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The views and opinions expressed in this journal are those of the contributors. Oil Technologists' Association of India does not necessarily concur with the same. All correspondence should be addressed to the Honorary Editor in Chief, Journal of Lipid Science and Technology, Head Quarter, OTAI Building, HBTU, Nawabganj, Kanpur-205002. email: editorinchief-jlst@otai.org

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The lipidomic revolution: Illuminating pathways to mankind's welfare

Dear Readers,

The *Journal of Lipid Science and Technology* has long been a beacon, illuminating the intricate world of lipids and their profound influence on biological systems. Today, we stand at the cusp of a new era, one where the burgeoning field of **lipidomics** is poised to revolutionize our understanding of health, disease, and ultimately, the welfare of humankind.

For decades, lipid research has unveiled the essential roles of fats as energy stores, structural components of membranes, and precursors to vital signaling molecules. Landmark discoveries, chronicled within these very pages, have linked lipid dysregulation to devastating conditions like cardiovascular disease and metabolic disorders. However, traditional lipid analysis often provided a limited snapshot, focusing on broad classes of lipids and overlooking the vast diversity and dynamic interplay of individual lipid species.

Lipidomics, with its sophisticated analytical platforms – primarily mass spectrometry coupled with advanced separation techniques – offers an unprecedented depth of insight. It allows us to move beyond simply measuring total cholesterol or triglycerides to comprehensively profile thousands of distinct lipid molecules within biological samples. This holistic view is unveiling a level of complexity that was previously unimaginable, revealing subtle yet critical alterations in lipidomes associated with various physiological states and disease processes.

The implications for human welfare are immense. Consider the advancements already being made:

- 1) **Precision diagnostics:** Lipidomic signatures are emerging as powerful biomarkers for early disease detection, risk stratification, and personalized medicine. For instance, specific lipid profiles can distinguish between subtypes of cardiovascular disease, predict the likelihood of developing type 2 diabetes, and even identify individuals at high risk of neurodegenerative conditions like Alzheimer's disease long before clinical symptoms manifest. This early detection paves the way for timely interventions and improved patient outcomes.
- 2) **Novel therapeutic targets:** By dissecting the intricate lipid networks perturbed in disease, lipidomics is uncovering novel therapeutic targets. Identifying specific enzymes, metabolic pathways, or signaling lipids that are dysregulated in a disease state opens avenues for the development of targeted therapies with enhanced efficacy and fewer side effects. The burgeoning interest in lipid-modulating drugs beyond traditional statins, focusing on specific lipid species and their metabolism, is a direct consequence of lipidomic insights.
- 3) **Personalized nutrition:** Lipidomics offers the exciting prospect of tailoring dietary recommendations based on an individual's unique lipid profile. Understanding how different dietary fats impact an individual's lipidome can lead to personalized nutritional strategies for disease prevention and management, moving beyond generic guidelines.
- 4) **Drug development and toxicology:** Lipidomic analysis can be invaluable in drug development, providing detailed information on drug efficacy and potential off-target effects on lipid metabolism. This can lead to the development of safer and more effective pharmaceuticals. Furthermore, lipidomic profiling can serve as a sensitive tool for toxicological studies, identifying early lipid-related indicators of environmental or chemical exposure.
- 5) **Understanding fundamental biology:** Beyond disease, lipidomics is deepening our understanding of fundamental biological processes. From cell signaling and membrane dynamics to inflammation and immunity, the precise roles of individual lipid species are being elucidated, providing a more complete picture of life at the molecular level.

The journey of lipidomics is still unfolding. Challenges remain in standardizing methodologies, validating biomarkers across diverse populations, and translating complex lipidomic data into clinically actionable insights. However, the momentum is undeniable. As technological advancements continue to enhance the sensitivity and throughput of lipidomic platforms, and as collaborative efforts foster data sharing and knowledge integration, the field will undoubtedly deliver on its promise.

At the *Journal of Lipid Science and Technology*, we are committed to showcasing the cutting-edge research that is driving this lipidomic revolution. We encourage researchers worldwide to contribute their innovative findings, their methodological advancements, and their visionary perspectives on how lipidomics can be harnessed to improve the welfare of mankind. The intricate world of lipids holds immense potential, and lipidomics is the key that will unlock its most profound secrets, paving the way for a healthier future for all.

Dr HB Singh
Editor-in-Chief

Dear Editor,

I am writing to express my strong appreciation for the insightful article published in the previous issue of the Journal of Lipid Science and Technology concerning the strategic responses of major meat companies to the burgeoning plant-based and cell-cultured protein sectors.

The article astutely highlights a pivotal moment in the food industry. The proactive engagement of established meat producers with alternative protein solutions underscores a significant recognition of evolving consumer preferences and the imperative for sustainable food systems. By examining the actions these companies are taking, the journal has provided a valuable perspective on the potential for synergy and innovation within the broader protein landscape.

Understanding how these industry giants are adapting, whether through investment, acquisition, or in-house development, is crucial for researchers, policymakers, and stakeholders alike. This forward-thinking analysis contributes significantly to our understanding of the future trajectory of protein production and consumption.

Thank you for bringing this timely and relevant discussion to the forefront. I believe this article will undoubtedly spark further important conversations and research within the lipid science and technology community and beyond.

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Dear Editor,

Thank you for bringing Mr D Mathur's thought-provoking opinion piece, "Navigating the Future of Oilseed Processing in a Climate-Conscious Era," published in our recent issue. Mr Mathur's insights resonate deeply with the journal's commitment to fostering discussions on sustainable advancements within lipid science and technology.

We wholeheartedly agree with his central thesis that the future vitality of oilseed processing is inextricably linked to the adoption of environmentally responsible practices. His articulation of key strategies - investing in green extraction technologies, maximizing the value of by-products, enhancing energy efficiency across operations, and establishing transparent supply chains - provides a clear and actionable roadmap for the industry.

Mr Mathur's opinion piece effectively underscores the critical need for the oilseed processing sector to proactively embrace sustainability not just as an ethical imperative, but as a fundamental driver of long-term success in a climate-conscious world. By highlighting these crucial areas of focus, he has offered a valuable perspective that we believe will stimulate important discussions and inspire innovation among our readerships.

We appreciate his contribution to the journal and his insightful perspective on this vital topic.

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Here are some recent developments and highlights in the field, reflecting the ongoing activity in lipid science and technology:

1) Lipids guiding evolution (April 2025)

Research from the CSIR-Centre for Cellular and Molecular Biology (CCMB) in India suggests that lipids, not just proteins, play a significant role in the evolution of organisms. The study focused on the interaction of lipids with the Respiratory Complex 1 in mitochondrial membranes, finding species-specific lipid preferences that impact the complex's structure and function. This highlights the expanding understanding of lipids beyond structural roles. (Source: *Vision IAS/The Hindu*)

2) Bhanu jena receives 2024 lipid science prize (January 2024)

Dr. Bhanu Jena from Wayne State University received the prestigious Lipid Science Prize for his discovery of the "porosome," the universal secretory machinery in cells composed of lipoproteins. His work has implications for understanding and treating diseases like cystic fibrosis, diabetes, and Alzheimer's. (Source: *Today@Wayne*)

3) Top trends in lipid research (August 2024)

An article in *Food Technology Magazine* highlighted key trends in lipid research, including omega-3-enriched foods, plant-based lipids, functional lipid gels and emulsions, encapsulation of bioactive lipids, and the development of reduced saturated fat and trans fat-free alternatives for healthier and more sustainable food formulations. (Source: *IFT.org*)

4) Lipid nanotechnology for vaccine development (April 2024)

The increasing importance of lipid nanoparticle (LNP) technology in developing effective vaccines, particularly mRNA vaccines like those for COVID-19, is highlighted. Research is ongoing to apply this technology to other infectious diseases and even areas like cancer treatment and gene therapy. (Source: *ET HealthWorld*)

5) Cholestosome™ technology explained (October 2024)

The European Journal of Lipid Science and Technology featured work explaining the Cholestosome™ technology, a novel delivery system made exclusively from 2,3-dialdehyde cellulose and cholesterol. This suggests advancements in lipid-based drug delivery systems. (Source: *Niagara University/European Journal of Lipid Science and Technology*)

6) Fungal messenger impairs immune cell function (November 2024)

Research published in *The Scientist* showed that farnesol, a fungal signaling molecule, can alter lipid synthesis in dendritic cells, leading to mitochondrial dysfunction and decreased inflammatory responses. This highlights the role of lipids in inter-species communication and immune modulation. (Source: *The Scientist*)

7) Hundreds of lipid antigens recognized by immune T cells (November 2023)

New research revealed a significant number of lipid antigens that can be recognized by adaptive immune T cells, expanding our understanding of the role of lipids in the immune system beyond just structural components. (Source: *The Scientist*)

8) Fish oil and hair loss in mice (January 2023)

A study in mice found that high dietary intake of fish oil can lead to hair loss due to the accumulation of omega-3 fatty acids in the skin, triggering an immune response. This indicates potential complex and sometimes unexpected effects of specific lipids. (Source: *The Scientist*)

9) Years of prozac alter brain lipids in monkeys (September 2021)

Research on young monkeys showed that long-term administration of the antidepressant fluoxetine was

linked to decreased concentrations of numerous brain lipids, suggesting a potential mechanism for some of the drug's side effects. This underscores the impact of pharmaceuticals on lipid metabolism in the brain. (Source: *The Scientist*)

10) Lipid droplets as bacteria-fighting machines (October 2020)

Research highlighted that lipid droplets within cells are not just inert fat storage units but actively recruit immune proteins and inhibit bacterial growth, revealing a novel role for these organelles in cellular defense. (Source: *The Scientist*)

11) Gut microbiota-derived lipids influence host immunity (May 2025)

Emerging research continues to highlight the crucial role of gut microbiota in modulating host immunity. Studies are increasingly focusing on how specific lipids produced by gut bacteria interact with the host's immune system, influencing inflammatory responses and overall health. This area is exploring potential therapeutic interventions through manipulation of the gut lipidome. (Source: *Nature Microbiology*)

12) Advanced lipid imaging techniques for disease diagnosis (April 2025)

Developments in high-resolution lipid imaging techniques, such as MALDI-MS imaging and stimulated Raman scattering (SRS) microscopy, are allowing researchers to visualize the spatial distribution and dynamics of lipids within tissues and cells with unprecedented detail. This is proving invaluable for understanding lipid accumulation in diseases like NAFLD and for mapping lipid changes in tumor microenvironments. (Source: *Journal of Lipid Research*)

13) Sustainable production of bio-based lipids for industrial applications (April-May 2025)

With growing concerns about sustainability, research is intensifying on the production of bio-based lipids from sources like algae, fungi, and microbial fermentation. These lipids are being explored as renewable feedstocks for biofuels, bioplastics, and other industrial applications, aiming to reduce reliance on fossil fuels and plant-based oils. (Source: *Bioresource Technology*)

14) Role of specialized pro-resolving mediators (SPMs) in inflammatory diseases (Ongoing)

Research continues to uncover the critical roles of SPMs, a class of bioactive lipids derived from omega-3 polyunsaturated fatty acids, in resolving inflammation and promoting tissue repair. Clinical trials are exploring the therapeutic potential of SPMs in various inflammatory conditions. (Source: *Journal of Experimental Medicine*)

15) Lipid metabolism in exercise physiology and performance (April 2025)

New studies are investigating the intricate interplay between lipid metabolism and exercise performance. Researchers are exploring how different types of dietary fats and exercise regimens influence lipid utilization, muscle energy storage, and endurance capacity. This has implications for optimizing athletic training and nutritional strategies. (Source: *Nutrients*)

16) Impact of environmental pollutants on lipid homeostasis (May 2025)

Emerging research is examining how exposure to environmental pollutants, such as microplastics and persistent organic pollutants (POPs), can disrupt lipid homeostasis in organisms, potentially contributing to

various health problems. Lipidomic approaches are being used to identify specific lipid alterations induced by these exposures. (Source: *Toxicological Sciences*)

17)Lipid-based nanocarriers for targeted drug delivery (Ongoing)

The development of sophisticated lipid-based nanocarriers, beyond LNPs, for targeted drug delivery continues to be a hot area. Researchers are engineering liposomes, solid lipid nanoparticles (SLNs), and nanostructured lipid carriers (NLCs) with enhanced stability, targeting capabilities, and controlled release properties for various therapeutic applications. (Source: *Journal of Controlled Release*)

18)Dietary lipids and cognitive function across lifespan (April-May 2025):

Ongoing research explores the long-term effects of dietary lipid intake, particularly omega-3 and omega-6 fatty acids, on cognitive development in children and cognitive decline in aging populations. Studies are investigating the underlying mechanisms and potential for dietary interventions to support brain health. (Source: *American Journal of Clinical Nutrition*)

19)Lipid signaling in plant stress responses (May 2025)

Lipid signaling pathways are increasingly recognized as crucial players in how plants respond to various environmental stresses, such as drought, heat, and pathogen attack. Research is identifying key lipid mediators and their roles in plant defense mechanisms, with implications for developing stress-tolerant crops. (Source: *Trends in Plant Science*)

20)Advancements in enzymatic modification of lipids for food applications (April 2025)

Biotechnology is being employed to enzymatically modify lipids, such as through interesterification and hydrolysis, to create novel fats and oils with improved functional properties for the food industry, including healthier fat profiles and enhanced stability. (Source: *Journal of the American Oil Chemists' Society*).

