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ADVANCING RUBBER SEED OIL FOR SUSTAINABLE DEVELOPMENT AND ENERGY SECURITY IN NIGERIA THROUGH THE LENS OF THE RUBBER RESEARCH INSTITUTE OF NIGERIA

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Abstract

Rubber seed oil (RSO), once regarded as an agricultural byproduct, is gaining attention as a promising resource for industrial and sustainable development. This study explores the untapped potential of RSO from Nigeria, highlighting its physicochemical properties, extraction methods, and diverse applications across the biofuel, pharmaceutical, and polymer sectors. Through a multidisciplinary lens, the work underscores Nigeria's strategic position as a key player in the global bioeconomy, driven by its abundant rubber seed resources and growing interest in renewable alternatives. Emphasis is placed on innovations that enhance oil yield, refine quality, and support eco-friendly utilization, positioning RSO as a viable candidate for replacing conventional oils in industrial processes. The study also sheds light on the challenges of commercialization, regulatory gaps, and the need for international collaboration to fully unlock RSO's potential. Ultimately, this work affirms that Nigeria's rich natural resources, particularly rubber seed oil, can serve as a cornerstone for sustainable progress in a resource-conscious world.

***Keywords**: Rubber seed oil, Bio-based materials, Renewable energy, Biodiesel, Sustainable extraction, Green chemistry.*

Graphical Abstract

1.0 INTRODUCTION

Rubber seed oil (RSO), obtained from the seeds of Hevea brasiliensis, represents a valuable yet largely underutilized bioresource. This is especially true in major natural rubber-producing countries such as Nigeria, where vast quantities of rubber seeds are generated as by-products of rubber cultivation [1-3]. Traditionally considered agricultural waste, these seeds have only recently attracted attention for their potential to serve as a renewable source of oil with diverse applications. The increasing global emphasis on sustainability and renewable resources has fueled interest in RSO as an environmentally friendly alternative to conventional oils [4-7].

Globally, rubber seed oil is recognized for its versatility and sustainability. Its applications span multiple sectors, including biodiesel production, industrial raw materials such as coatings and polymers, and even nutritional supplements following appropriate detoxification. The oil's unique chemical composition, rich in unsaturated fatty acids, lends itself well to these varied uses, positioning it as a multifunctional resource. Despite these advantages, RSO remains underexploited due to challenges related to seed collection, processing, and awareness [7-8].

The Rubber Research Institute of Nigeria (RRIN) has been at the forefront of efforts to harness the potential of rubber seed oil. As a premier research institution dedicated to advancing rubber science and technology, RRIN has developed extraction methods, characterized the physicochemical properties of RSO, and evaluated its suitability for biodiesel and industrial applications. These efforts not only address local economic and environmental challenges but also align with global initiatives aimed at diversifying bio-based economies and reducing carbon footprints. Through its research, RRIN is contributing to the growing body of knowledge that supports the commercialization and wider adoption of RSO [8-10].

This mini review aims to provide a comprehensive overview of rubber seed oil, focusing on its chemical characteristics, industrial and biodiesel applications, and nutritional relevance. Particular emphasis is placed on the pivotal role of RRIN in advancing RSO research and the future prospects for scaling its use from Nigeria to the global stage. By synthesizing current research and highlighting emerging opportunities, this review underscores the potential of rubber seed oil as a sustainable resource capable of contributing to energy security, industrial innovation, and economic development worldwide.

2.0 RUBBER SEED OIL

2.1 Source of Rubber Seed Oil

Rubber seed oil (RSO) is obtained from the seeds of

Hevea brasiliensis, the rubber tree, which serves as the primary global source of natural rubber. These trees are extensively cultivated in tropical regions, notably Southeast Asia, West Africa, and parts of South America. In Nigeria, where rubber cultivation is a key agricultural activity, large volumes of rubber seeds are generated as by-products during the latex harvesting process. These seeds are housed within fruit pods that typically mature around six months after pollination, with each pod usually containing three seeds [9].
Historically, rubber seeds have been underutilized—often considered agricultural waste or, in some instances, diverted for use as animal feed. However, research and development initiatives, particularly by the Rubber Research Institute of Nigeria (RRIN), have highlighted the significant potential of these seeds due to their high oil content, which ranges from 40% to 50% by weight depending on the cultivar and agroecological conditions. The oil is rich in unsaturated fatty acids, giving it versatile applicability in the production of industrial oils, biodiesel, and potentially edible oils with appropriate refining [10-11].

The harvesting of rubber seeds generally aligns with latex tapping cycles but necessitates distinct post-harvest handling to preserve seed integrity and oil quality. Seeds are collected from mature pods that fall naturally to the ground beneath the plantation canopy. This collection process contributes to sustainable agricultural practices by valorizing what would otherwise be discarded biomass [12-13]. Through the efforts of RRIN and other stakeholders, the full potential of rubber seeds is increasingly being realized, transforming a once-neglected by-product into a valuable resource for Nigeria's agro-industrial sector.

2.2 Extraction Process of Rubber Seed Oil

2.2.1 Seed Preparation

The extraction of oil from rubber seeds involves several critical steps, each influencing the yield and quality of the final product. The process broadly includes seed preparation, oil extraction, and oil purification. At the Rubber Research Institute of Nigeria (RRIN), significant emphasis is placed on the preparatory processing of rubber seeds prior to oil extraction, as this phase plays a pivotal role in determining both the efficiency of oil recovery and the quality of the extracted oil. Before any extraction method can be applied, the seeds must be systematically processed to remove their hard outer shell and prepare the inner kernel for optimal oil release. This preparatory sequence is not only critical for enhancing oil yield but also essential for maintaining product quality and reducing impurities [14-15]. Figure 1 illustrates the schematic representation of these preparatory steps—cleaning, drying, dehulling, and grinding—which have been standardized through RRIN's research to support best practices in rubber seed oil production.

The initial step, cleaning, involves the removal of dirt, plant debris, and other extraneous materials that may have accumulated during harvesting and handling. This step is essential to prevent contamination and ensure the purity of the seed material as it progresses through the processing stages. RRIN's protocols advocate for thorough cleaning to uphold the integrity of the final oil product, particularly when intended for edible or high-value industrial applications [17].

After cleaning, the seeds are subjected to drying to reduce moisture content. Moisture reduction is critical in preventing microbial activity and rancidity, thereby extending the shelf life of the seeds and preserving oil quality. The drying process may involve traditional sun drying or controlled mechanical drying systems, depending on the scale of operation. According to RRIN's standards, seeds should be dried to a moisture content below 10% to achieve stable storage and facilitate efficient oil extraction [10, 18].

