in the extracted product (Fernando et al., 2021). These residues can be harmful to human health and the environment. In contrast, SC-CO_2 is a clean and pure solvent that does not leave any harmful residues or chemical traces in the final product. This ensures that the extracted palm oil and its constituents are free from solvent contaminants. The use of organic solvents in conventional extraction processes can also lead to environmental pollution, as these solvents may be released into the air or water during extraction and purification steps. SC-CO_2, on the other hand, is a closed-loop system where the CO_2 can be easily captured, recycled, and reused, as shown in *Figure 1*. This closed-loop nature of SC-CO_2 extraction minimises emissions and prevents the release of harmful substances into the environment, contributing to a cleaner and healthier ecosystem.

SC-CO_2 extraction aligns with sustainability goals by reducing the overall environmental footprint of the palm oil industry (Fomo et al., 2020). The closed-loop system not only prevents CO_2 emissions but also minimises waste generation. Since SC-CO_2 can be recycled and reused, there is less need for the disposal of solvent waste, reducing the industry's impact on landfills and waste management systems. SC-CO_2 extraction also aligns with increasingly stringent environmental regulations and safety standards (National Academies of Sciences, Engineering and Medicine, 2017). As governments and regulatory bodies around the world place greater emphasis on environmentally friendly practices and worker safety, SC-CO_2 extraction provides a solution that helps companies meet these requirements while ensuring compliance with environmental regulations.

In summary, SC-CO_2 extraction offers a range of environmental benefits for the palm oil industry. Its non-toxic and non-flammable properties, along with the absence of harmful residues, make it a safe and sustainable choice. The closed-loop system minimises environmental pollution and waste generation, contributing to a greener and more environmentally responsible palm oil extraction process.

Improved Oil Quality and Yield

Improved oil quality and yield are critical advantages of SC-CO_2 extraction in the palm oil industry, owing to the precise control it offers over critical extraction parameters (Temelli, 2009). SC-CO_2 extraction provides a high degree of control over parameters such as temperature and pressure. This precision allows operators to tailor the extraction process to their specific requirements. In the context of palm oil extraction, this means that the process can be optimised to target certain compounds while leaving undesirable components behind selectively.

One of the notable improvements in oil quality achieved through SC-CO_2 extraction is the significant reduction in undesirable components, such as free fatty acids (Friedrich & Pryde, 1984). Free fatty acids can negatively impact the quality and shelf life of palm oil. By using SC-CO_2 extraction, these unwanted compounds can be effectively removed, resulting in palm oil with a reduced free fatty acid content. SC-CO_2 extraction is also a gentle process that operates at moderate temperatures (Majid et al., 2019). This is crucial for preserving the quality of the extracted oil, especially in the case of heat-sensitive compounds. Unlike some conventional extraction methods that may expose the oil to high temperatures, SC-CO_2 extraction minimises the risk of degradation or alteration of the oil's chemical composition, ensuring that the extracted palm oil retains its desired characteristics.

SC-CO_2 extraction is known for its ability to yield higher quantities of valuable compounds found in palm oil, such as carotenes and tocopherols (Akanda et al., 2012; Lau et al., 2006). These compounds contribute not only to the nutritional value of the oil but also to its market value. The ability to extract more of these bioactive compounds enhances the overall quality and marketability of the palm oil product. The improved quality and higher yield of valuable compounds achieved through SC-CO_2 extraction translate into a more valuable end product. Palm oil producers can command better prices for high-quality, nutrient-rich palm oil in the market. This value addition can significantly impact the economic viability of palm oil extraction operations.

In summary, SC-CO_2 extraction's ability to offer precise control over extraction parameters, reduce undesirable components, preserve oil quality and enhance the yield of valuable compounds makes it an attractive choice in the palm oil industry. This technology not only results in higher-quality palm oil but also increases its overall value, contributing to improved product quality and economic advantages for palm oil producers.

Economic Advantages

The economic advantages of SC-CO_2 extraction in the palm oil industry are notable, offering long-term benefits that outweigh the initial investment in specialised equipment. SC-CO_2 extraction's ability to improve the quality of palm oil and yield higher quantities of valuable compounds directly contributes to increased profitability for palm oil producers. Higher-quality palm oil with reduced levels of undesirable components, such as free fatty acids, is often more marketable and can command better prices in the market (Bello-Bravo et al., 2015). This enhanced product quality translates into improved revenue streams for producers.