The ever-evolving landscape of lipid science and technology

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The study of lipids has always been a cornerstone of nutritional science, biochemistry, and food technology. From their fundamental roles in cellular structure and energy storage to their involvement in complex metabolic pathways, lipids are undeniably crucial to life. The field of lipid science and technology is dynamic, constantly evolving with new research, methodologies, and applications. In this opinion piece, I will explore some of the exciting current trends and future directions in this ever-evolving landscape.

Current trends: The development of advanced analytical techniques, such as mass spectrometry, has revolutionized our understanding of the lipidome. Lipidomics allows for the comprehensive analysis of the thousands of different lipid species present in biological systems. This has led to breakthroughs in identifying novel biomarkers for disease, understanding the role of lipids in cellular signaling, and unraveling the complexities of lipid metabolism.

The modification of natural lipids to create structured lipids with specific functional properties is a growing area of interest. Enzymatic and chemical techniques are employed to alter the fatty acid composition and positional distribution within triacylglycerols. These tailored lipids have potential applications in functional foods, infant formula, and medical nutrition.

Research continues to uncover the diverse health benefits of various bioactive lipids. Omega-3 fatty acids, sphingolipids, and oxylipins are just a few examples of lipids that play critical roles in inflammation, cardiovascular health, and brain function. The development of novel delivery systems to enhance the bioavailability of these beneficial lipids is an active area of investigation.

Lipids are increasingly being utilized in the development of nanocarriers for drug delivery. Liposomes, solid lipid nanoparticles, and nanostructured lipid carriers offer advantages such as biocompatibility, biodegradability, and the ability to encapsulate both hydrophilic and hydrophobic drugs. These systems hold great promise for targeted drug delivery and improved therapeutic outcomes.

With increasing global demand for lipids and concerns about environmental sustainability, there is a growing focus on exploring alternative lipid sources. Microalgae, fungi, and other microorganisms are being investigated as potential sources of oils and fats for food, feed, and industrial applications. Advances in biotechnology and metabolic engineering are playing a key role in optimizing lipid production from these sources.

The demand for plant-based alternatives to animal fats is rising, driven by health, environmental, and ethical considerations. Research is focusing on understanding the structure and functionality of plant lipids, as well as developing technologies to process and modify them for use in food products. This includes exploring novel plant sources, extraction methods, and techniques to improve the sensory attributes and stability of plant-based fats.

Future directions: Based on above current strength and deep understanding, future directions and challenges are obviously challenging. A deeper understanding of the interactions between dietary lipids and individual genetic and metabolic profiles will pave the way for personalized nutrition recommendations. Lipidomics data, combined with other omics technologies, will enable the development of tailored dietary interventions to optimize health and prevent disease. The development

of new imaging techniques will allow for the visualization of lipids in living cells and tissues with unprecedented spatial and temporal resolution. This will provide valuable insights into the dynamic roles of lipids in cellular processes and disease pathogenesis.

Also, application of AI and machine learning will accelerate discoveries in lipid science. These technologies can be used to analyze complex lipidomics datasets, predict lipid properties, and design novel lipid-based materials. Significant research and development efforts are needed to scale up the production of lipids from sustainable sources, such as microalgae and fungi,

to meet growing global demand. This will require advances in cultivation technologies, bioreactor design, and downstream processing. Lipid science and technology will play a critical role in addressing global health challenges such as obesity, cardiovascular disease, and metabolic disorders. Further research is needed to elucidate the complex relationships between dietary lipids, metabolism, and disease risk, and to develop effective interventions.

We have summarised twenty recent research areas and findings related to oils and fats, along with their potential sources, which you can then use to find more detailed information.

1. New insights into the health benefits of extra virgin olive oil

Recent studies highlight that extra virgin olive oil contains high levels of monounsaturated fats and polyphenols, which are linked to reduced inflammation and decreased risk of cardiovascular diseases. Researchers emphasize the importance of olive oil as part of the Mediterranean diet for heart health. (Source: *Journal of Nutritional Biochemistry*, 2024)

2. Innovations in plant-based oils for sustainable production

Researchers are developing new extraction methods to produce plant-based oils with lower environmental impact. These innovations include using eco-friendly extraction techniques from algae and novel crops that require fewer resources. The goal is sustainable oils that meet global demand without depleting natural resources. (Source: *Sustainable Agriculture Reviews*, 2024)

3. Omega-3 rich oils from microalgae as alternative to fish oil

Studies indicate that oils derived from microalgae are effective sources of omega-3 fatty acids for supplements, offering a sustainable alternative to fish oils. Microalgae oils are also free of contaminants like mercury, making them safer for consumption. (Source: *Marine Drugs*, 2023)

4. Trans fats ban and its impact on food industry

Following global bans on artificial trans fats, food manufacturers are reformulating products, replacing trans fats with healthier alternatives like fully hydrogenated oils and emulsifiers. The transition is believed to decrease trans fat-related cardiovascular risks significantly. (Source: *Food Chemistry*, 2024)

5. Oleic acid-enriched oils for skin care applications

Recent research explores oleic acid-rich oils, such as argan and avocado oil, for their benefits in skin hydration and anti-inflammatory properties. Natural oils with high oleic acid content are gaining popularity in dermatology and cosmetic formulations. (Source: *Journal of Cosmetic Dermatology*, 2024)

6. Fortification of vegetable oils with vitamin D

New initiatives focus on fortifying edible vegetable oils with vitamin D to combat deficiencies, especially in regions with limited sun exposure. This approach uses simple oil-based supplements to improve overall public health. (Source: *Public Health Nutrition*, 2023)

7. Palm oil sustainability and zero-deforestation efforts

Research continues into sustainable palm oil production, with certifications and traceability initiatives helping to reduce deforestation and habitat destruction. Adoption of better harvesting and processing practices is essential for environmental sustainability. (Source: *Environmental Science & Policy*, 2024)

8. Impact of dietary fats on gut microbiota

Emerging evidence suggests that different types of dietary fats influence gut microbiota composition. Omega-3 and medium-chain triglycerides (MCTs) promote beneficial microbial populations, impacting immune function and metabolism. (Source: *Gut Microbes*, 2024)

9. Hydrogenated oils alternatives in food processing

Innovations focus on replacing hydrogenated oils in baked goods, snacks, and fried foods with interesterified fats and interesterified fats derived from sustainable sources, aiming to reduce trans fat content while maintaining product quality. (Source: *Food Hydrocolloids*, 2023)

10. Research on fatty acid profiles and cancer prevention

Preliminary studies are exploring how specific fatty acids, such as conjugated linoleic acid (CLA) in certain oils, might play roles in modulating cancer cell growth. This research could lead to dietary strategies for cancer risk reduction. (Source: *Cancer Epidemiology, Biomarkers & Prevention*, 2024)

11. Bioactive compounds in sesame oil for anti-inflammatory effects

Recent studies demonstrate that sesame oil contains lignans such as sesamin and sesamol, which exhibit potent anti-inflammatory and antioxidant properties. These compounds may help in reducing chronic inflammation-related diseases. (Source: *Food & Function*, 2023)

12. Development of cold-pressed pumpkin seed oil for heart health

Research is promoting the health benefits of pumpkin seed oil, rich in phytosterols and unsaturated fatty acids. Cold-pressing methods preserve bioactive components, making it a promising functional oil for cardiovascular health. (Source: *Foods*, 2024)

13. High oleic sunflower oil as a cholesterol-lowering alternative

Studies show that high oleic sunflower oil has a favorable fatty acid profile that helps reduce LDL cholesterol levels. It's being recommended as a healthier frying and cooking oil alternative. (Source: *Journal of Clinical Lipidology*, 2024)

14. Lipid oxidation in cooking oils and its impact on health

New research emphasizes the importance of monitoring lipid oxidation during cooking, as oxidized fats may generate harmful compounds linked to inflammatory responses and oxidative stress. Antioxidants like tocopherols can mitigate these effects. (Source: *Food Chemistry*, 2024)

15. Pollution and lipid profile alterations in marine oils

Marine oils, especially from fish and krill, are being

studied for how environmental pollutants influence their lipid composition and safety. Cleaner harvesting practices are critical for maintaining the health benefits of these oils. (Source: *Environmental Pollution*, 2023)

16. Innovative enzymatic processes for omega-3 enrichment

Enzymatic modification techniques are enhancing plant oils with omega-3 fatty acids, enabling production of enriched functional oils without chemical solvents. This method presents sustainable options for omega-3 supplementation. (Source: *Biotechnology Advances*, 2023)

17. Coconut oil's role in brain development and cognitive function

Research indicates that medium-chain triglycerides (MCTs) in coconut oil may provide energy substrates for brain cells and show promise in managing neurodegenerative conditions like Alzheimer's disease. (Source: *Nutrients*, 2024)

18. Impact of dietary fats on lipid rafts and cell signaling

Emerging research explores how different types of dietary fats influence plasma membrane lipid rafts, impacting cell signaling pathways involved in immune response and disease progression. (Source: *Cellular Signalling*, 2024)

19. Algal oils as sources of EPA and DHA for infant nutrition

New formulations of infant formulas incorporate algal oils rich in EPA and DHA, providing sustainable, plant-based omega-3 options to support neural and visual development in infants. (Source: *Pediatric Research*, 2023)

20. Extraction of virgin oil from underutilized seeds for functional foods

Research is ongoing into extracting high-quality, virgin oils from underutilized seeds like jatropha and neem, which possess unique bioactive compounds with antioxidant and antimicrobial properties, suitable for functional and nutraceutical products. (Source: *Industrial Crops and Products*, 2023)

Food quality management systems across the globe

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Introduction

The global food system is an intricate and dynamic network, connecting diverse environments, production methods, and consumer demands across continents. Ensuring the safety, quality, and authenticity of food products within this complex supply chain is not merely a regulatory obligation but a fundamental imperative for public health, economic stability, and fostering consumer trust. Major foodborne illness outbreaks, such as the 1993 *E. coli* O157:H7 outbreak linked to undercooked hamburgers in the U.S. that led to the implementation of mandatory HACCP for meat (Source: Food Poisoning News, 2025), or the 2008 melamine contamination in infant formula in China (Source: WHO/FAO, 2009), underscore the catastrophic consequences of food safety failures. These incidents often serve as catalysts for significant regulatory reforms and the development of more robust Food Quality Management Systems (FQMS).

FQMS are comprehensive frameworks that integrate policies, procedures, and practices across the entire food value chain – from farm to fork. They are designed not only to comply with statutory and regulatory requirements but also to proactively identify, assess, control, and prevent potential hazards, thereby ensuring consistent product quality and safety. This review article offers an in-depth analysis of the evolution, core principles, major international standards, regional regulatory landscapes, prevailing challenges, and transformative future trends shaping food quality management globally.