The third stage is dehulling, where the outer seed coat (testa) is removed to expose the oil-rich kernel. This can be achieved manually or through mechanical means, and is considered a vital operation, as it not only improves the oil extraction efficiency but also minimizes the introduction of unwanted fibrous material into the extraction process. Research at RRIN has shown that effective dehulling significantly enhances oil recovery rates and reduces downstream refining burdens [9-10].

Finally, the kernels undergo grinding or crushing to break them into smaller particles or flakes. This process increases the surface area of the kernel mass, allowing for better penetration of solvents or improved mechanical pressing during extraction [10]. RRIN's investigations have confirmed that proper grinding enhances oil yield by promoting more efficient oil release from the cellular matrix of the seed. Together, these preparatory steps—as depicted in Figure 1—form the foundation for successful rubber seed oil extraction and are critical to ensuring a high-quality, market-ready product.

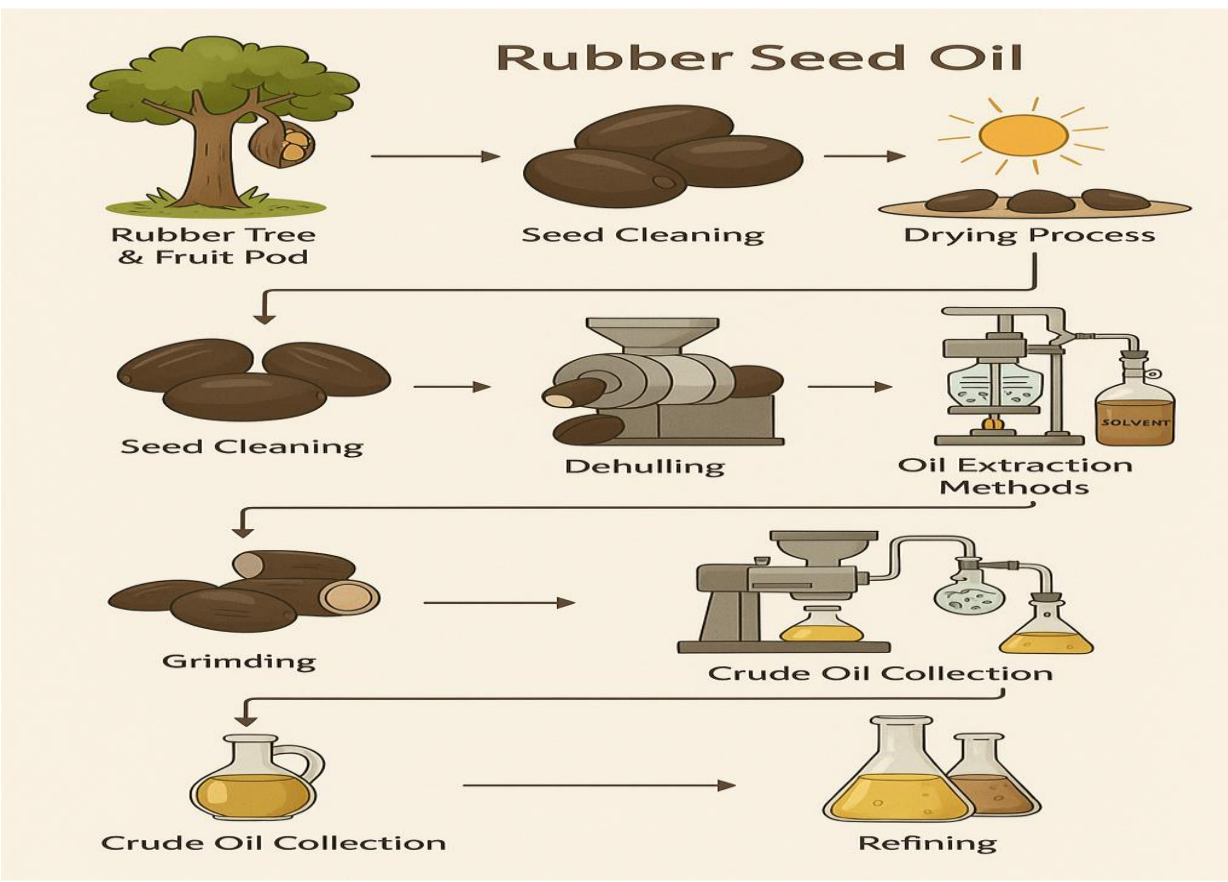

Figure 1: The preparatory steps for rubber seed oil extraction, including cleaning, drying, dehulling, and grinding of the seeds to optimize oil yield and quality.

2.2.2 Oil Extraction Methods

2.2.2.1 Mechanical Expression

At the Rubber Research Institute of Nigeria (RRIN), extensive research has been devoted to developing and optimizing various techniques for extracting oil from rubber seed kernels, with the goal of maximizing yield, ensuring quality, and enhancing commercial viability. The choice of extraction method is determined by several key factors, including technological accessibility, desired oil purity, cost-effectiveness, and intended end use [5].

One of the most widely investigated and applied methods at the Institute is mechanical expression, which can be implemented through cold or hot pressing. This traditional, solvent-free technique employs either screw or hydraulic presses to physically expel oil from ground rubber seed kernels. Cold pressing is performed at ambient or controlled low temperatures, thereby preserving the integrity of heat-sensitive compounds and resulting in oil with minimal need for further chemical refinement. In contrast, hot pressing involves preheating the seed material prior to pressing, which enhances oil fluidity and extraction efficiency but may lead to the degradation of certain nutritional or functional components [6, 9].

Mechanical expression aligns with RRIN's commitment to environmentally responsible processing technologies, offering a cleaner and safer alternative to chemical extraction methods. Despite its eco-friendly profile and suitability for both edible and industrial-grade oil, the oil yield—typically between 35% and 40%—is relatively lower than that achieved through solvent-based extraction techniques. Nonetheless, mechanical pressing remains a viable and scalable option for local and medium-scale processors [15]. The extraction process as practiced and studied at RRIN is illustrated in Figure 2.