SC-CO_2 extraction allows for the selective extraction of valuable bioactive compounds like carotenes and tocopherols, which are in demand due to their nutritional and health benefits. These compounds enhance the market value of the palm oil product. By diversifying their product offerings with value-added extracts, palm oil producers can tap into additional revenue streams, further bolstering their economic prospects. SC-CO_2 extraction's precise control over extraction parameters ensures efficient resource utilisation. This efficiency minimises the wastage of raw materials and reduces the need for reprocessing or additional treatments, which can be costly. The technology's ability to target specific compounds also ensures that valuable palm oil components are fully extracted, optimising resource utilisation and minimising losses.

Over the long term, SC-CO_2 extraction can lead to reduced production costs. The fine-tuned control over temperature, pressure and other parameters results in more efficient extraction processes (Knez et al., 2019). This efficiency can translate into energy savings, reduced solvent usage, and lower maintenance costs. Additionally, the elimination of the need for certain post-extraction treatments or additional refining steps can further reduce operational expenses. Palm oil producers adopting SC-CO_2 extraction can gain a competitive edge in the market. Higher-quality palm oil and the availability of value-added extracts not only command better prices but also attract discerning consumers and industries looking for premium, sustainable products. This competitive advantage can help palm oil producers secure long-term contracts and partnerships, contributing to financial stability.

The economic advantages of SC-CO_2 extraction extend to long-term sustainability. By investing in environmentally friendly and sustainable extraction practices, palm oil producers can align themselves with the growing consumer and regulatory demand for environmentally responsible products. This positions them for continued success in an evolving market landscape. In conclusion, while SC-CO_2 extraction may require initial investments in equipment, its economic advantages become apparent over time. Improved product quality, increased yield of valuable compounds, efficient resource utilisation, reduced production costs, and a competitive edge in the market all contribute to the long-term profitability and sustainability of palm oil production operations.

CHALLENGES AND BARRIERS IN SC-CO_2 EXTRACTION FOR PALM OIL EXTRACTION

While SC-CO_2 extraction holds immense promise for revolutionising the palm oil industry, it has its set of challenges and hurdles. These technical, economic, and safety considerations, among others, present complexities that must be navigated to fully harness the potential of SC-CO_2 extraction in palm oil production. As this article explores the intricacies of SC-CO_2 extraction in the palm oil sector, it is imperative to shed light on the challenges that accompany this innovative technology. From the technical intricacies of equipment and process optimisation to energy consumption and regulatory compliance, these hurdles demand careful consideration.

In this section, we delve into the technical challenges and limitations that arise from the complexity of SC-CO_2 extraction equipment and the need for meticulous process optimisation. We also address the energy consumption and equipment costs that may pose economic challenges, particularly for smaller producers. Additionally, safety considerations and regulatory compliance are paramount to ensuring the responsible use of SC-CO_2 extraction technology. By understanding these challenges and actively seeking solutions, the palm oil industry can pave the way for a more sustainable and efficient future, harnessing the full potential of SC-CO_2 extraction while mitigating its inherent complexities.

Technical Challenges and Limitations

Technical challenges and limitations in SC-CO_2 extraction for palm oil extraction are multifaceted, encompassing equipment complexity, process optimisation, matrix effects and scale-up challenges. One of the primary technical challenges lies in the complexity of the equipment required for SC-CO_2 extraction (An et al., 2021). This process demands specialised high-pressure vessels capable of withstanding the elevated pressures necessary for supercritical conditions. Precise control systems are also essential to manage parameters such as pressure, temperature, and flow rates. However, the initial investment in such advanced equipment can be prohibitively high, particularly for smaller palm oil producers or those operating with limited financial resources. This complexity can pose a significant barrier to entry into SC-CO_2 extraction technology.

Attaining ideal extraction conditions represents a pivotal element in SC-CO_2 extraction, albeit often presenting a formidable task. Factors such as pressure, temperature, and flow rate necessitate meticulous calibration to achieve a delicate equilibrium between effective compound extraction and maintaining the integrity of the extracted oil (Dhara et al., 2022). Identifying the ideal set of parameters often involves extensive experimentation, testing, and iterative adjustments. The need for precise control further underscores the technical expertise required for successful SC-CO_2 extraction. The variability in the composition of palm fruit and its matrix presents a significant technical hindrance. Factors such as moisture content, fruit ripeness, and the presence of impurities can substantially influence the efficiency of SC-CO_2 extraction (Srinivas & King, 2010). Variations in these matrices can lead to inconsistent yields and product quality. As a result, robust quality control measures and process adaptations may be necessary to accommodate the inherent matrix diversity of palm fruit.