Key principles of food quality management systems

An effective FQMS is anchored by several foundational

principles, which are universally recognized and integrated into various standards and regulations worldwide:

Hazard analysis and critical control points (HACCP): HACCP is a systematic, preventive, and science-based approach to food safety. It originated from NASA's requirements for safe food for space missions in the 1960s and was later adopted by the food industry. It identifies potential food safety hazards (biological, chemical, and physical) and establishes control measures at specific points in the food production process. Its seven core principles, as outlined by the **Codex Alimentarius Commission (CAC)**, are:

- 1. Conduct a hazard analysis:** Identify potential hazards specific to a product and process, such as *Salmonella* in poultry or glass fragments in packaged goods.
- 2. Determine the critical control points (CCPs):** Pinpoint steps where control can be applied and is essential to prevent or eliminate a food safety hazard or reduce it to an acceptable level (e.g., cooking temperature for pathogens, metal detection for foreign objects).
- 3. Establish critical limits:** Set measurable parameters that must be met at each CCP to ensure control (e.g., "cook to 74°C for 15 seconds").
- 4. Establish a monitoring system:** Implement planned observations or measurements to assess if a CCP is under control, ensuring deviations are detected quickly (e.g., continuous temperature logging during cooking).
- 5. Establish corrective actions:** Define procedures to follow when monitoring indicates a deviation from a critical limit, ensuring affected products are

controlled and the process is brought back into control.

6. **Establish verification procedures:** Regularly confirm that the HACCP system is working effectively through methods like internal audits, review of records, and microbiological testing.
7. **Establish documentation and record-keeping procedures:** Maintain comprehensive records of all aspects of the HACCP plan, including hazard analyses, CCP monitoring logs, and corrective actions, for demonstration of compliance and continuous improvement.

Reference: Codex Alimentarius Commission. (2020). General Principles of Food Hygiene (CXC 1-1969). FAO/WHO.

Good manufacturing practices (GMP) and good hygiene practices (GHP): These are fundamental operational conditions and procedures essential for the production of safe and wholesome food. GMPs broadly cover aspects such as:

- **Facility design and maintenance:** Ensuring premises are cleanable, prevent pest entry, and allow for logical flow of operations.
- **Equipment suitability and calibration:** Using appropriate, well-maintained equipment that is regularly calibrated.
- **Raw material control:** Proper receipt, inspection, and storage of ingredients.
- **Process control:** Standardized operating procedures for all production steps.
- **Pest control and sanitation:** Effective programs to prevent and eliminate pests and maintain cleanliness.
- GHPs specifically focus on the individual, covering personal hygiene, health status (e.g., reporting illnesses), appropriate attire, and prevention of cross-contamination by food handlers. These practices form essential prerequisite programs

(PRPs) upon which HACCP systems are built.

Reference: Many national food safety regulations, e.g., US FDA 21 CFR Part 110 (Current Good Manufacturing Practice in Manufacturing, Packing, or Holding Human Food); European Commission (EC) Regulation 852/2004 on the hygiene of foodstuffs.

Traceability: This principle refers to the ability to track the movement of a food product and its ingredients both backward (from consumer to source) and forward (from source to consumer) through all stages of production, processing, and distribution. It is a critical tool for:

- **Rapid recall:** Facilitating the swift and efficient removal of unsafe products from the market, minimizing consumer exposure and economic damage during a food safety incident.
- **Authenticity and fraud prevention:** Verifying the origin, history, and composition of food products, thereby combating food fraud and ensuring consumer confidence in labelling claims.
- **Supply chain transparency:** Providing visibility across complex supply chains, which is increasingly demanded by consumers and regulators alike.

Reference: ISO 22005:2007. (2007). Traceability in the feed and food chain — General principles and basic requirements for system design and implementation. International Organization for Standardization.

Risk assessment and management: This involves a systematic and proactive approach to identifying potential food safety and quality hazards, assessing their likelihood and severity of occurrence, and implementing appropriate control measures to mitigate them. It comprises three interconnected components:

- **Risk assessment:** A scientific process that identifies hazards, characterizes their adverse health effects, assesses exposure, and characterizes the overall risk.

- **Risk management:** The process of weighing policy alternatives, in consultation with all interested parties, considering risk assessment and other legitimate factors, and, if need be, selecting appropriate prevention and control options.
- **Risk communication:** The interactive exchange of information and opinions concerning hazards and risks among risk assessors, risk managers, consumers, and other interested parties.

Reference: Codex Alimentarius Commission. (2009). Principles and Guidelines for the Conduct of Microbiological Risk Assessment (CAC/GL 30-1999). FAO/WHO.

Continuous improvement: FQMS are not static; they are dynamic systems that require ongoing review, evaluation, and adaptation to new scientific knowledge, emerging risks, technological advancements, and regulatory changes. This principle is typically embodied by the **Plan-Do-Check-Act (PDCA) cycle**, a widely adopted management tool:

- **Plan:** Establish the objectives of the FQMS and the processes necessary to deliver results in accordance with the food safety policy. This involves identifying risks and opportunities.
- **Do:** Implement the planned processes and controls.
- **Check:** Monitor and measure processes and product performance against policies, objectives, and requirements. Analyze the results to identify deviations or areas for improvement.
- **Act:** Take actions to continually improve food safety performance based on the insights gained from the “Check” phase, adjusting plans and processes as necessary.

Reference: ISO 9001:2015. (2015). Quality management systems — Requirements. International Organization for Standardization; ISO 22000:2018. (2018). Food safety management systems — Requirements for any organization in the food chain. International Organization for Standardization.

Supplier and raw material control: Given the global nature of food sourcing, controlling the quality and safety of incoming raw materials and services from suppliers is paramount. This principle involves:

- Establishing clear specifications and quality agreements for all raw materials and services.
- Conducting supplier audits and performance evaluations to ensure compliance with FQMS requirements.
- Implementing robust incoming material inspection and testing procedures.
- Maintaining an approved supplier list based on their demonstrated ability to meet defined standards.
- This proactive control significantly reduces the risk of contaminated or substandard materials entering the production process.

Reference: Global Food Safety Initiative (GFSI) Guidance Document (Version 7.2). (2018). GFSI.

Personnel competence and training: Human error is a significant contributor to food safety incidents. This principle emphasizes the importance of ensuring that all personnel involved in food handling — from sourcing to final distribution — are adequately trained, possess the necessary competencies, and are fully aware of their responsibilities regarding food safety and quality. This includes:

- Initial and ongoing training on general hygiene practices (e.g., handwashing, personal protective equipment).
- Specific training on HACCP principles relevant to their roles, allergen management, and critical control point monitoring procedures.
- Awareness of food defense and food fraud prevention.
- Regular competency assessments to ensure knowledge retention and application.

Reference: WHO. (2006). Five Keys to Safer Food Manual. World Health Organization.

Document control and record keeping: A well-structured FQMS relies heavily on robust documentation and accurate record-keeping. This principle mandates:

- Developing and maintaining clear, concise, and up-to-date procedures, work instructions, and specifications for all relevant processes.
- Ensuring that all records (e.g., monitoring logs, calibration records, training records, corrective action reports) are legible, identifiable, traceable, and easily retrievable.
- Implementing effective document control systems to ensure that only the latest approved versions of documents are in use and that obsolete documents are promptly removed.
- These records provide objective evidence of compliance, facilitate audits, and enable effective investigation of non-conformities.

Reference: ISO 22000:2018. (2018). Food safety management systems — Requirements for any organization in the food chain. International Organization for Standardization.

Major international standards and frameworks

Several international standards and initiatives provide a harmonized approach to FQMS, facilitating global trade and ensuring a baseline level of safety and quality:

Codex alimentarius: As mentioned, the Codex Alimentarius Commission, jointly established by the FAO and WHO, develops international food standards, guidelines, and codes of practice. While not legally binding, Codex standards are widely recognized as a global reference point for food safety regulations and international trade. They are instrumental in reducing technical barriers to trade and provide a common language for food safety. Key outputs include standards for specific commodities, maximum residue limits for

pesticides, guidelines for food additives, and the foundational *General Principles of Food Hygiene* (CXC 1-1969) which endorses HACCP.

Reference: Food and Agriculture Organization (FAO) and World Health Organization (WHO). (Ongoing). Codex Alimentarius Commission publications.

ISO 22000 (Food safety management systems):

This international standard, published by the International Organization for Standardization (ISO), specifies requirements for a Food Safety Management System (FSMS). ISO 22000 integrates the principles of HACCP with prerequisite programs (PRPs) and the management system principles of ISO 9001 (Quality Management Systems). It provides a framework for organizations across the entire food chain, from primary producers to packaging manufacturers, transport and storage operators, and retail/food service providers, to ensure food safety. It promotes interactive communication throughout the food chain and systematic management of food safety hazards.

Reference: ISO 22000:2018. (2018). Food safety management systems — Requirements for any organization in the food chain. International Organization for Standardization.

Global food safety initiative (GFSI):

GFSI is a business-driven initiative that provides a platform for collaboration between food safety experts from retail, manufacturing, and food service companies. GFSI does not publish its own standard but *benchmarks* various existing food safety certification programs (known as ‘schemes’) against a comprehensive set of internationally recognized food safety requirements. This benchmarking process ensures the equivalence and credibility of these schemes, allowing businesses to gain certification to a single GFSI-recognized scheme and be accepted by many international buyers. This “once certified, accepted everywhere” approach reduces audit fatigue and compliance costs. Key GFSI-recognized schemes include:

- o **BRCGS (Brand reputation through compliance global standards):** One of the most widely adopted global standards, particularly strong in the UK and Europe. It covers food safety, quality, legality, and operational criteria.
- o **FSSC 22000 (Food safety system certification):** A comprehensive certification scheme that combines the requirements of ISO 22000 with industry-specific prerequisite programs (PRPs) detailed in the ISO/TS 22002-x series (e.g., ISO/TS 22002-1 for food manufacturing).
- o **SQF (Safe quality food):** A recognized certification program, especially prevalent in North America, that covers both food safety and quality aspects. It offers different levels of certification.
- o **IFS (International featured standards):** A food safety standard primarily used by retailers and wholesalers to qualify and select their food suppliers, popular in Europe.

Reference: Global Food Safety Initiative. (Ongoing). GFSI Benchmarking Requirements & Guidance Document. GFSI.

Regional/national regulations and approaches

While international standards provide a common ground, national and regional regulations often impose specific requirements tailored to local contexts, public health priorities, and traditional practices. These regulations dictate the minimum legal requirements for food businesses operating within their jurisdictions.

Europe (European union - EU): The EU operates under a highly harmonized and comprehensive “farm-to-fork” food law framework, emphasizing traceability, scientific risk assessment, and the precautionary principle.

- o **General food law (Regulation (EC) No 178/2002):** This foundational legislation lays down general principles and requirements of food law, establishing the **European Food Safety Authority**

(**EFSA**), and setting out procedures in matters of food safety. It mandates traceability “one step back and one step forward” for all food and feed businesses.

- o **The hygiene package (e.g., regulation (EC) No 852/2004 and 853/2004):** These regulations specify detailed hygiene rules for food businesses, including requirements for HACCP implementation, premises, equipment, and personal hygiene.
- o **EFSA’s role:** EFSA provides independent scientific advice and risk assessments to underpin EU legislation and policies across the food chain, ensuring decisions are evidence-based.

Reference: European Parliament and Council. (2002). Regulation (EC) No 178/2002 of 28 January 2002 laying down the general principles and requirements of food law, establishing the European Food Safety Authority and laying down procedures in matters of food safety. Official Journal of the European Union.

North America:

- o **United States (US):** The US food safety landscape underwent a significant shift with the **Food Safety Modernization Act (FSMA)**, signed into law in 2011. FSMA moved the focus from responding to contamination to preventing it. Key provisions include:

- **Preventive controls for human food and animal food rules:** Mandate food facilities to implement comprehensive food safety plans that include a hazard analysis and risk-based preventive controls.
- **Produce safety rule:** Establishes science-based minimum standards for the safe growing, harvesting, packing, and holding of fruits and vegetables.
- **Foreign supplier verification programs**

(FSVP) rule: Requires importers to verify that foreign suppliers meet US food safety standards.

- **FDA food traceability rule (FSMA section 204):** Imposes additional record-keeping requirements for certain high-risk foods to enable faster and more effective traceback during outbreaks.
- The Food and Drug Administration (FDA) regulates most food products, while the U.S. Department of Agriculture (USDA) Food Safety and Inspection Service (FSIS) regulates meat, poultry, and certain egg products.

Reference: U.S. Food and Drug Administration. (2011). FDA Food Safety Modernization Act (FSMA).

- o **Canada:** The Canadian Food Inspection Agency (CFIA) is the primary federal body responsible for enforcing food safety regulations, including the Safe Food for Canadians Act (SFCA) and its regulations (SFCR). The SFCA came into force in 2019 and aims to make food safer for Canadians, enable more effective responses to food safety emergencies, and maintain Canada's international reputation as a trusted supplier of safe food. It introduced requirements for licensing, preventive control plans, and traceability for many food businesses, aligning closely with HACCP principles.