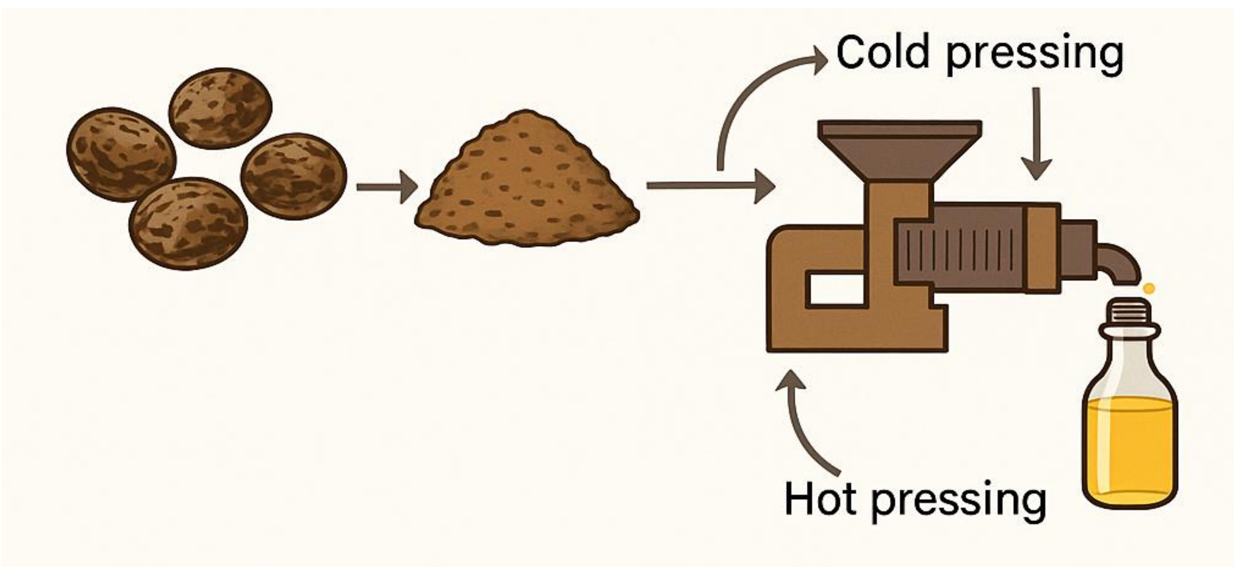

Figure 2: Rubber seed oil extraction via mechanical expression.

2.2.2.2 Solvent Extraction

Solvent extraction is a widely used method for recovering oil from rubber seed powder or flakes by employing organic solvents such as hexane or petroleum ether. In this process, the prepared seed material is soaked in the solvent, allowing the oil to dissolve into the liquid phase. The mixture is then subjected to distillation to recover the solvent, leaving behind the extracted oil. This technique is particularly favoured in industrial applications due to its high efficiency, often yielding oil recovery rates of up to 50–55% [5, 9].

Despite its effectiveness, solvent extraction requires stringent control of processing conditions, including temperature and time, to maintain the quality of the extracted oil and prevent degradation. Additionally, careful removal of solvent residues is essential, particularly when the oil is intended for edible use, to ensure product safety and compliance with health standards [6, 15]. The overall process is illustrated in Figure 3, which presents a schematic representation of the extraction of rubber seed oil (RSO).

Figure 3. Schematic representation of the extraction of RSO [16]

2.2.3 Enzymatic and Supercritical Fluid Extraction (Emerging Methods)

Enzymatic extraction utilizes targeted enzymes to degrade the structural components of seed cell walls, thereby enhancing the release of oil. This method offers the advantage of improved yield while preserving the quality of the oil, all with minimal reliance on harsh chemicals. Similarly, supercritical CO_2 extraction employs carbon dioxide in its supercritical state—under high pressure and moderate temperature—as a solvent [17-18]. This technique provides a clean, selective, and environmentally friendly alternative to conventional methods, eliminating concerns about residual solvents in the final product. Although both enzymatic and supercritical CO_2 extraction are still primarily in the research or pilot-scale stages for rubber seed oil (RSO), they present significant potential for producing high-purity oil suitable for specialty or high-value applications. These emerging technologies may pave the way for more sustainable and refined oil extraction processes in the future [19-20].

2.2.3 Oil Purification and Quality Control

After extraction, crude rubber seed oil contains various impurities such as free fatty acids, phospholipids, proteins, and color pigments that must be removed through refining before the oil can be used commercially. The standard refining process involves several key steps. First is degumming, which removes phospholipids and mucilaginous substances through hydration and centrifugation. This is followed by neutralization, where the oil is treated with an alkali to neutralize free fatty acids and reduce its overall acidity. The next step is bleaching, which involves the use of adsorbents to eliminate pigments and other impurities that affect the oil's color. Finally, deodorization is carried out using steam distillation under vacuum conditions to remove volatile compounds responsible for unpleasant odors and to enhance the oil's flavour [21-22].

These refining processes are essential to improve the oil's stability, appearance, and overall usability, making it suitable for a range of applications including industrial use, biodiesel production, and in some cases, edible purposes. Rubber seed oil is derived from the seeds of the rubber tree, a widely cultivated but underutilized resource in Nigeria and other tropical regions [23]. The extraction methods employed—ranging from mechanical pressing to solvent-based and advanced techniques—are chosen based on desired oil yield, quality, and environmental impact. Ensuring proper seed handling and adopting effective refining methods are critical for producing high-quality rubber seed oil that aligns with both industrial and nutritional requirements. Ongoing research efforts, notably by the Rubber Research Institute of Nigeria, continue to focus on optimizing extraction and refining processes, increasing yield, and promoting the broader commercial adoption of rubber seed oil on a global scale [24].

Table 1: Summary of key refining steps for rubber seed oil and their effects on oil quality.

Refining Step	Purpose	Method	Impact on Oil Quality
Degumming	Remove phospholipids	Hydration & centrifugation	Reduces impurities
Neutralization	Reduce acidity	Alkali treatment	Lowers free fatty acids
Bleaching	Remove pigments	Adsorbent treatment	Improves color

3.0 CHEMICAL COMPOSITION AND PHYSICOCHEMICAL PROPERTIES

Rubber seed oil (RSO) is characterized by a unique fatty acid profile, with unsaturated fatty acids comprising approximately 78–82% of the total composition. Among these, linoleic acid (C18:2) is the predominant unsaturated component, while palmitic (C16:0) and stearic (C18:0) acids constitute the main saturated fatty acids. RSO is classified as a semi-drying oil, possessing an iodine value in the range of 120–140 g I_2/100 g oil, indicative of its capacity for oxidative polymerization [25-26]. This property is particularly valuable for applications in industrial coatings, paints, and polymer-based materials. Additionally, RSO exhibits physicochemical properties—such as specific gravity, viscosity, acid value, and peroxide value—that fall within acceptable limits for use as biodiesel feedstock and other industrial raw materials [26-27]. Analytical assessments conducted by the Rubber Research Institute of Nigeria (RRIN) have confirmed the consistency and quality of RSO derived from locally cultivated rubber seeds, further affirming its potential across diverse downstream applications (Figure 4).