Transitioning from laboratory-scale SC-CO_2 extraction to large-scale industrial operations is a complex undertaking. While laboratory experiments provide valuable insights, scaling up the process introduces engineering and logistical challenges. Maintaining the efficiency and consistency of the extraction process at an industrial scale requires careful consideration of equipment size, throughput rates, and overall process design. Scaling up without compromising product quality or yield demands a thorough understanding of both the technology and the specific characteristics of palm oil extraction. In summary, the technical challenges and limitations of SC-CO_2 palm oil extraction encompass the intricate nature of the equipment, the need for precise process optimisation, the impact of matrix variations and the complexities of scaling up from laboratory to industrial settings. Addressing these challenges requires a combination of technical expertise, innovative engineering solutions, and a commitment to optimising the process for efficient and high-quality palm oil extraction.

Energy Consumption and Equipment Costs

Energy consumption and equipment costs are pivotal considerations when evaluating SC-CO_2 palm oil extraction processes, as they significantly impact both the feasibility and economic viability of adopting this technology (Kayathi et al., 2021). SC-CO_2 extraction involves operating equipment under high pressures and temperatures, which can translate into substantial energy requirements. The compression and maintenance of CO_2 in its supercritical state demand energy-intensive processes. This energy consumption can be a notable concern, especially in regions with elevated energy prices or unreliable power sources. The cost of energy used during extraction directly influences the overall production costs and profitability of palm oil extraction via SC-CO_2. Therefore, optimising energy efficiency is a key challenge in the implementation of this technology.

The initial capital investment associated with SC-CO_2 extraction equipment is a significant factor to consider (Hussain & Wahab, 2018). Specialised high-pressure vessels, precise control systems, and safety features are essential components of SC-CO_2 extraction setups, making the technology capital-intensive. These upfront equipment costs may act as a deterrent for smaller palm oil producers or those with limited financial resources. As a result, the potential benefits of SC-CO_2 extraction, including improved oil quality and higher yields, need to be carefully weighed against the initial investment. Its economic justification for this investment may become evident over time as the technology's advantages are realised.

In summary, the high energy consumption and substantial equipment costs associated with SC-CO_2 palm oil extraction are pivotal challenges and considerations for stakeholders in the palm oil industry. Balancing the need for energy-intensive operations with long-term economic benefits, improved product quality and increased yields will determine the feasibility and attractiveness of adopting SC-CO_2 extraction technology for palm oil production. Furthermore, ongoing research and technological advancements may lead to more energy-efficient and cost-effective SC-CO_2 extraction solutions, potentially mitigating some of these challenges in the future.

Safety Considerations

Safety considerations are of paramount importance in SC-CO_2 palm oil extraction due to the use of high-pressure equipment and the need to protect both personnel and the environment (Norhuda & Jusoff, 2009). SC-CO_2 extraction relies on high-pressure vessels to maintain CO_2 in its supercritical state. Although CO_2 itself is non-toxic and non-flammable, the elevated pressures involved can pose safety risks if not properly managed. To address this, rigorous safety protocols and training are essential. Operators and maintenance personnel must receive thorough training in the safe operation of high-pressure equipment, including recognising potential hazards, understanding emergency procedures and using protective gear. Regular equipment inspections and maintenance are also crucial to ensure the integrity of pressure vessels.

Ensuring the safety of individuals working with SC-CO_2 extraction equipment is of utmost importance. This includes not only those directly involved in the extraction process but also maintenance and support staff. Safety measures should encompass comprehensive training on the proper handling of SC-CO_2 equipment, safe operating procedures and emergency response protocols. The provision of personal protective equipment (PPE) is essential to minimise risks, and its correct use should be enforced. Additionally, equipment design should prioritise operator safety, with features that prevent accidental exposure to high pressures or temperatures.

While SC-CO_2 is generally considered environmentally friendly, there are environmental concerns related to potential CO_2 emissions during the extraction process. To mitigate this, strict containment measures should be in place to prevent the release of SC-CO_2 into the atmosphere. Any potential leaks or emissions must be promptly identified and addressed. Regular monitoring and maintenance of the extraction system are crucial to minimise environmental impact. Furthermore, efforts should be made to capture and recycle any released CO_2 to minimise its contribution to GHG emissions, aligning with sustainability goals. In summary, safety considerations in SC-CO_2 palm oil extraction revolve around managing high-pressure equipment, ensuring worker safety through training and protective measures and addressing potential environmental impacts associated with CO_2 emissions. Stringent safety protocols, ongoing training and proactive maintenance are essential components of a safe and responsible SC-CO_2 extraction process.