Reference: Government of Canada. (2019). Safe Food for Canadians Act and Regulations. Canadian Food Inspection Agency.

Asia: The Asian region presents a diverse regulatory landscape, with countries at various stages of developing and implementing their FQMS frameworks.

- o **China:** The State Administration for Market Regulation (SAMR), along with the National Health Commission (NHC), oversees food safety. Following major incidents, China has significantly strengthened its food safety laws and regulations,

including the Food Safety Law of the People's Republic of China, imposing stricter controls on domestic production and imported foods, and emphasizing corporate responsibility and severe penalties for violations.

- o **India:** The Food Safety and Standards Authority of India (FSSAI), established under the Food Safety and Standards Act, 2006, is the apex body responsible for regulating and supervising food safety and standards. FSSAI lays down science-based standards for food articles and regulates their manufacture, storage, distribution, sale, and import to ensure the availability of safe and wholesome food. It consolidates various food laws into a single framework.

Reference: Food Safety and Standards Authority of India (FSSAI). (2006). Food Safety and Standards Act, 2006.

- o **Japan:** The Ministry of Health, Labour and Welfare (MHLW) is responsible for food safety, with a strong emphasis on risk assessment and strict controls on food additives and contaminants. Japan has also adopted HACCP principles and requires their implementation for certain food categories, particularly those dealing with raw materials or high-risk products.

Australia and New Zealand: These two countries share a joint food regulatory framework under Food Standards Australia New Zealand (FSANZ). FSANZ develops and maintains the bi-national Food Standards Code, which details requirements for food safety, identification, labeling, handling, and treatment of food produced or imported for sale in Australia and New Zealand. It includes provisions for food hygiene, primary production standards, and contaminant limits.

Reference: Food Standards Australia New Zealand (FSANZ). (Ongoing). Australia New Zealand Food Standards Code.

Challenges in global FQMS implementation

Despite significant advancements in FQMS, implementing and maintaining robust systems across the globe faces several persistent challenges:

Harmonization of standards and regulations: While international standards like ISO 22000 and GFSI schemes aim for convergence, variations in national legal requirements, interpretation, and enforcement mechanisms create complexities. For example, a food product compliant in the EU might require additional labeling or testing to meet US FDA standards, leading to increased compliance burdens and potential non-tariff trade barriers. This lack of full harmonization can hinder the free flow of goods and increase operational costs for multinational food companies.

Supply chain complexity and opacity: The increasingly globalized, fragmented, and multi-tiered nature of food supply chains makes end-to-end visibility challenging. Food products often cross multiple borders and pass through numerous hands (e.g., smallholder farms, aggregators, processors, distributors, retailers). This opacity makes it difficult to trace contamination quickly during an outbreak, manage diverse supplier standards, and identify vulnerable points for fraud. For instance, an ingredient sourced from a small, unregulated farm in one country may be mixed with ingredients from audited sources in another, complicating the entire safety profile.

Food fraud and economically motivated adulteration (EMA): The intentional misrepresentation, dilution, substitution, or mislabeling of food products for economic gain poses a significant threat to consumer health and trust. High-value products like olive oil, honey, and seafood are particularly susceptible. The 2013 horsemeat scandal in Europe, where beef products were found to contain undeclared horsemeat, severely eroded consumer confidence and highlighted the need for more robust authenticity testing and supply chain verification [Source: European Parliament, 2013]. Detecting such fraud often requires

sophisticated analytical techniques and intelligence sharing.

Emerging risks and climate change impacts: New and unforeseen challenges constantly emerge. The rise of antimicrobial resistance in foodborne pathogens, the impact of climate change on agricultural yields and pest prevalence, and the introduction of novel foods or processing technologies all present new risks that FQMS must adapt to. For example, changes in weather patterns can affect mycotoxin contamination levels in crops, requiring new monitoring strategies.

Resource limitations for small and medium-sized enterprises (SMEs): SMEs, particularly in developing countries, often struggle to adopt and maintain comprehensive FQMS due to limited financial resources, technical expertise, and human capital. The costs associated with implementing HACCP, obtaining certifications (e.g., GFSI-recognized), and conducting regular testing can be prohibitive, hindering their ability to access global markets and improve local food safety.

Technological integration and data management: While technology offers powerful solutions, the effective integration of advanced tools like blockchain, AI, and IoT into existing FQMS requires significant investment in infrastructure, specialized expertise, and ensuring interoperability across disparate systems used by different supply chain actors. Data silos and a lack of standardized data formats can impede the seamless flow of crucial food safety information.

Consumer awareness and education: While consumers increasingly demand safe and quality food, there can be a significant gap in understanding the complexities of food safety management. Misinformation, varying risk perceptions, and a lack of awareness about proper food handling at home can also contribute to foodborne illnesses, highlighting the need for continuous consumer education alongside industry efforts.

Future trends and innovations

The future of FQMS is poised for significant

transformation, driven by rapid technological advancements, evolving consumer demands for transparency, and a greater emphasis on sustainability and resilience:

Digitalization and data analytics: The widespread adoption of digital tools will revolutionize FQMS. Real-time data collection from various points in the supply chain (e.g., smart sensors in storage, digital logs) combined with advanced analytics will enable:

- o **Predictive analytics:** AI and ML algorithms can analyze historical data, weather patterns, and supplier performance to predict potential food safety risks (e.g., pathogen growth, spoilage) before they occur, allowing for proactive interventions.
- o **Optimized resource allocation:** Data-driven insights can help optimize sampling plans, inspection schedules, and resource deployment for more efficient food safety management.
- o **Automated compliance monitoring:** Digital platforms can automate compliance checks, reduce manual record-keeping, and streamline audit processes.

Reference: Food Safety Magazine. (2023). Harnessing the Power of Data Analytics for Food Safety.

Blockchain for enhanced traceability: Blockchain technology offers a secure, immutable, and transparent ledger for tracking food products and their attributes from farm to fork. Each transaction (e.g., harvest, processing, packaging, shipment) is recorded as a block on the chain, creating an unalterable history. This significantly enhances:

- o **Transparency:** Provides end-to-end visibility for all authorized participants in the supply chain.
- o **Food fraud prevention:** Makes it much harder to introduce counterfeit or adulterated products into the chain without detection.
- o **Rapid recall:** Enables near-instantaneous

traceback of contaminated products, drastically reducing recall times and affected batches. Walmart’s partnership with IBM Food Trust for tracing leafy greens and other produce is a prominent example, reportedly reducing traceback time from days to seconds [Source: IBM, 2018; Logistics Bureau, 2024].

Reference: Kamble, S., Gunasekaran, A., & Arha, H. (2020). Modeling the blockchain enabled sustainable food supply chain. International Journal of Production Economics, 227, 107872.

Artificial intelligence (AI) and machine learning (ML): Beyond predictive analytics, AI and ML are finding diverse applications in FQMS:

- o **Automated quality control:** Computer vision systems powered by AI can inspect food products for defects, foreign objects, or irregularities in real-time on production lines, improving consistency and reducing human error.
- o **Pathogen detection:** AI-driven tools can accelerate the detection and identification of foodborne pathogens from laboratory data.
- o **Sensory evaluation:** ML models can analyze data from sensors (e.g., electronic noses/tongues) to predict sensory attributes like flavor, texture, and aroma, automating parts of quality assessment.

Reference: Irjmets.com. (2025). Artificial Intelligence in Food Quality Control. International Research Journal of Modern Engineering and Technology Sciences, 07(01), 1738138873.

Internet of things (IoT): The deployment of IoT sensors and connected devices throughout the food supply chain allows for real-time monitoring of critical environmental and processing parameters:

- o **Cold chain management:** Sensors in refrigeration units, storage facilities, and transport vehicles

continuously monitor temperature and humidity, immediately alerting if conditions deviate from critical limits, thus preventing spoilage and bacterial growth.

- o **Smart packaging:** IoT-enabled smart packaging can indicate freshness or temperature abuse through color changes or digital displays.
- o **Automated process control:** Sensors can feed data directly to control systems to maintain optimal processing conditions (e.g., cooking temperatures, pH levels) in real-time.

Reference: Normex.ca. (2024). The Role of IoT Sensors in Preventing Foodborne Illnesses.

Whole genome Sequencing (WGS): WGS is transforming foodborne disease outbreak investigations and surveillance. By sequencing the entire DNA of foodborne pathogens, scientists can:

- o **Precise source attribution:** Identify the exact strain of a pathogen, enabling highly accurate tracing of the outbreak source.
- o **Real-time surveillance:** Monitor the evolution and spread of pathogens in food environments, facilitating earlier detection of potential outbreaks.
- o **Enhanced risk assessment:** Provide detailed genetic information for understanding pathogen virulence and antimicrobial resistance profiles.

Reference: Allard, M. W., et al. (2019). Advances in whole genome sequencing for foodborne pathogen detection and surveillance. Frontiers in Cellular and Infection Microbiology.

Integration of sustainability and ESG metrics:

Driven by consumer demand, regulatory pressure, and corporate responsibility, FQMS are increasingly incorporating Environmental, Social, and Governance (ESG) considerations:

- o **Reduced food waste:** Implementing FQMS that optimize processes, improve shelf-life, and enhance

traceability can significantly reduce food waste across the supply chain.

- o **Ethical sourcing:** Ensuring that raw materials are sourced from suppliers adhering to fair labor practices and environmentally sustainable agricultural methods.
- o **Sustainable packaging:** Developing FQMS that consider the environmental impact of packaging materials and promote recyclable or biodegradable options.

Reference: Swire Pacific Sustainability Report (2024). Supply Chain Management and ESG Integration.

Clean labelling and transparency: Consumers are increasingly demanding clear, concise, and transparent information about food ingredients, sourcing, and production methods. This pushes manufacturers towards simpler formulations, fewer artificial additives, and greater honesty and detail in labeling. FQMS must support these demands by providing robust verification processes for all label claims.

Remote auditing and digital verification: The COVID-19 pandemic accelerated the adoption of remote auditing technologies. This trend will continue, offering a more cost-effective and efficient solution for maintaining compliance and quality standards, especially for global supply chains, while still ensuring necessary oversight.

Conclusion

Food Quality Management Systems are paramount in navigating the inherent complexities and dynamic challenges of the global food supply chain. They serve as critical safeguards for public health, foster unwavering consumer confidence, and enable seamless international trade by providing a structured approach to managing food safety and quality risks. While significant progress has been made through the widespread adoption of international standards like ISO 22000, the influence of GFSI-recognized schemes, and

the development of robust national regulations like FSMA and EU Food Law, persistent challenges such as the full harmonization of standards, the inherent opacity of complex supply chains, and the pervasive threat of food fraud continue to demand vigilance.

The future of FQMS is undoubtedly rooted in technological advancement and data-driven insights. Embracing digitalization, leveraging disruptive technologies such as AI and blockchain for enhanced traceability and predictive risk management, and integrating sustainability into core quality practices will be crucial. Furthermore, building a truly resilient and safer global food system necessitates continuous, proactive collaboration among governments, regulatory bodies, industry stakeholders, and academic institutions. By fostering a culture of shared responsibility and continuous improvement, the global food industry can collectively strive towards ensuring that safe, quality, and authentic food is accessible to all.

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Lipid-based nutraceuticals and pharmaceuticals: synergies in managing chronic diseases

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Abstract

Chronic illnesses including diabetes, cancer, heart disease, and neurological disorders pose serious threats to world health and call for a variety of strategies for care and prevention. This analysis examines how medications and nutraceuticals may work together to manage chronic illnesses. Supplementing traditional pharmacological therapies with bioactive substances that have anti-inflammatory, antioxidant, and lipid-modulating properties is a potential use for nutraceuticals. Pharmaceuticals, on the other hand, provide efficient treatments that enhance patient outcomes and lower morbidity by focusing on certain biological processes that are essential to the development of illness. A more comprehensive and individualized strategy to managing chronic diseases can be attained by fusing the therapeutic accuracy of pharmaceuticals with the preventative advantages of nutraceuticals. The incorporation of these therapies into clinical practice is anticipated to increase as research on their effectiveness reveals more opportunities to improve quality of life and lessen the burden of chronic illnesses. In this review we have covered some nutraceuticals and pharmaceutical and their applications in managing chronic diseases. In this review, we have covered literature from the last two decades.