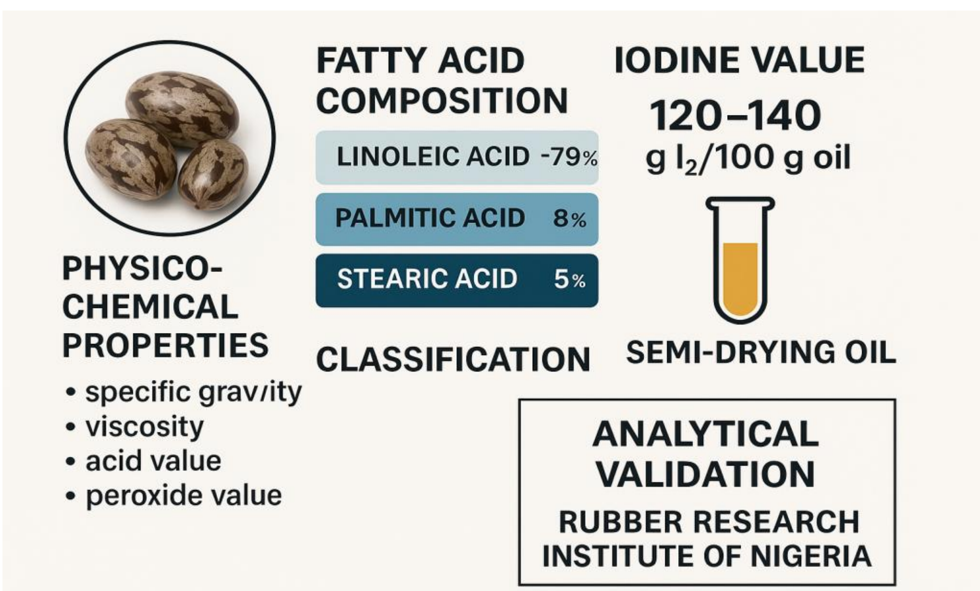

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Figure 4. The key physicochemical and compositional properties of Rubber Seed Oil (RSO), including its high unsaturated fatty acid content (notably linoleic acid), iodine value range (120–140 g I_2/100 g oil), and classification as a semi-drying oil.

Table 2: Fatty acid composition of rubber seed oil compared to other vegetable oils.

Fatty Acid	RSO (%)	Palm Oil (%)	Soybean Oil (%)
Linoleic (C18:2)	38–42	10–12	50–55
Oleic (C18:1)	22–25	38–40	20–25
Palmitic (C16:0)	10–12	42–45	10–12

3.1 Biodiesel Production and Engine Performance

Among the most promising applications of rubber seed oil (RSO) is its conversion into biodiesel through transesterification, offering a renewable and sustainable alternative to fossil-based fuels [28]. This pathway has gained significant attention due to the growing global concerns about the environmental impacts of conventional diesel, the volatility of crude oil prices, and the anticipated depletion of fossil fuel reserves. Various studies have emphasized the viability of RSO as a non-edible feedstock for biodiesel production, owing to its high oil content (ranging from 35–50% by weight) and favorable fatty acid composition [29]. For instance, Helallo *et al.* (2021) [28] and Trirahayu *et al.* (2022) [28] both demonstrated optimized extraction techniques yielding up to 61.3% oil by weight and biodiesel yields above 80%, aligning with RRIN's reported yields exceeding 90% under optimized transesterification protocols.

The physicochemical properties of RSO biodiesel, such as viscosity, flash point, calorific value, and cetane number, have been shown to meet international standards (ASTM D6751 and EN 590), as observed by Ifijen *et al.* (2025) [26], Helallo *et al.* (2021) [28], and Njoku *et al.* (2000) [29]. These parameters confirm RSO biodiesel's compatibility with internal combustion engines without requiring modifications. Furthermore, performance evaluations of RSO-based biodiesel blends—particularly B20 and B50—reveal combustion efficiencies that are comparable or even superior to those of petroleum diesel, with improved torque and brake thermal efficiency in some cases. As highlighted by RRIN, these blends also demonstrate notable environmental benefits, including significant reductions in carbon monoxide (CO), unburned hydrocarbons (HC), and particulate matter (PM) emissions, thereby reinforcing RSO biodiesel's potential to contribute to cleaner air and lower carbon footprints.

In addition to its energy applications, RSO has been explored for value-added industrial uses. Elabor *et al*. (2023) demonstrated its polymerization into environmentally friendly alkyd resins for the surface coating industry, particularly when blended with soybean oil to enhance drying performance and color characteristics [27]. This diversification further underscores the industrial relevance of RSO beyond biodiesel, reflecting its potential as a versatile bio-based resource.

Nonetheless, key technical challenges persist, especially regarding oxidative stability and cold flow properties—limitations often associated with the high unsaturation level of RSO. These were addressed by Njoku *et al.* (2000), who noted that while transesterification significantly improves the fuel properties of RSO, it can slightly reduce oxidative stability [30]. Similarly, Oyekunle *et al*. (2024) emphasized the need for further catalyst development and techno-economic evaluations to ensure consistent and economically viable production [15]. These findings complement RRIN's ongoing efforts to enhance fuel stability, shelf life, and cold weather operability of RSO biodiesel, particularly for tropical applications.

Across the studies reviewed, there is a shared consensus that the abundance of rubber plantations and the underutilized nature of rubber seeds present a unique opportunity for biofuel production without interfering with food resources. The research conducted by RRIN and supported by findings from scholars such as Ifijen *et al.* (2025) [26] and Trirahayu *et al.* (2022) [28] illustrates the economic feasibility and scalability of biodiesel production from rubber seed oil. The integration of process optimization, simulation modelling (e.g., ASPEN Hysys), and methanol recovery techniques further strengthen the case for large-scale implementation.

The collective body of research underscores the transformative potential of RSO as a biodiesel feedstock capable of diversifying Nigeria's energy portfolio and contributing to global renewable energy objectives. By overcoming technical challenges and investing in scalable technologies, RSO biodiesel can emerge as a key component in the transition toward sustainable and environmentally responsible fuel alternatives.