Regulatory Compliance

Regulatory compliance is a critical aspect of adopting and operating SC-CO_2 extraction technology in the palm oil industry. Ensuring adherence to local and international regulations and standards is essential for legal, safety, and environmental reasons. SC-CO_2 extraction, while considered more environmentally friendly than some traditional extraction methods, still needs to comply with environmental regulations. This includes ensuring that emissions of CO_2 or other substances are within allowable limits and that waste disposal methods are in line with environmental standards. Operators may need to obtain permits or approvals from environmental agencies.

Operating SC-CO_2 extraction equipment involves high-pressure systems, which are subject to safety regulations. These regulations may vary depending on the jurisdiction and may cover the design, construction, inspection and operation of pressure vessels. Compliance with safety standards is crucial to prevent accidents and protect workers. Regular inspections and certifications may be required to demonstrate compliance. If the palm oil extracted using SC-CO_2 is intended for human consumption, it must meet food safety and quality standards. This includes compliance with regulations related to food additives, contaminants, and packaging. Ensuring the purity and safety of the extracted oil is essential to meet these standards and gain market acceptance.

The safety of workers involved in SC-CO_2 extraction is subject to occupational health and safety regulations. These regulations may specify requirements for training, protective equipment, emergency response plans and safe operating procedures. Complying with The Occupational Health and Safety (OHS) regulations is essential to protect the well-being of employees. For palm oil producers involved in international trade, compliance with export and import regulations is crucial. These regulations may relate to customs documentation, tariffs, trade agreements and product specifications. Meeting these requirements ensures smooth international transactions.

Obtaining certifications related to sustainability, quality and safety can be beneficial for palm oil producers using SC-CO_2 extraction. Certifications like Roundtable on Sustainable Palm Oil (RSPO) and Malaysian Sustainable Palm Oil (MSPO) demonstrate a commitment to sustainable practices. Additionally, certifications related to food safety (e.g., ISO 22000) or organic production can enhance the marketability of palm oil products (Overbosch & Blanchard, 2023). Proper disposal of waste generated during the SC-CO_2 extraction process, such as spent palm fruit materials, may be subject to waste management regulations. Compliance with these regulations is essential to minimise environmental impact and legal liability.

Regulatory compliance often involves thorough record-keeping and reporting. Maintaining comprehensive documentation of processes, safety measures, emissions data, and other relevant information is essential for demonstrating compliance and responding to regulatory inquiries. Navigating the regulatory landscape can be complex, and it may require legal counsel or regulatory experts to ensure full compliance. While compliance adds complexity and costs to SC-CO_2 extraction operations, it is essential for legal and ethical operation, ensuring the safety of workers and the environment and gaining market access for palm oil products.

Maintenance and Upkeep

Maintenance and upkeep of SC-CO_2 extraction equipment are critical aspects of ensuring its safe and efficient operation in the palm oil industry. Regular inspections of the SC-CO_2 extraction equipment are essential to identify wear and tear, potential issues, or signs of malfunction. These inspections should encompass all components, including high-pressure vessels, pumps, valves and control systems (Patrignani & Lanciotti, 2016). The frequency of inspections may vary but should adhere to a predefined schedule to catch problems early. Maintenance schedules should include routine servicing of the equipment. This involves tasks such as lubricating moving parts, replacing worn seals, and cleaning critical components. Properly maintained equipment operates more efficiently and has an extended lifespan.

Instrumentation and control systems, such as pressure gauges and temperature sensors, should be regularly calibrated to ensure accurate readings. Periodic testing of safety features and emergency shutdown systems is also vital to verify their functionality in case of an emergency. Over time, components of SC-CO_2 extraction equipment may wear out or become damaged. The timely replacement of these parts is crucial to prevent equipment breakdowns and maintain operational efficiency. Common replacement parts may include seals, gaskets and valves.

Safety components, such as pressure relief valves, should be inspected and tested to ensure they meet safety standards. These safety features are essential for preventing accidents in high-pressure systems (Dinh et al., 2012). Personnel responsible for equipment maintenance should receive proper training on the specific maintenance requirements of SC-CO_2 extraction equipment. They should be familiar with safety protocols, troubleshooting procedures, and the correct use of maintenance tools and equipment. Having a well-defined emergency response plan is essential in case of equipment failures or safety incidents. Personnel should be trained on how to respond to emergencies, including shutdown procedures, evacuation protocols, and first aid.