Introduction

Chronic diseases, including cardiovascular diseases, diabetes, cancer, and neurodegenerative disorders, remain a major global health challenge, accounting for approximately 71% of deaths worldwide¹ (WHO,

2021). The intricacy of these illnesses demands multi-targeted strategies for treatment and prevention, which is fueling interest in pharmacological and nutraceutical therapies. Pharmacies, which are chemically manufactured or naturally occurring substances used as medications, and nutraceuticals, which are bioactive compounds obtained from dietary sources, frequently have similar goals when it comes to treating chronic illnesses, especially when it comes to lipid-based pathways². The convergence of these two fields in the development of lipid-based delivery systems is an emerging area of research with immense therapeutic potential. A recent survey suggested that the nutraceutical market is expanding globally and the probability states that it may reach up to \$340 billion by the year 2024. The compound annual growth rate (CAGR) of nutraceuticals is estimated to be 7.2% in the year 2016 to 2024. This increment in the growth of the nutraceuticals-based industry is associated with various factors such as a rise in demand for nutraceuticals, an awareness among people for the benefits of nutrition and an incremental rate observed in the healthcare graph³⁻⁴.

Considering lipid-based systems improve the stability, bioavailability, and therapeutic effectiveness of lipophilic substances, they are important in both pharmaceutical and nutraceutical contexts. Triglycerides, phospholipids, and cholesterol are examples of lipids that are fundamental to cell membranes and play a role in several important biological processes, including as inflammation, cell signaling, and metabolic control⁵. Lipid-based drug delivery systems (LBDDS)—which include

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liposomes, solid lipid nanoparticles (SLNs), and nano-emulsions have been demonstrated in pharmaceutical research to enhance the administration of hydrophobic medicines, which are intended to treat conditions including cancer and cardiovascular disease⁶. Nutraceuticals based on lipids, such as carotenoids, phytosterols, and omega-3 fatty acids, have been shown to have preventive benefits against illnesses of a similar kind by lowering oxidative stress, enhancing cardiovascular health, and modifying lipid metabolism⁷.

Given their similar modes of action, medicines and nutraceuticals work well together to manage chronic illnesses. For instance, lipid-lowering pharmaceutical statins also cut cholesterol and prevent cardiovascular events, while omega-3 fatty acids, which are often used as nutraceuticals, have anti-inflammatory qualities and reduce cardiovascular risk⁸. Lipid-based carriers enhance the bioavailability of both classes of compounds, offering a unique strategy to integrate nutraceutical and pharmaceutical therapies.

Furthermore, new developments in lipid-based delivery methods have sparked the creation of hybrid strategies that optimize therapeutic results by merging medicines with nutraceuticals. For example, standard chemotherapy medications have been effectively combined with curcumin, a nutraceutical having anti-inflammatory and anticancer characteristics, encapsulated in lipid-based nanoparticles to improve pharmacological efficacy and minimize adverse effects in cancer treatment⁹. These hybrid lipid-based systems represent a promising frontier in the fight against chronic diseases, where combining the benefits of nutraceuticals with pharmaceutical precision could provide comprehensive treatment strategies.

The goal of this study is to investigate how lipid-based nutraceuticals and medications work in concert to manage chronic illnesses, with an emphasis on inflammatory, metabolic, and cardiovascular conditions. Additionally, it addresses how cutting-edge lipid-based drug delivery methods might boost the effectiveness of these bioactive substances, emphasizing how nutraceuticals may be incorporated into traditional pharmacological treatment paradigms.

Nutraceuticals have emerged as a complementary approach to conventional medicine in managing chronic diseases, providing health benefits beyond basic nutrition. These bioactive compounds, derived from foods or food products, offer therapeutic effects through mechanisms like anti-inflammatory, antioxidant, lipid-lowering, and immune-modulating activities. Below are some key nutraceuticals and their applications in managing chronic diseases:

1. Cardiovascular disease (CVD)

Cardiovascular diseases are a leading cause of mortality worldwide, and various nutraceuticals have shown potential in reducing risk factors such as high cholesterol, hypertension, and inflammation.

- (i) **Coenzyme Q10 (CoQ10):** CoQ10 is an antioxidant that stimulates energy synthesis in cells and has showed potential in enhancing endothelial function, decreasing blood pressure, and relieving symptoms in heart failure patients¹⁰.
- (ii) **Phytosterols:** These plant-derived substances, which are found in nuts, seeds, and whole grains, are useful in the management of hyperlipidaemia because they can reduce LDL cholesterol levels by competing with cholesterol for absorption in the intestines¹¹.
- (iii) **Omega-3 Fatty Acids:** Omega-3 fatty acids, which are found in fish oil and flaxseeds, have been extensively researched for their potential cardiovascular advantages, which include decreasing blood pressure and triglycerides. Additionally, they have anti-inflammatory properties, which makes them essential for treating long-term illnesses including rheumatoid arthritis and heart disease¹².
- (iv) **Polyphenols:** Polyphenols are powerful antioxidants and anti-inflammatory agents that may be found in foods like dark chocolate, tea, and berries. These bioactive substances aid in reducing inflammation and oxidative stress, two factors that are crucial to the pathophysiology of metabolic illnesses including diabetes and cardiovascular

disease¹².

2. Diabetes and metabolic syndrome

Controlling blood sugar levels and increasing insulin sensitivity are essential for managing metabolic syndrome, which includes obesity, hypertension, and dyslipidaemia, as well as diabetes.

- (i) **Berberine:** Through the activation of AMP-activated protein kinase (AMPK), this plant alkaloid has been demonstrated to reduce blood glucose levels, simulating the effects of metformin in the management of type 2 diabetes¹³.
- (ii) **Cinnamon:** Cinnamon extracts have been shown to have insulin-sensitizing properties, which enhance glucose metabolism and reduce fasting blood glucose levels in type 2 diabetics¹⁴.

3. Cancer

The potential of nutraceuticals to stop or reduce the development of cancer by regulating the cell cycle, triggering apoptosis, and inhibiting angiogenesis is being studied.

- (i) **Resveratrol:** Resveratrol is a substance that is present in red wine, berries, and grapes that has antioxidant and anti-inflammatory properties. It has been demonstrated to reduce cancer cell growth and increase the effectiveness of chemotherapy¹⁵.
- (ii) **Green tea polyphenols (EGCG):** It has been discovered that the green tea compound epigallocatechin gallate (EGCG) inhibits the development of cancer cells by preventing angiogenesis and encouraging apoptosis in malignant cells¹⁶.
- (iii) **Curcumin:** Curcumin, which is derived from turmeric, possesses strong anti-inflammatory and antioxidant characteristics. It has been demonstrated to cause apoptosis and prevent the growth of cancer cells in a number of cancer types, including colorectal, breast, and prostate cancers¹⁷.

4. Neurodegenerative diseases

The antioxidant and anti-inflammatory qualities of nutraceuticals have attracted attention because they may be able to prevent or reduce the course of neurodegenerative disorders such as Parkinson's disease (PD) and Alzheimer's disease (AD).

- (i) **Omega-3 fatty acids:** Omega-3 fatty acids, and DHA in particular, are essential for brain function in addition to their cardiovascular advantages. They promote synaptic plasticity, lessen neuroinflammation, and may be able to postpone the onset of cognitive loss in neurodegenerative illnesses¹⁸.
- (ii) **Ginkgo biloba:** Traditional medicine has employed this plant extract to improve cognitive performance. It has antioxidant qualities and increases cerebral blood flow, which may help Alzheimer's sufferers¹⁹.
- (iii) **Curcumin:** It contributes to neuroprotection via lowering oxidative stress and amyloid-beta plaques, both of which are linked to the advancement of Alzheimer's disease¹⁸.
- (iv) **Probiotics and gut microbiome:** The impact of the gut-brain axis on neurodegenerative illnesses, especially Parkinson's, is becoming more well acknowledged. By lowering inflammation coming from the gut and increasing the synthesis of neurotransmitters, altering the gut microbiota with probiotics may slow the course of the illness²⁰.

5. Inflammatory diseases and immune modulation

Numerous chronic illnesses, such as autoimmune diseases, metabolic syndrome, and arthritis, are rooted in chronic inflammation. These disorders can be managed with the use of nutraceuticals that possess immune-modulating and anti-inflammatory qualities.

- (i) **Turmeric (Curcumin):** Apart from its anticancer properties, curcumin is a strong anti-inflammatory substance that hinders pro-inflammatory cytokines, which makes it advantageous for the treatment of ailments including inflammatory bowel disease and

rheumatoid arthritis²¹.

- (ii) **Probiotics:** Good bacteria from fermented foods and supplements support gut health, which is directly related to immune function. Irritable bowel syndrome (IBS) and autoimmune illnesses may benefit from probiotics' ability to regulate the immune system²².
- (iii) **b-Glucans:** These polysaccharides, which are present in barley and oats, are known to affect immune function by increasing the activity of natural killer cells and macrophages. This enhances the body's protection against infections and can lessen inflammation²³.

6. Osteoarthritis and bone health

Through chondroprotective and anti-inflammatory processes, nutraceuticals can improve bone health and reduce osteoarthritis symptoms.

- (i) **Calcium and vitamin D:** The health of the bones depends on these nutrients. A sufficient diet rich in both calcium and vitamin D is necessary to prevent osteoporosis and bone fractures. Vitamin D also improves calcium absorption²⁴.

In the prevention, management, and treatment of chronic diseases many of which are complicated and multifaceted pharmacological therapies are essential. Chronic illnesses that require long-term, multi-targeted therapy approaches include diabetes, cancer, cardiovascular disease, and neurological disorders. An outline of the main pharmacological uses for managing chronic diseases may be seen below:

1. Cardiovascular disease (CVD)

Heart failure, hypertension, and coronary artery disease are among the most common cardiovascular disorders that cause death globally. Blood pressure, thrombotic hazards, and cholesterol levels are frequently the targets of CVD medications.

- (i) **Statins:** Statins are HMG-CoA reductase inhibitors that lower LDL cholesterol and have been shown

to lessen the risk of myocardial infarction, stroke, and cardiovascular mortality (e.g., atorvastatin, simvastatin). They are frequently recommended as the initial course of therapy for high cholesterol²⁵.

- (ii) **b-Blockers (e.g., metoprolol, atenolol):** Beta-blockers are frequently used in conjunction with other medications to treat hypertension because they lower heart rate and cardiac strain, improving outcomes in situations including heart failure and arrhythmias²⁶.
- (iii) **ACE inhibitors (e.g., lisinopril):** These drugs block the angiotensin-converting enzyme, reducing blood pressure by dilating blood vessels²⁷.

2. Diabetes and metabolic syndrome

Type 2 diabetes and metabolic syndrome are characterized by insulin resistance, hyperglycemia, dyslipidemia, and hypertension, all of which raise the risk of cardiovascular events.

- (i) **Metformin:** Metformin lowers the amount of glucose produced by the liver and increases insulin sensitivity, making it the first-line therapy for type 2 diabetes. Additionally, it improves cardiovascular and weight results²⁸.
- (ii) **GLP-1 receptor agonists (e.g., liraglutide):** In order to assist regulate blood glucose levels, these medications increase insulin production, block glucagon release, and slow stomach emptying. They also encourage weight reduction and have cardioprotective properties²⁹.
- (iii) **SGLT2 inhibitors (e.g., canagliflozin):** SGLT2 inhibitors lower blood glucose levels and cause glycosuria by reducing the kidneys' ability to reabsorb glucose. Additionally, they protect the heart and kidneys, which makes them useful in the treatment of diabetes and heart disease³⁰.
- (iv) **Insulin:** Insulin treatment is essential for the management of advanced type 2 and type 1 diabetes. Insulin comes in two types: long-acting

and rapid-acting. It helps regulate blood sugar levels and guards against diabetes consequences including neuropathy and nephropathy³¹.

3. Cancer

The goal of pharmaceutical cancer treatments is to minimise injury to healthy tissue while specifically targeting tumour cells. Treatments are becoming more individualised based on the genetic and molecular characteristics of the tumour due to developments in precision medicine.