3. 2 Industrial and Nutritional Applications

3.2.1 Surface Coatings and Alkyd Resins

The semi-drying nature of rubber seed oil (RSO), attributed to its high proportion of unsaturated fatty acids such as linoleic, linolenic, and oleic acids, makes it a viable renewable feedstock for alkyd resin synthesis. Several studies have explored the modification, synthesis, and performance enhancement of alkyd resins derived from RSO, highlighting its potential as a sustainable replacement for petrochemical-based binders in the surface coatings industry [31-33]. RSO's inherent film-forming capabilities and reactive sites facilitate polymerization through condensation reactions with polyols and anhydrides, forming the backbone of both solvent-based and waterborne alkyd resins [34-35].

Research has demonstrated that modification strategies such as blending RSO with linseed oil or maleinization significantly enhance resin performance. For example, Ifijen *et al.* (2021) synthesized alkyds from RSO-linseed oil blends and observed favorable drying schedules and improved resistance to water, acid, and brine [36]. Although the alkali resistance was somewhat limited, these findings indicate a clear advancement in RSO-based resin robustness. Similarly, Aigbodion (2003) employed maleic anhydride to produce maleinized RSO (MRSO), which was then used to formulate water-soluble alkyds. These exhibited good chemical resistance and lower volatile organic compound (VOC) emissions than their solvent-based counterparts, highlighting their environmental benefits [37].

Alkyd resins derived from thermally treated RSO have shown enhanced performance characteristics. Aigbodion and Pillai (2000) reported that heating RSO to 300 ± 5 °C not only improved its drying ability but also led to alkyd resins with favorable molecular weight profiles and narrower polydispersity, critical for achieving consistent film properties [38]. The resulting alkyd films demonstrated good resistance to water and alkali and were largely unaffected by acidic and saline environments. These properties were further improved by introducing modifiers such as cashew nutshell liquid-formaldehyde resin, which significantly enhanced chemical resistance and hardness [39].

Furthermore, Ifijen *et al.* (2022) reviewed advancements in the synthesis of both solvent-based and waterborne alkyd resins and concluded that incorporating functional materials like titanium oxide, acrylate, and gum rosin significantly improves coating attributes such as gloss retention, thermal stability, adhesion, and abrasion resistance [9]. While waterborne alkyds were found to be more eco-friendly than solvent-based ones, challenges remain regarding balancing drying performance and mechanical strength. Nevertheless, the modification techniques consistently resulted in alkyd resins with superior film formation, hardness, and resistance—key performance metrics for coatings.

These findings collectively affirm RSO's suitability for eco-friendly alkyd resin applications, supporting a shift towards sustainable manufacturing practices in paints, varnishes, and adhesives. The successful adaptation of RSO in pilot-scale resin formulations, such as those explored by RRIN, mirrors broader trends in green chemistry, where renewable resources are leveraged to reduce environmental impact without compromising performance. By optimizing the drying ability and durability of RSO-derived alkyds through blending, functionalization, and processing innovations, researchers have unlocked new industrial potentials for an otherwise underutilized agricultural by-product.

3.2.2 Polymer and Composite Materials

The structural richness of rubber seed oil (RSO), particularly its high degree of unsaturation, provides essential reactive sites for chemical modification and polymer integration, positioning it as a promising candidate for sustainable polymer development. These unsaturated bonds are readily epoxidized, introducing oxirane rings that facilitate copolymerization and cross-linking reactions with various polymer matrices [40]. Bakare *et al.* (2025) explored this potential by synthesizing epoxidized rubber seed oil (ERSO) using acetic and formic acids under identical conditions [40]. Their study confirmed that both reaction routes yielded ERSO samples with physicochemical and structural properties comparable to commercial epoxy vegetable oils, suggesting that RSO can serve as a renewable, functional monomer in polymer chemistry.

Incorporation of RSO into advanced composite systems has also been demonstrated. Obazee *et al.* (2020) successfully synthesized graphene-reinforced polyurethane nanocomposites by reacting RSO-based polyols with diisocyanates [41]. The introduction of exfoliated graphene nanosheets not only enhanced mechanical and thermal properties—such as hardness, tensile strength, and thermal stability—but also maintained structural compatibility with neat polyurethanes. The success of this hybridization underscores the adaptability of RSO in forming high-performance, bio-based nanocomposites, replacing petroleum-derived polyols in polyurethane systems.

The compatibility of RSO-derived materials with biodegradable polymers is further evidenced by Thuy and Lan (2021), who demonstrated that blending epoxidized rubber seed oil (ERO) and its esterified form (EERO) with polylactic acid (PLA) significantly enhanced mechanical flexibility and impact strength [42]. The ERO-PLA bioblend notably increased elongation at break by over nine times and improved impact strength by 139%. These enhancements were attributed to strong intermolecular interactions and partial miscibility between PLA and the epoxidized oils, confirmed by a decrease in glass transition temperature and supportive NMR analysis. The incorporation of ERO also resulted in elevated thermal decomposition temperatures and improved flow behavior, showcasing its dual role as a plasticizer and polymer reactant. This indicates that RSO-derived epoxides can effectively replace petroleum-based plasticizers, promoting the development of biodegradable, high-performance plastics aligned with circular economy principles.

Supporting this biopolymer integration strategy, Aniyan *et al.* (2019) investigated the thermal and rheological properties of RSO for lubricant applications, also blending it with synthetic polymers such as polypropylene (PP) and low-density polyethylene (LDPE) [43]. These additions enhanced the viscosity and stability of the RSO-based composites, suggesting that RSO can act synergistically with common synthetic resins to yield functional hybrid materials while maintaining environmental benefits due to its bio-based origin.

A further avenue of application is in microbial polymer production. Kynadi and Suchithra (2017) demonstrated the successful use of RSO as a carbon source for *Bacillus cereus* in the microbial synthesis of polyhydroxyalkanoates (PHA), a class of biodegradable polymers [44]. Remarkably, RSO enabled high PHA accumulation of up to 524 mg/g cell dry weight, with a final yield of 1.80 g/L—marking the first such report using an underutilized, non-edible oil feedstock. This bioconversion process presents a low-cost, sustainable alternative for biopolymer production while valorizing agricultural waste streams.

Together, these studies affirm that the unsaturated nature of RSO can be harnessed to produce a wide range of bio-based, biodegradable composites through chemical and biological pathways. Whether through epoxidation, polyol derivatization, copolymer blending, or microbial bioconversion, RSO proves to be a highly functional and versatile input in the development of sustainable materials. Its growing utility across polymer platforms not only supports innovation in green materials science but also reinforces the broader transition toward a circular economy by reducing dependence on fossil-derived polymers.