Maintaining detailed records of all maintenance activities is crucial for tracking the history of equipment maintenance and ensuring compliance with safety and regulatory requirements (Mobley, 2011). These records can also help identify recurring issues and inform decisions about equipment upgrades or replacements. Implementing a preventive maintenance programme can help identify potential issues before they lead to equipment failure. This proactive approach involves regular check-ups, cleaning, and adjustments to keep the equipment in optimal working condition. Periodic assessments of equipment performance and maintenance practices should be conducted to identify areas for improvement. This may involve upgrading equipment to more efficient models or implementing enhanced maintenance procedures. In summary, maintaining SC-CO_2 extraction equipment in the palm oil industry is a multifaceted process that includes routine inspections, scheduled servicing, part replacements, safety measures, training, and documentation. A well-maintained system not only operates efficiently but also enhances safety and minimises downtime, ultimately contributing to the overall success of palm oil extraction processes.

PROSPECT FOR SUSTAINABLE PALM OIL PRODUCTION

The prospects for sustainable palm oil production are closely tied to innovative technologies like SC-CO_2 extraction, which have the potential to revolutionise the palm oil industry. SC-CO_2 extraction has emerged as a game-changing technology with the potential to transform the palm oil industry towards sustainability. By offering a cleaner and more efficient method for palm oil extraction, SC-CO_2 can significantly reduce the environmental footprint of palm oil production. Its ability to selectively extract valuable compounds while improving oil quality and yield positions it as a sustainable alternative to traditional extraction methods.

The adoption of SC-CO_2 extraction aligns with the industry's growing emphasis on reducing its environmental impact. Unlike conventional solvent-based extraction processes that employ toxic and environmentally harmful solvents, SC-CO_2 is non-toxic, non-flammable and does not produce hazardous residues. This inherently reduces pollution, making it a more sustainable choice. Sustainable palm oil production has become a global priority to address these concerns. SC-CO_2 extraction fits into this sustainability narrative by offering a greener alternative that minimises habitat destruction and ecosystem disruption.

Many sustainability certification standards, such as the RSPO and MSPO require adherence to environmentally friendly practices. SC-CO_2 extraction aligns with these standards and can help palm oil producers attain certification, thereby accessing premium markets and demonstrating their commitment to sustainability. Consumer demand for sustainable products is on the rise. Manufacturers and retailers are increasingly seeking sustainable palm oil sources to meet consumer expectations and enhance their brand image. Palm oil produced using SC-CO_2 extraction can be marketed as a sustainable and environmentally responsible choice, opening up opportunities for market growth.

Continued investment in research and development to refine SC-CO_2 extraction processes specific to palm oil can unlock even more excellent sustainability benefits. This may include optimising extraction conditions, reducing energy consumption and finding innovative uses for by-products, further enhancing the industry's sustainability profile. Collaboration among stakeholders in the palm oil industry, including producers, governments, NGOs and research institutions, can facilitate the adoption of sustainable practices like SC-CO_2 extraction. Knowledge sharing and best practice dissemination can accelerate the industry's transition towards sustainability. In conclusion, the prospects for sustainable palm oil production are promising, with SC-CO_2 extraction playing a pivotal role in this transformation. By reducing environmental impact, conserving biodiversity and aligning with sustainability goals, SC-CO_2 extraction technology offers a path towards a more sustainable and responsible palm oil industry, meeting the demands of consumers, certification standards and global environmental priorities.

FUTURE DIRECTIONS AND RESEARCH OPPORTUNITIES

Future directions and research opportunities in SC-CO_2 extraction technology for palm oil production offer exciting possibilities for enhancing sustainability, efficiency and product quality. Continued research into the optimisation of SC-CO_2 extraction parameters, such as pressure, temperature, flow rate and co-solvent use, can lead to improved extraction efficiency and higher yields of valuable compounds. Fine-tuning these parameters for different palm oil varieties and fruit maturation stages can enhance the versatility of the technology.