- (i) **Chemotherapy (e.g., paclitaxel, doxorubicin):** Chemotherapy medicines interfere with cell division to target quickly dividing cells and cause tumour cell death. Chemotherapy can harm healthy cells even while it is effective, leading to adverse effects including nausea and immunosuppression³².
- (ii) **Hormonal therapy (e.g., tamoxifen, anastrozole):** Cancers that are susceptible to hormones, including prostate and breast cancer, are treated with hormonal therapy. These medications prevent the production or utilisation of hormones by the body that promote the growth of cancer³³.
- (iii) **Immunotherapy (e.g., pembrolizumab, nivolumab):** Through immunotherapy, cancer cells are recognised and eliminated by the immune system. Pembrolizumab and other checkpoint inhibitors target proteins that stop the immune system from attacking cancer cells, improving the prognosis of malignancies including lung and melanoma³⁴.
- (iv) **Targeted therapies (e.g., imatinib, trastuzumab):** These medications target certain molecular markers that are specific to cancer cells. For example, trastuzumab targets HER2-positive breast cancer cells, minimising harm to normal tissue, whereas imatinib targets the BCR-ABL fusion protein in chronic myeloid leukaemia³⁵.

4. Neurodegenerative diseases

The gradual loss of neurones and cognitive and motor abilities is a hallmark of neurodegenerative disorders

like Alzheimer's and Parkinson's.

- (i) **Levodopa/carbidopa:** Levodopa is converted into dopamine in the brain to assist control motor symptoms in Parkinson's disease; this combination is the gold standard therapy. Levodopa cannot be broken down before it reaches the brain due to carbidopa³⁶.
- (ii) **NMDA receptor antagonists (e.g., memantine):** Memantine protects neurones against excessive excitation and cell death, which are frequent in Alzheimer's disease, by controlling glutamate activity in the brain³⁷.
- (iii) **Dopamine agonists (e.g., pramipexole, ropinirole):** These medications are used in the early stages of Parkinson's disease to treat symptoms including stiffness and tremors by imitating the effects of dopamine³⁸.
- (iv) **Cholinesterase inhibitors (e.g., donepezil, rivastigmine):** By stopping the breakdown of acetylcholine, a neurotransmitter essential in learning and memory, these medications cure Alzheimer's disease. In the early stages of the disease, they could lessen cognitive deterioration³⁹.

5. Chronic inflammatory diseases

Long-term inflammation and immune system modulation treatment are necessary for chronic inflammatory illnesses such psoriasis, inflammatory bowel disease (IBD), and rheumatoid arthritis (RA).

- (i) **Nonsteroidal anti-inflammatory drugs:** NSAIDs are useful in the treatment of inflammatory diseases like arthritis because they block the cyclooxygenase enzymes (COX-1 and COX-2), which decrease inflammation, pain, and fever⁴⁰.
- (ii) **Biologics (e.g., infliximab, adalimumab):** These monoclonal antibodies effectively treat psoriasis, RA, and IBD by targeting immune system proteins implicated in inflammatory reactions, such as TNF-alpha⁴¹.

(iii) **Disease-modifying anti-rheumatic drugs:** By modifying the immune response, DMARDs delay the course of rheumatoid arthritis and other inflammatory illnesses. Often, methotrexate is utilized as a first-line therapy⁴².

6. Osteoporosis and bone health

Osteoporosis is a chronic condition characterized by reduced bone density, increasing the risk of fractures.

(i) **Denosumab:** This monoclonal antibody decreases bone resorption and increases bone mass in diseases such as osteoporosis by blocking the receptor activator of nuclear factor-kappa B ligand (RANKL)⁴³

Conclusion

In this review, we have covered literature from the last two decades. We have discussed in this study that how current developments in pharmaceuticals and nutraceuticals have significantly enhanced the treatment of chronic illnesses including diabetes, cancer, heart disease, neurological diseases, and osteoporosis. Nutraceuticals are becoming recognized as important adjunctive treatments, including advantages such increased insulin sensitivity and anti-inflammatory properties. In the meantime, medications especially those like bisphosphonates remain essential for lowering the risk of fracture and successfully treating symptoms. These advancements highlight the necessity of personalized medicine strategies, in which treatment regimens may be customized to meet the specific needs of each patient in order to get the best results. To ensure that these treatments give people dealing with chronic health issues the best quality of life possible, ongoing research is essential.

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Oleogels in food: A smart shift toward healthy and sustainable fats

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Abstract

With the rising prevalence of non-communicable diseases (NCDs), there is an increasing demand for healthier food products that contain low levels of saturated fat and no trans-fat. Solid fats play a crucial role in the texture and sensory qualities of food products, which makes their removal challenging for the food industry. Oleogelation is a process that transforms liquid oils into solid-like gels using specific structuring agents known as oleogelators. This novel method helps reduce saturated fat content in foods while maintaining desirable product characteristics. Oleogelators can include low molecular weight compounds, polymeric gelators, as well as newer, more sustainable options such as hybrid and upcycled gelators. These agents stabilise oleogels, allowing them to mimic the properties of traditional solid fats. The formation of oleogels can be achieved through various techniques, including hot homogenization (a process where oil and gelator are mixed at elevated temperatures to ensure uniform distribution), cold homogenization, solvent exchange, and melt blending, depending on the properties of the gelator and the oil system used. Due to their versatile textural, rheological, and thermal properties, oleogels have found widespread application in the food industry, including in bakery products, confectionery, meat alternatives, dairy innovations, and frying. Furthermore, oleogels show significant promise in emerging fields such as nutraceutical delivery and 3D printed foods, positioning them as sustainable fat replacers for the food industry.

1. Introduction

Global health initiatives are intensifying efforts to combat diet-related diseases through stricter regulations. In 2023, the World Health Organization (WHO) expanded its “REPLACE” initiative, enforcing comprehensive bans on industrially produced trans fats across 25 countries to align with updated cardiovascular health guidelines (WHO, 2023). The European Union’s Farm-to-Fork Strategy, a cornerstone of the European Green Deal, has set ambitious targets to reduce saturated fats

in processed foods by 2030, promoting reformulation strategies that prioritize unsaturated oils and innovative fat alternatives like oleogels. Oleogelation is an advanced technique that converts liquid oils into semi-solid gels, offering a healthier replacement to traditional solid fats, which are often high in trans fats and saturated fats. This process relies on structuring agents such as natural waxes, polymers, or small molecules that form tiny networks at the nano- and micro-scales, trapping the oil within them. As a result, oleogels can mimic the texture, consistency, and stability of solid fats while maintaining the nutritional benefits of liquid oils (Chaves et al., 2018). This technology has gained attention in the food industry as a way to reduce unhealthy fats in processed foods without compromising taste, mouthfeel, or functionality (Puscas et al., 2020). Oleogels can be used in different applications, including spreads, baked goods, and processed meats, providing an alternative to hydrogenated oils. Additionally, they contribute to global health initiatives aimed at lowering the risk of cardiovascular diseases (CVDs) associated with excessive saturated and trans-fat consumption. For many years, dietary guidelines treated all fats as unhealthy. However, recent research now differentiates between harmful fats, such as trans and saturated fats, and healthier unsaturated fats. Health organizations like the U.S. Food and Drug Administration (FDA), World Health Organization (WHO), recommend limiting saturated fat intake to less than 10% of total calories and eliminating industrial trans fats, as they are strongly linked to heart disease (WHO, 2018; FDA, 2020).

Oleogels offer a promising solution by replacing solid fats like palm oil and butter with structured unsaturated oils, such as olive, sunflower, or flaxseed oil. These gels can reduce the saturated fat content in food products

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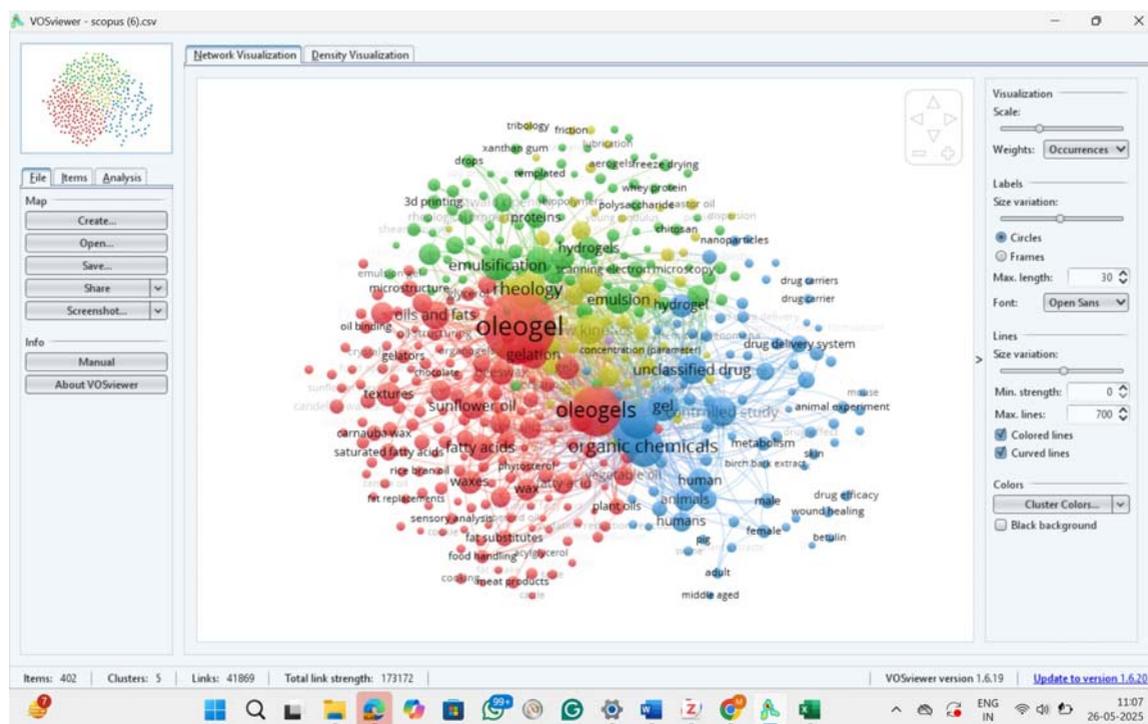


Fig. 1: Bibliometric analysis through Vos Viewer with the term “oleogel”.

by up to 80% in some cases while maintaining desirable texture and stability (Marangoni & Garti, 2018). This technology aligns with global efforts to develop healthier food formulations without compromising taste or functionality.

2. Bibliometric analysis

A bibliometric analysis was conducted using VOSviewer to visualize the keyword cooccurrence network related to oleogel. The analysis revealed four major keyword clusters:

Cluster 1 (Red): beeswax, bakery product, crystallinity, fat intake, gels, hardness, palmitic acid, physicochemical properties, X-ray diffraction.

Cluster 2 (Green): 3D printing, aerogels, delivery system, emulsions, oleofoam, food chemistry, polysaccharides, protein, rheology, starch, water.

Cluster 3 (Blue): animal experiments, antioxidants, drug delivery, metabolism, wound healing.

Cluster 4 (Yellow): biopolymer, cellulose, hydrogen bond, lubrication, kinetics, phase transitions.

3. Oleogelators: Key agents in structuring liquid oils

Oleogelators perform an important role in the formation of oleogels by converting liquid oils into semi-solid structures. These agents are broadly classified into two categories based on their molecular weight: polymeric gelators and low-molecular-weight gelators (LMWGs). The choice of oleogelator depends on the intended food application, as each type influences the gel's thermal stability, mechanical properties, and overall functionality.

3.1 Low-molecular-weight gelators (LMWGs)

LMWGs, such as natural waxes (e.g., carnauba wax, beeswax) and fatty acids, create crystalline networks that stabilize liquid oils through Van der Waals interactions and hydrogen bonding (Marangoni & Garti, 2018). These gelators are particularly suitable for applications requiring firm textures and heat resistance, such as bakery products and confectionery items (Patel et al., 2014). Their ability to form stable crystalline structures allows them to maintain integrity during processing and storage. For example, beeswax, a widely studied LMWG, consists of long-chain esters,

hydrocarbons, and free fatty acids that promote efficient structuring of oils (Doan et al., 2022). Carnauba wax, derived from the leaves of the Brazilian palm tree (*Copernicia prunifera*), exhibits high melting temperatures (H^o82–86°C), making it ideal for applications requiring stability at elevated temperatures (Flöter et al., 2021). Fatty acid-derived oleogels, such as those based on stearic acid, also form robust networks with desirable firmness, suitable for replacing solid fats in spreads and margarine formulations.