3.2.3 Nutritional and Therapeutic Potential

While crude rubber seed oil (RSO) is non-edible due to the presence of cyanogenic glycosides—naturally occurring, toxic compounds found in unprocessed seeds—research efforts at the Rubber Research Institute of Nigeria (RRIN) have made significant strides in developing effective detoxification methods. These advancements have led to the production of refined RSO that meets safety standards for potential human consumption. In addition to its detoxified safety profile, RSO is particularly rich in unsaturated fatty acids—especially linoleic acid—as well as antioxidant phytochemicals and essential micronutrients. This unique nutritional composition positions RSO as a promising candidate for use in dietary supplements, nutraceutical formulations, and functional foods. Furthermore, its potential health-promoting properties, including cardiovascular and anti-inflammatory benefits, align with global trends favoring plant-based and sustainable nutritional sources. These developments open new avenues for RSO beyond industrial applications, offering a dual-purpose resource for both health and industry.

Chaikul *et al.* (2024) investigated the bioactive potential of rubber seed oil (RSO), a non-edible oil derived from *Hevea brasiliensis*, focusing on its safety and functional applications, particularly in skin health and anti-aging formulations [45]. The study addressed the key concern of cyanogenic glycoside content—specifically linamarin—which renders crude RSO unsafe for human consumption. However, their refined RSO preparation was found to be completely free of linamarin at concentrations up to 100 µg/mL, affirming its detoxified status. This aligns with ongoing research at the Rubber Research Institute of Nigeria (RRIN), which has developed and validated detoxification methods to render RSO safe for potential nutritional and cosmeceutical uses, thereby opening a new frontier for RSO as a refined plant-based ingredient in human health applications.

Gas chromatography-mass spectrometry (GC-MS) analysis revealed that the primary fatty acids in RSO were oleic acid ($43.37 \pm 0.76\%$) and linoleic acid ($38.49 \pm 0.81\%$), both unsaturated and known for their health benefits, along with saturated palmitic ($11.47 \pm 0.12\%$) and stearic ($6.66 \pm 0.05\%$) acids. This composition mirrors findings from RRIN and underscores the oil's nutritional potential, particularly its alignment with global shifts toward plant-based, functional foods rich in unsaturated fatty acids and antioxidant components. Moreover, the study showed that RSO, in the concentration range of 0.0001–0.1 mg/mL, was non-cytotoxic to both HaCaT keratinocytes and human dermal fibroblasts (HDF), maintaining cell viability above 80%. This cytocompatibility is presented in Figure 2, which also illustrates similar safe response profiles for the individual fatty acids and vitamin C.

Further reinforcing its functional potential, RSO demonstrated significant anti-aging properties, including stimulation of cell proliferation, antioxidant activity, and inhibition of matrix metalloproteinase-2 (MMP-2)—a critical enzyme linked to skin collagen degradation. In particular, the oil enhanced proliferation in HaCaT cells in a concentration-dependent manner, achieving stimulation rates comparable to palmitic, oleic, and linoleic acids. At 0.1 mg/mL, RSO induced a proliferative response of 33.81 ± 1.76%, approaching that of vitamin C (49.84 ± 0.46%), as shown in Figure 3. These findings highlight the regenerative capacity of RSO on skin cells, supporting its use in formulations targeting skin repair and rejuvenation.

Antioxidant activity, crucial for mitigating oxidative stress and slowing skin aging, was another key outcome. In HaCaT cells and HDF, RSO significantly reduced cellular free radicals induced by AAPH and hydrogen peroxide, respectively. As depicted in Figure 4, treatments with RSO, oleic acid, linoleic acid, and vitamin C all resulted in decreased free radical content and improved cell viability. Conversely, saturated fatty acids like palmitic and stearic acids did not show antioxidant effects, leading to viability levels comparable to oxidant-only controls. These results underscore the unique value of RSO's unsaturated fatty acid profile in conferring protective, bioactive benefits. Altogether, this study contributes to the growing body of evidence supporting RSO's transition from a toxic, non-edible by-product to a detoxified, bio-functional oil. With a favorable lipid profile, demonstrated antioxidant and regenerative properties, and RRIN-backed detoxification protocols, RSO emerges as a viable candidate for incorporation into dietary supplements, functional foods, and cosmeceuticals. These developments strongly align with circular economy strategies and global nutrition trends focused on sustainable, plant-derived bioactives.