Developing scalable SC-CO_2 extraction systems for industrial use is essential. Research into cost-effective scaling techniques and equipment design will be crucial to making SC-CO_2 extraction accessible to a broader range of palm oil producers, from smallholders to large plantations. Exploring novel co-solvents and their effects on SC-CO_2 extraction can also improve the selectivity and efficiency of the process. Research into eco-friendly and food-grade co-solvents that enhance the solubility of specific compounds while maintaining product safety is an area of potential innovation. Investigating methods to preserve the nutrient and bioactive compound content of palm oil during SC-CO_2 extraction is also essential for maintaining product quality. Innovative techniques, such as encapsulation or controlled release, can help prevent oxidation and degradation.

Investigating ways to utilise by-products and waste streams generated during SC-CO_2 extraction can contribute to sustainability. Research can focus on converting these by-products into value-added products, such as biofuels, animal feed or fertilisers, reducing waste and increasing overall resource efficiency. Research efforts to reduce the energy consumption of SC-CO_2 extraction equipment can enhance its economic viability and environmental sustainability. Innovations in heat recovery, process integration, and energy-efficient designs can help lower operational costs. Furthermore, developing continuous SC-CO_2 extraction processes can improve productivity and reduce processing times. Research into continuous flow systems and their scalability for palm oil production can be a significant area of exploration. Advancements in automation and control systems can improve the precision and reproducibility of SC-CO_2 extraction processes.

Developing intelligent sensors and real-time monitoring tools can enhance process control and product consistency.

Conducting comprehensive life cycle assessment (LCA) to evaluate the environmental impact of SC-CO_2 extraction compared to traditional methods can provide valuable data for decision-makers. LCA studies can guide sustainability initiatives and inform stakeholders about the technology's eco-efficiency. Furthermore, encouraging collaboration among researchers, industry experts and policymakers is vital to drive innovation in SC-CO_2 extraction technology. Research consortia and knowledge-sharing platforms can facilitate the exchange of ideas and accelerate technology development.

Research should focus on aligning SC-CO_2 extraction practices with evolving sustainability standards and regulatory requirements. Staying informed about changing regulations and proactively adapting technology to meet compliance standards is crucial. Moreover, research efforts should extend to market expansion strategies and consumer education. Creating awareness about the benefits of palm oil produced using SC-CO_2 extraction can drive demand for sustainable palm oil products and incentivise industry-wide adoption. In summary, the future of SC-CO_2 extraction technology for palm oil production holds immense potential for sustainable, efficient, and high-quality oil extraction. Study in these areas can lead to innovations that not only benefit the palm oil industry but also contribute to broader sustainability and environmental conservation goals. Collaborative efforts and interdisciplinary research will be key drivers of progress in these directions.

CONCLUSION

In conclusion, SC-CO_2 extraction technology has emerged as a promising and environmentally friendly approach for revolutionising the palm oil industry. This manuscript has provided an in-depth exploration of the prospects, advantages, challenges, and research opportunities associated with SC-CO_2 extraction in palm oil production. The environmental benefits of SC-CO_2 extraction, characterised by its non-toxic nature, minimal waste generation and recyclability, position it as a sustainable alternative to traditional solvent-based extraction methods. This technology aligns with global sustainability goals and offers a pathway to reduce deforestation, conserve natural resources and produce palm oil of higher quality.

SC-CO_2 extraction empowers palm oil producers with precise control over extraction parameters, enhancing oil quality while increasing yields of valuable compounds like carotenes and tocopherols. These improvements contribute to the economic viability of palm oil production, making it an attractive choice for both small-scale and large-scale operations. However, challenges and hurdles exist, including the complexity of equipment, energy consumption, safety considerations, regulatory compliance and maintenance costs. Addressing these challenges through continued research and innovation is essential to unlock the full potential of SC-CO_2 extraction in the palm oil industry. Prospects for sustainable palm oil production are promising, driven by the potential of SC-CO_2 extraction to align with sustainability goals, reduce environmental impact, and promote responsible practices. As palm oil remains a critical commodity in various industries, embracing this innovative technology can lead to a more sustainable and responsible palm oil sector.

Looking ahead, future research directions and opportunities in SC-CO_2 extraction technology include optimising process parameters, scaling up operations, exploring eco-friendly co-solvents, utilising waste streams, enhancing energy efficiency, and preserving nutrient and bioactive compounds. Collaboration, regulatory alignment and consumer awareness will play pivotal roles in realising the full potential of SC-CO_2 extraction in palm oil production. In conclusion, the adoption and further development of SC-CO_2 extraction technology hold great promise for reshaping the palm oil industry, fostering sustainability, and meeting the demands of a changing world while preserving our environment for future generations.

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