3.2 Polymeric gelators

In contrast, polymeric gelators such as ethyl cellulose (EC) create thermo-reversible gels, which are highly beneficial for applications involving repeated heating and cooling cycles, such as frying. Ethyl cellulose, a modified cellulose derivative, forms a three-dimensional entangled network in oil, providing high thermal stability and resistance to oil migration (Davidovich-Pinhas et al., 2016). Unlike crystalline gelators, polymer-based oleogels exhibit unique viscoelastic properties that can be tailored based on concentration and processing conditions.

3.3 Emerging sustainable alternatives

As the demand for sustainable and plant-based food

ingredients grows, researchers are exploring novel oleogelators derived from renewable sources. Plant proteins (e.g., pea and soy proteins) and polysaccharides (e.g., chitosan, alginate) have demonstrated potential not only in structuring oils but also in enhancing emulsion stability and controlled nutrient delivery (Zhu et al., 2023). Proteins function by forming self-assembled networks in oil, while polysaccharides contribute to gel stability through hydrogen bonding and electrostatic interactions. These naturally derived gelators are gaining interest for their biocompatibility and ability to improve the nutritional profile of food products.

3.4 Innovations in gelators

Recent advancements in oleogelation have focused on developing innovative gelators that enhance both functionality and sustainability. Two key areas of progress include hybrid gelator systems and the use of upcycled structuring agents.

3.4.1 Hybrid gelator systems: Enhancing gel strength and stability

Hybrid oleogel systems involve the combination of different gelators to optimize texture, stability, and performance in food applications. One notable example is the combination of monoglycerides with citrus wax,

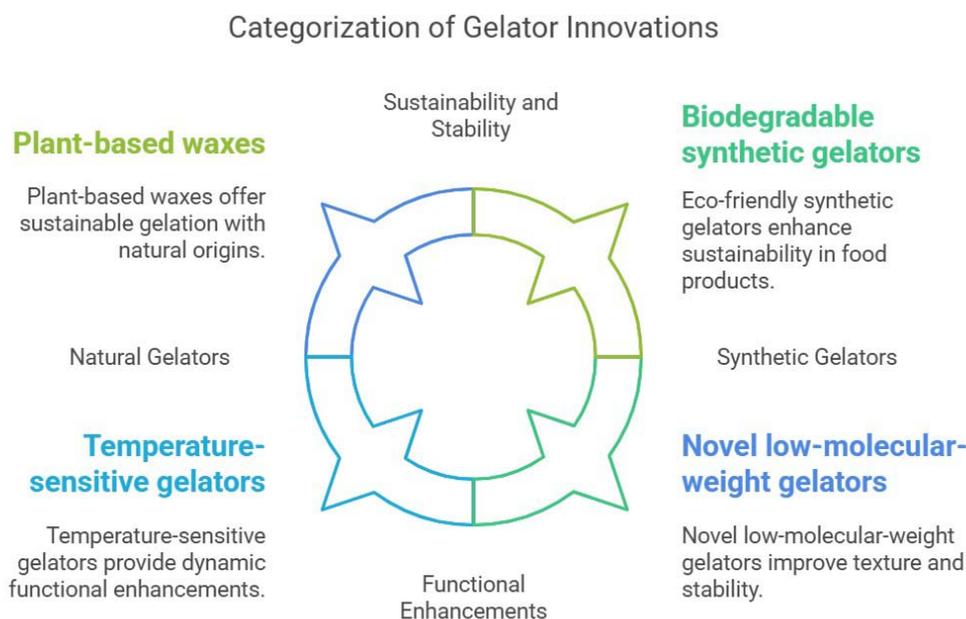


Fig. 2: Schematic illustration of various categories of oleogelators.

which has been found to significantly enhance the gel strength and oil-binding capacity of oleogels used in chocolate formulations. This combination improves the textural properties of chocolate-based products, reducing oil migration and preventing fat bloom, a common defect that affects the appearance and shelf life of chocolates (Marangoni & Garti, 2018). Hybrid systems also provide tailored melting behavior, making them suitable for applications where controlled fat crystallization is essential, such as in confectionery and bakery products (Patel et al., 2014).

3.4.2 Upcycled gelators: Sustainable and cost-effective solutions

The food industry is increasingly turning to upcycled ingredients to improve sustainability and reduce waste. In oleogel technology, upcycled gelators derived from food processing by-products are gaining attention for their functionality and environmental benefits.

Rice Bran Wax: A by-product of rice milling, rice bran wax is a highly effective gelator that can structure liquid oils at low concentrations (1–2%). It forms stable crystalline networks, providing a firm texture comparable to traditional wax-based oleogels (Martins et al., 2020). Additionally, rice bran wax offers a sustainable alternative to synthetic structuring agents, reducing dependence on non-renewable sources.

Spent Coffee Wax: Extracted from used coffee grounds, spent coffee wax is another promising upcycled gelator. Rich in bioactive compounds, it not only enhances oil structuring but also provides antioxidant properties, extending the shelf life of food products (Zhu et al., 2023). Incorporating spent coffee wax into oleogels lowers production cost while contributing to waste valorization, aligning with circular economy principles.

4. Oleogel formation

Oleogelation is a novel oil-structuring approach in which the incorporation of gelators into liquid oils facilitates the transformation into semi-solid systems with tailored physicochemical and functional properties (Wang et al., 2023). Various types of gelling agents are used to form

oleogels, including hydrocolloids and lipophilic gelling agents.

4.1 Gelling agents

Hydrocolloids, characterized by their complex supramolecular interactions, exhibit the capacity to generate novel material architectures. Proteins, due to their amphiphilic nature, readily adsorb at oil–water interfaces, making them effective emulsifying agents. However, the functional attributes of proteins are susceptible to degradation under specific environmental conditions, including acidic pH, elevated temperatures, high ionic strength, and the presence of organic solvents, thereby imposing limitations on their broad industrial applicability. Polysaccharides, which are high molecular weight, hydrophilic, and biodegradable polymers, are conventionally employed as thickening agents to modulate the viscosity of aqueous phases for emulsion stabilization. Despite their functional versatility, many polysaccharides lack sufficient hydrophobic domains, resulting in limited interfacial activity compared to proteins (Iqbal et al., 2019). The extensive availability of food-grade proteins and polysaccharides, coupled with the versatile nature of protein-polysaccharide interaction mechanisms, constitutes a fundamental basis for the rational design of hydrogel matrices that can subsequently be transformed into oleogels.

Alginates, extracted from brown macroalgae, possess the ability to interact with divalent cations, leading to the formation of cross-linking junctions and consequent gelation. Hydrogels composed of alginate present several advantageous characteristics, including high oil retention capacity, inhibition of lipid oxidation processes, controlled modulation of lipid digestion kinetics, and the sustained release of encapsulated target compounds. Furthermore, diverse bacterial species serve as additional sources of carbohydrate-based hydrocolloids, exemplified by xanthan gum. Notably, the combination of xanthan gum with plant-derived galactomannans, such as guar gum and locust bean gum, results in a synergistic augmentation of viscosity (Davidovich-Pinhas, 2019).

Proteins are capable of forming protein-based oleogels, and their macroscopic properties can be tailored

by manipulating the intermolecular interactions within the oleogel network, as well as by modifying the physicochemical characteristics of the aqueous phase during processing. This modulation is achieved by attenuating the electrostatic repulsive forces between charged protein molecules through adjustments in pH values towards their isoelectric point or by the addition of electrolyte solutions. Consequently, the inter-protein distances are reduced, allowing attractive Van der Waals forces to become the dominant interparticle interaction. Thus, the interplay between repulsive and attractive forces dictates the resultant network architecture during the aggregation process.

Proteins can also serve as oleogel-forming agents through two main strategies; emulsion templated method and solvent exchange method with the specific protein source exhibiting variability. The emulsion-template approach necessitates the utilization of proteins exhibiting surface-active properties. The inclusion of polysaccharides can enhance this characteristic by fortifying the interfacial network through augmented attractive interactions with the protein molecules. Conversely, the solvent exchange methodology mandates that the proteins undergo aggregation upon thermal treatment, thereby enabling the utilization of a broader spectrum of globular proteins. While the solvent exchange process affords greater control over the final material properties, it necessitates the use of an intermediate solvent. Furthermore, the presence of intramolecular and intermolecular disulfide bridges within the protein aggregates contributes to enhanced structural stability, thereby retarding their potential for disintegration.

Lipophilic gelling agents

Waxes are among the most effective oleogelators due to their superior structuring capabilities, textural benefits, and high oil-binding capacity in oleogel systems (Soleimani et al., 2020). In contrast to many other oleogelators, waxes are multicomponent systems composed primarily of wax esters, alongside free fatty acids, fatty alcohols, and hydrocarbons (Doan et al., 2017). This compositional complexity contributes to a more intricate gelation mechanism. Consequently, the

gelation behavior of wax-based oleogels is strongly influenced by the specific chemical composition of the wax, including factors such as the degree of unsaturation and alkyl chain length of wax esters, as well as the presence of free fatty acids, fatty alcohols, and other minor constituents (Li et al., 2022).

A wide array of lipid-based compounds is currently being investigated for their potential roles as structuring agents and, in certain cases, as emulsifiers in water-in-oleogel (W/O) emulsions. These include compounds such as 12-hydroxystearic acid (Tamura et al., 1997), myverol (Ojeda-Serna et al., 2019), α -oryzanol, β -sitosterol, sterols (Sawalha et al., 2012), monoacylglycerols, and various natural waxes including rice bran (Hwang et al., 2013; Wijarnprecha et al., 2019), candelilla (Silva et al., 2019a, 2019b; Toro-Vazquez et al., 2013), carnauba (Ögütçü & Yılmaz, 2014), beeswax (Lee et al., 2019), paraffin (Hodge & Rousseau, 2003), and sunflower wax (Hwang et al., 2013).

Waxes are chemically defined as long-chain fatty acids esterified with fatty alcohols, characterized by low polarity and high melting points, which enable their efficient crystallization in liquid oils. Their molecular composition typically includes wax esters, free fatty acids, fatty alcohols, and linear hydrocarbons. Among oleogelators, waxes are recognized as particularly promising due to their ability to form stable gels at low concentrations (often below 0.5% w/w), cost-effectiveness, and regulatory approval for use in food systems (Patel, 2015). The mechanism of wax-induced gelation is attributed to the organization of n-alkanes or wax esters into microcrystalline platelets, which aggregate into an extensive three-dimensional network capable of entrapping liquid oil (Blake et al., 2014; Martini et al., 2015; Patel, 2015). Understanding the application of waxes in emulsion systems could facilitate broader utilization, given their proven functionality in oleogel matrices. Studies have identified critical concentrations for effective gelation in canola oil: sunflower wax (1%), rice bran wax (1%), carnauba wax (4%), and candelilla wax (2%) (Blake et al., 2014). In W/O emulsions, waxes can act as stabilizing agents independently of traditional emulsifiers. These networks form through Van der Waals interactions and physical

entrapment, providing excellent oil retention and thermal stability, enhancing emulsion stability. Solidification of wax at the oil-water interface or migration of crystals toward the interface increases the system's viscosity, thereby limiting molecular diffusion and enhancing stability (Visintin et al., 2008; Silva et al., 2021).

Polymeric agents

The structuring of edible oils using food-grade polymers—commonly referred to as polymeric oleogelation—has emerged as a promising strategy in food and nutrition science within the domains of food science and nutrition. In recent years, growing interest has been directed toward the development of oleogels due to their potential to offer healthier alternatives to traditional solid fats. This has been particularly pertinent considering the widespread concern surrounding the health risks associated with excessive consumption of saturated and trans fats.

Substantial research efforts have been concentrated on the use of glycerol monostearate (GMS) as a primary oleogelator. In contrast, polyglyceryl esters (PGEs)—despite their functional diversity and food-grade status—have received relatively limited scientific exploration in the context of oleogelation. Sánchez et al. (2011) demonstrated that GMS-based oleogels exhibit higher mechanical strength than those structured with sorbitan monostearate. Their study involved formulating oleogel with various liquid oils, and superior mechanical strength was exhibited by GMS-based gels compared to those structured using sorbitan monostearate. This work was conducted with the aim of developing environmentally sustainable lubricants, yet the findings remain highly relevant to the food sector.