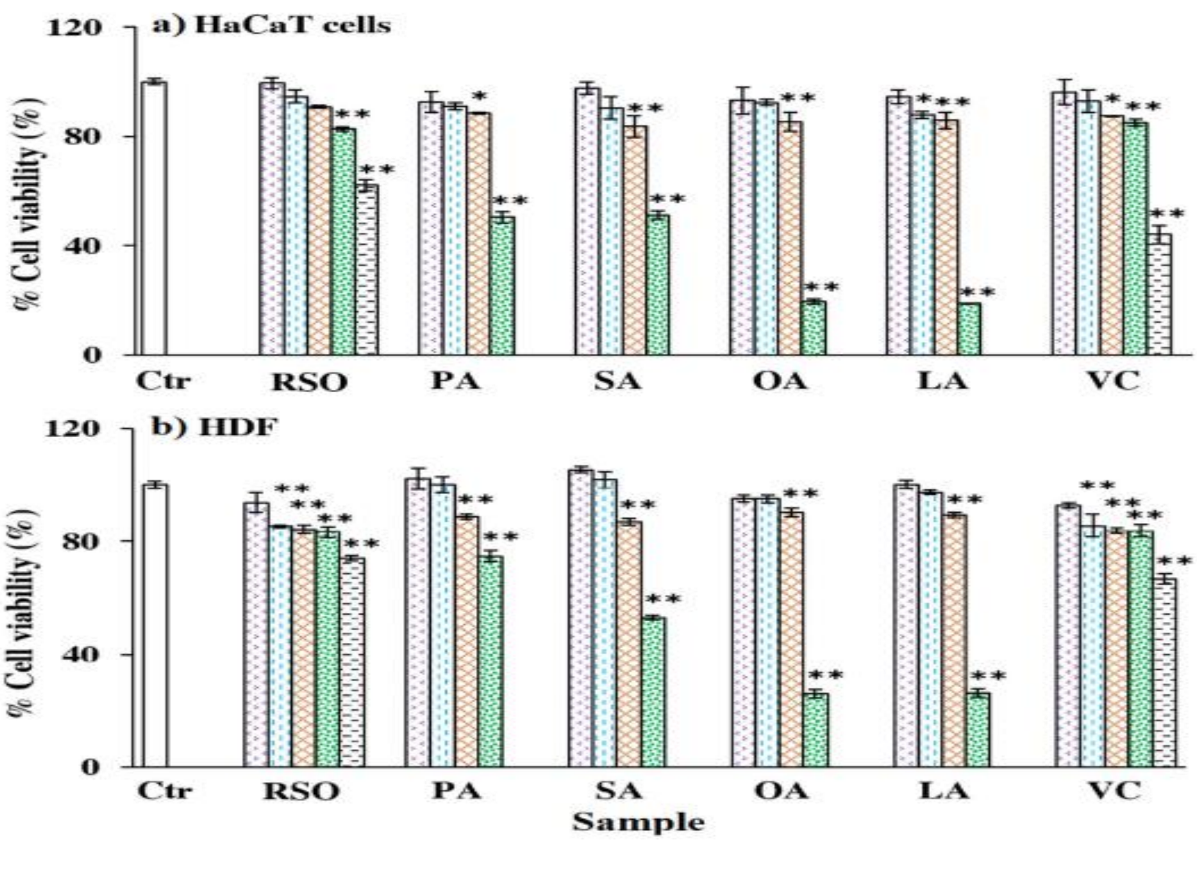

Figure 5. Cytotoxicity assay of RSO, fatty acids in RSO, including palmitic (PA), stearic (SA), oleic (OA), and linoleic (LA) acids, and vitamin C (VC) at concentrations of 0.0001–1 mg/mL in HaCaT cells and HDF. * and ** indicate the significant difference compared to control (Ctr) at $p < 0.05$ and 0.01, respectively [45].

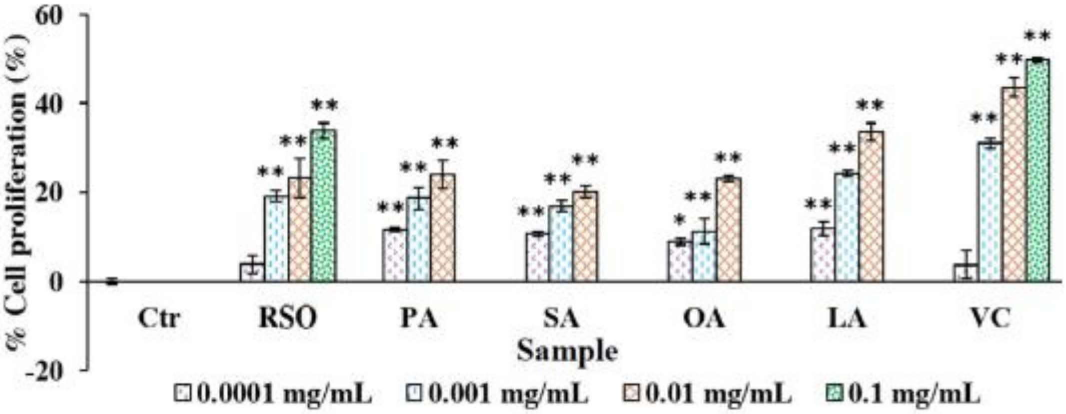

Figure. 6. Cell proliferating stimulation of RSO, fatty acids in RSO, including palmitic (PA), stearic (SA), oleic (OA), and linoleic (LA) acids, and vitamin C (VC) at non-cytotoxic concentrations of 0.0001–0.1 mg/mL in HaCaT cells. * and ** indicate the significant difference compared to control (Ctr) at $p < 0.05$ and 0.01, respectively [45].

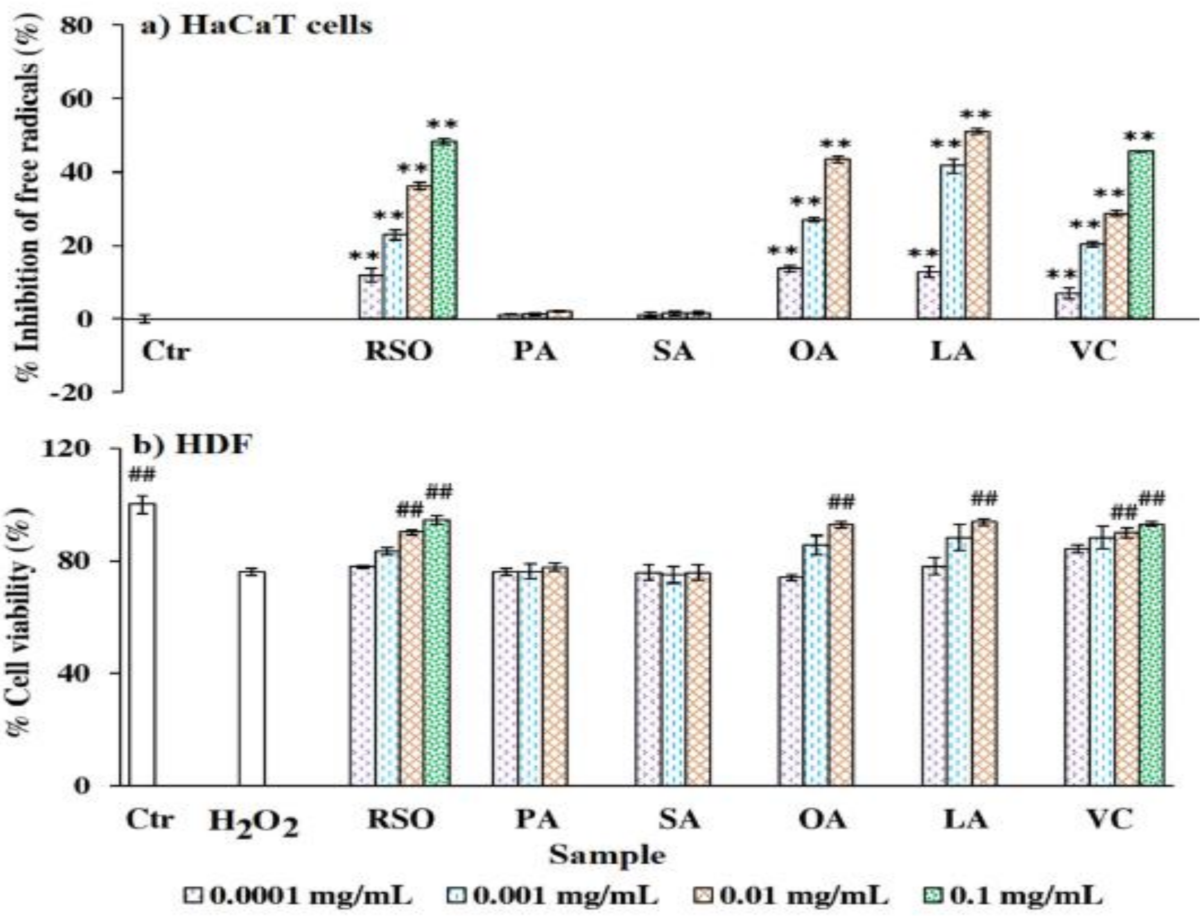

Figure 7. Antioxidant activity of RSO, fatty acids in RSO, including palmitic (PA), stearic (SA), oleic (OA), and linoleic (LA) acids, and vitamin C (VC) at non-cytotoxic concentrations of 0.0001–0.1 mg/mL in HaCaT cells by

cellular antioxidant activity and HDF by addition of hydrogen peroxide (H_2O_2). * and ** indicate the significant difference compared to control (Ctr) at $p < 0.05$ and 0.01, whereas # and ## indicate the significant difference compared to oxidative control (H_2O_2) at $p < 0.05$ and 0.01, respectively [45].

Liu *et al.* (2022) [46], Gandhi *et al.* (1990) [47], and Alam *et al*. (2024) [48] provide converging evidence that supports the safe and functional use of rubber seed oil (RSO) as a health-promoting, plant-based nutritional oil. Collectively, these studies reinforce the growing perspective that RSO, though traditionally underutilized and classified as non-edible due to the presence of cyanogenic glycosides in raw seeds, can be detoxified and developed into a viable dietary oil with significant nutraceutical potential. Their findings complement the Rubber Research Institute of Nigeria's (RRIN) ongoing efforts to refine and detoxify RSO, enabling its use in human consumption and broadening its applications in functional foods and dietary supplements.

Gandhi *et al.* (1990) conducted one of the earliest comprehensive toxicological evaluations of RSO, assessing its safety profile in a 13-week feeding study involving weanling rats [47]. The study revealed no acute toxicity or organ-specific damage, and key nutritional indicators such as food intake, growth rate, feed efficiency, and organ morphology in RSO-fed rats were comparable to those fed groundnut oil (GNO). Notably, the digestibility of RSO reached 97%, surpassing that of GNO (94%). These results demonstrate that, when processed to remove free fatty acids and deodorized for sensory acceptability, RSO is not only safe but nutritionally suitable for inclusion in human diets. The findings offer early yet pivotal evidence that aligns with the current global trend toward valorizing plant-based oils for health-conscious consumers.

Further extending the nutritional promise of RSO, Liu *et al.* (2022) explored its antioxidant and anti-inflammatory effects in lipopolysaccharide (LPS)-induced RAW 264.7 macrophages [46]. The study demonstrated that RSO supplementation reduced reactive oxygen species (ROS) and malondialdehyde (MDA) levels, while increasing total antioxidant capacity (T-AOC). Moreover, RSO downregulated the expression of pro-inflammatory cytokines such as TNF-α, IL-1β, and IL-6, while upregulating anti-inflammatory cytokine IL-10 at both the protein and mRNA levels. Mechanistically, these benefits were linked to the activation of the Nrf2 antioxidant pathway and suppression of the NF-κB/TLR4-mediated inflammatory response. These molecular insights support the use of RSO not just as a source of essential fatty acids, but also as a functional food ingredient capable of modulating oxidative stress and immune responses—key pillars of modern preventive nutrition and wellness strategies.

Alam *et al.* (2024) added a valuable geographical perspective by analyzing RSO samples extracted from rubber seeds sourced across different regions of Bangladesh [47]. The study highlighted that while regional variation influenced physicochemical attributes such as iodine value (132–137 g I_2/100 g) and acid value (13.3–18.2 mg KOH/g), the fatty acid profile remained consistently rich in polyunsaturated fatty acids, including linoleic and linolenic acids. Intriguingly, RSO samples demonstrated antimicrobial activity against gram-positive bacteria regardless of their geographical origin, with zones of inhibition ranging from 2.33 to 11.17 mm. These findings reinforce the broader functional relevance of RSO as a bioactive plant oil, capable of delivering not only nutritional lipids but also antimicrobial agents—potentially useful in food preservation or nutraceutical formulations.

Together, these studies present a compelling case for repositioning RSO as a bio-functional edible oil, particularly when detoxified using protocols validated by RRIN. With its high content of unsaturated fatty acids, absence of toxicity post-refinement, and demonstrable antioxidant, anti-inflammatory, and antimicrobial effects, RSO aligns with the global move toward sustainable, plant-based dietary ingredients. As such, RSO holds promise not just as an industrial oil, but as a novel component in the formulation of health-supporting, circular economy–aligned food and supplement products.

4.0 CONCLUSION

Rubber seed oil (RSO) represents a promising and multifaceted bioresource with significant potential to contribute to sustainable development, economic diversification, and environmental stewardship. The abundant availability of rubber seeds in Nigeria, coupled with advances in efficient and eco-friendly extraction and refining techniques, positions RSO as a viable alternative to conventional oils for biodiesel production, industrial applications, and even nutritional uses following proper detoxification. Research led by the Rubber Research Institute of Nigeria (RRIN) has been instrumental in unlocking this potential by optimizing extraction methods, characterizing physicochemical properties, and validating applications across energy, polymer, and health sectors. Despite its promise, challenges remain in scaling up production, ensuring product safety, enhancing supply chain logistics, and fostering market acceptance. Addressing these issues requires concerted efforts in research, policy support, infrastructure development, and public-private partnerships. By overcoming these barriers, Nigeria can capitalize on RSO as a sustainable, value-added commodity that supports rural livelihoods, reduces environmental waste, and contributes meaningfully to global renewable energy goals. The strategic development and commercialization of rubber seed oil align with global priorities for circular bioeconomies and low-carbon futures. Continued innovation and collaboration will be vital in transforming RSO from an underutilized agricultural byproduct into a globally competitive, multifunctional resource that drives sustainable industrial growth and energy security.

Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability Statement:

All data supporting this study are available upon request from the corresponding author.

Authors' Contribution

Ikhazuagbe Hilary Ifijen contributed to conceptualization, and original draft writing, while Isiaka O. Bakare, Efosa. O. Obazee, Emmanuel A. Fagbemi, Patrick. O. Ayeke, Nyaknno U. Udokpoh, Andrew O. Ohifuemen, Farouk U. Mohammed contributed by reviewing and editing the manuscript.

Authors' Declaration

The authors certify that this research is original, has not been published previously, and is not under consideration by any other journal. We assume full responsibility for the integrity of the data and the accuracy of the reported findings and will accept all liability for any claims about the content

Ethical Declarations Human/Animal Studies

The authors declare that no human/animal was used for the studies

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