Further advancements were made by Wang & Marangoni (2015), wherein emulsion-based gels were developed using GMS and sodium stearoyl lactylate (SSL) in combination with xanthan gum. It was observed that the inclusion of xanthan gum contributed significantly to the stabilization of the α -crystalline phase within the GMS/SSL system, thereby enhancing the structural integrity of the emulsion gels. Building on this work, Wang et al. (2016) investigated the effect of palm

stearin on GMS-structured emulsions. It was found that the addition of palm stearin modified the melting characteristics of the system, resulting in improved cold storage stability, although a compromise in emulsion stability was observed under ambient conditions.

While most GMS-related studies have focused on its role within emulsion-based systems, a shift has recently been observed toward the use of GMS as a direct oleogelator—either alone or in combination with additional amphiphilic agents—for the direct structuring of edible oils without requiring an aqueous phase. This represents a significant advancement in the application of low-molecular-weight gelators (LMWGs) in lipid structuring. Complementary to the work on monoglycerides, research conducted by Nakajima & Hamada (2012) involved the synthesis of di-, tri-, and tetra-fatty acid esters derived from linear polyglycerol oligomers (comprising 2–10 glycerol units). The oleogelation potential of these polyglyceryl esters was evaluated, and it was reported that triglycerol esters with appropriately long alkyl chains demonstrated the capacity to form oleogels, as later supported by the findings of Keskin Uslu and Yılmaz (2021).

In parallel, attention has been increasingly directed toward polymeric oleogelators, particularly ethyl cellulose (EC), which currently stands as the only polymeric structuring agent approved for direct use in food systems. EC is known to exhibit a semicrystalline molecular structure and to undergo a thermoreversible sol-gel transition in the presence of liquid oils. This transition is driven by physical (non-covalent) interactions, including hydrogen bonding and Van der Waals forces. The nature and stability of the resulting gel matrix are significantly influenced by external parameters such as shear forces, processing temperature, and the polarity or composition of the oil phase. The versatility of EC-based oleogels has enabled their incorporation into various food applications. These include their use as fat replacers in reduced-fat spreads, as oil-binding agents in baked goods, and as thermal stabilizers in chocolate products to prevent oil migration and improve shelf life. The capacity of EC to form stable, heat-resistant, and physically structured gels has

been widely reported, notably in the work of Davidovich-Pinhas et al. (2016).

Over the past decade, the adverse health effects associated with the consumption of saturated and trans fats have been increasingly documented across scientific literature and media platforms. As a result, considerable pressure has been exerted on food manufacturers to reformulate lipid-based products with a focus on nutritional optimization. Oleogelation has consequently emerged as a viable strategy to replace traditional solid fats with structured unsaturated oils, allowing for the development of products with improved lipid profiles without compromising textural or sensory quality.

Despite the clear potential of oleogelation, its broader implementation is currently hampered by a limited selection of food-approved structuring agents capable of effectively inducing gelation in edible oils. A range of materials—including natural waxes, phytosterol-sterol ester complexes, emulsifiers, and plant-derived resins—have been examined. Nevertheless, food-approved polymers remain among the most promising candidates due to their molecular tunability, biocompatibility, and functionality. However, a major barrier to their use in oleogelation lies in their hydrophilic nature, which significantly impairs their dispersion within hydrophobic oil phases and limits their ability to form the required three-dimensional gel networks.

To overcome these challenges, efforts must be directed toward the development of novel incorporation strategies for water-soluble polymers in oil-based systems. Potential approaches may include chemical modification to increase lipophilicity, emulsification techniques, or the use of interfacial compatibilizers to promote the dispersion and gelation of hydrophilic polymers within lipid matrices. If such approaches are successfully realized, they could enable the next generation of polymer-based oleogels, ultimately transforming the formulation of healthier, structured lipid products across the food industry.

4.2 Preparation methods:

The formulation of oleogels—semi-solid systems formed

by structuring edible oils—has been widely explored as a strategy for delivering healthier lipid profiles in food and nutraceutical products. These systems are typically prepared through the incorporation of a gelator into an oil phase, facilitated by a variety of processing methods, such as hot homogenization, cold homogenization, solvent evaporation, and melt blending, each selected based on the chemical nature of the gelator, the properties of the oil phase, and the desired functional characteristics and requirements of the final oleogel system.

Component selection in oleogel formulation

Before processing is initiated, the selection of appropriate formulation components must be undertaken. The oil phase—which may consist of a single oil or a blend—is chosen based on several factors, including chemical compatibility with the gelator, oxidative stability, and the intended release profile for any active compounds. Similarly, the gelator which may be a low-molecular-weight compound (e.g., waxes, monoglycerides) or a polymeric material (e.g., ethyl cellulose) must be selected based on its ability to self-assemble into a stable three-dimensional network capable of immobilizing the oil phase.

Hot homogenization technique

In the hot homogenization method, the oleogelator is initially combined with the oil phase at temperatures exceeding the gelator's melting point. Under these thermal conditions, the gelator is solubilized or dispersed homogeneously within the oil. The mixture is then subjected to high shear processing, typically using equipment such as high-speed homogenizers or high-pressure homogenizers, to ensure a fine dispersion and to eliminate agglomerates or crystalline inconsistencies. Following homogenization, the system is allowed to cool gradually under controlled conditions. During cooling, self-assembly of the gelator molecules occurs through non-covalent interactions, leading to the formation of a three-dimensional, viscoelastic network that entraps the oil within its structure. This technique is particularly suitable for thermally stable gelators, and it has been shown to produce homogeneous oleogels with consistent

textural properties (Manzoor et al., 2022; Pinto et al., 2021).

Cold homogenization approach

In contrast, the cold homogenization technique is conducted at or below ambient temperatures, making it an ideal method for structuring oleogels that incorporate temperature-sensitive gelators or active ingredients susceptible to thermal degradation. In this approach, the oleogelator and oil are mixed without prior heating, relying instead on mechanical agitation to promote dispersion. This method is especially valuable in systems where the textural, functional, or sensory properties of the gel may be adversely affected by heat. It has also been employed for formulations in which cooling conditions favor the development of the gel network, offering a gentle and efficient pathway to oleogel formation (Huang et al., 2023).

Solvent evaporation method

In the solvent evaporation technique, the gelator is first dissolved in a suitable organic solvent (e.g., ethanol, hexane), which is then mixed with the selected oil phase. Once dispersion is achieved, the solvent is gradually removed through methods such as rotary evaporation, vacuum drying, or ambient air drying. As the solvent is eliminated, the gelator becomes uniformly distributed within the oil, and gel network formation is initiated. This method is particularly advantageous for gelators with poor solubility in oils, or when precise control over gel structure is desired. Additionally, porous hydrophilic additives such as proteins or polysaccharides may be employed during the process to enhance oil absorption and network stability, thereby improving the mechanical strength and rheological behavior of the resulting oleogel. Such materials are often used in solvent exchange systems where oleogelation occurs as the solvent is replaced with oil (Urbaniak & Musial, 2019).

Melt blending process

In the melt blending method, both the oleogelator and oil are heated together to a temperature above the gelator's melting point, facilitating dissolution and homogeneous dispersion. This is typically carried out

using controlled heating equipment such as water baths or heating mantles, ensuring that the system remains within the thermal stability limits of both the oil and any active compounds. Continuous stirring during heating is used to promote uniform mixing. Upon controlled cooling, the gelator molecules organize into a structured network that entraps the oil, resulting in an oleogel with desirable textural and viscoelastic properties. While this method is relatively simple and equipment-independent, it may be unsuitable for gelators or bioactives that are prone to thermal degradation. During the blending phase, additional excipients—including antioxidants, preservatives, or active pharmaceutical ingredients (APIs)—can be incorporated, provided compatibility and uniform distribution are maintained (Pawar et al., 2024).

Post-processing characterization of oleogels

Following gel formation, oleogels are subjected to comprehensive characterization to assess their physical, mechanical, and functional properties. Initial evaluations include visual inspection to assess color, transparency, phase separation, and homogeneity. Subsequently, texture analysis including penetration tests and rheological measurements—is conducted to determine gel strength, spreadability, elasticity, and viscosity. These parameters are critical in defining the application potential of the oleogel in food, pharmaceutical, or cosmetic systems. It should be noted that while the described steps provide a standardized framework, processing parameters such as temperature, mixing speed, and cooling rate may vary depending on the type of gelator employed, the intended application, and the desired functional attributes of the final product (Mattice & Marangoni, 2019; Singh et al., 2017; Pawar et al., 2024).

5.1 Characteristics/properties of oleogels

5.1.1 Textural properties of oleogels

Fats perform a multifaceted function in food systems by contributing to sensory appeal, structural integrity, satiety, and resistance to oxidation (Gupta & Singh, 2024). In the case of edible oleogels (OGs), the required textural attributes vary depending on their culinary application. For example, OGs used as spreads or fillings

typically demand a smooth texture with minimal adhesiveness, while those developed for baking or frying require increased firmness and higher thermal stability. By selecting suitable structuring agents and fine-tuning processing methods, it is possible to customize the texture of OGs to meet sensory goals and particular functionalities (Pera-Cri'an et al., 2023).

One of the main objectives in the formation of oleogel for food services is to provide a viable alternative to solid fats. To serve as effective fat substitutes, OGs should emulate the stability and physical characteristics of traditional fats (Gupta & Singh, 2024). Achieving this requires the use of appropriate oleogelators, and ongoing innovations in oleogelation technologies are enhancing the effectiveness of these systems (Parmar et al., 2022).

To assess the suitability of OGs for various food applications, their mechanical and sensory properties must be quantitatively evaluated. Texture analyzers are commonly employed to measure parameters such as cohesiveness, adhesiveness, firmness, and spreadability (Trujillo-Ramírez et al., 2019). In addition, structural evaluation tools such as microscopy and X-ray diffraction offer valuable qualitative insights. Research has shown that combining different types of oleogelators and base oils can result in textures that are well-suited to specific food products, demonstrating the versatility and adaptability of OGs in food formulation (Sarkisyan et al., 2021).

5.1.2 Rheological properties

Stable shear rheology, uses a constant pressure or stress to quantify the flow characteristics of a material, giving information about its viscosity and shear-thinning behavior. Note that sample damage may occasionally occur as a result of these rheological tests (Martins et al., 2023). In further study, the effect of organogelator and fat source on the rheological characteristics of olive oil organogels prepared with different ratios of cocoa butter to olive oil was investigated. The investigation revealed that the type of fat used significantly affects gelling ability, and rheological properties, crystallization, especially at the critical Myverol concentration of 2%. The gelling and crystallization temperatures, together

with the storage modulus values, were raised by the saturation level of cocoa butter (Gravelle, 2023).

Rheological characterization is a fundamental analytical approach used to evaluate the flow and deformation behavior of oleogels (OGs), which are increasingly explored as fat alternatives in food formulations. Steady shear rheology, conducted under constant shear stress or rate, provides critical insights into a material's viscosity and flow characteristics, such as shear-thinning behavior. However, high shear forces can potentially damage the sample microstructure, an important consideration during experimental design (Martins et al., 2023). The effect of organogelator concentration and fat source on the rheological behavior of oleogels has been extensively studied. For instance, Gravelle (2023) examined the effects of combining cocoa butter and olive oil in various ratios and reported that crystallization, gelation, and viscoelastic behavior were significantly impacted by fat type. At a critical Myverol concentration of 2%, the presence of saturated fats in cocoa butter was found to elevate the crystallization and gelation temperatures, as well as enhance the storage modulus, reflecting improved gel strength.

Rheological data are especially valuable in the food sector, where the mechanical properties of fat systems must be tailored to meet specific textural and stability requirements in food matrices. Rheological measurements—such as loss modulus (G''), storage modulus (G'), and complex viscosity—enable a deeper understanding of the structural integrity and functional performance of OGs (Feng et al., 2023). Both steady and oscillatory shear tests are employed: while steady shear elucidates viscosity and flow characteristics, oscillatory tests apply sinusoidal strains or stresses to reveal the viscoelastic nature of the gel, distinguishing between solid-like and liquid-like behavior (Puebla-Duarte et al., 2023).

Importantly, the gelator concentration plays a pivotal role in defining rheological outcomes. Once a threshold concentration is surpassed, significant changes in the mechanical behavior of OGs are observed, indicating the formation of a stable gel network (Feng et al., 2023). It is also crucial to record, as these authors point out,

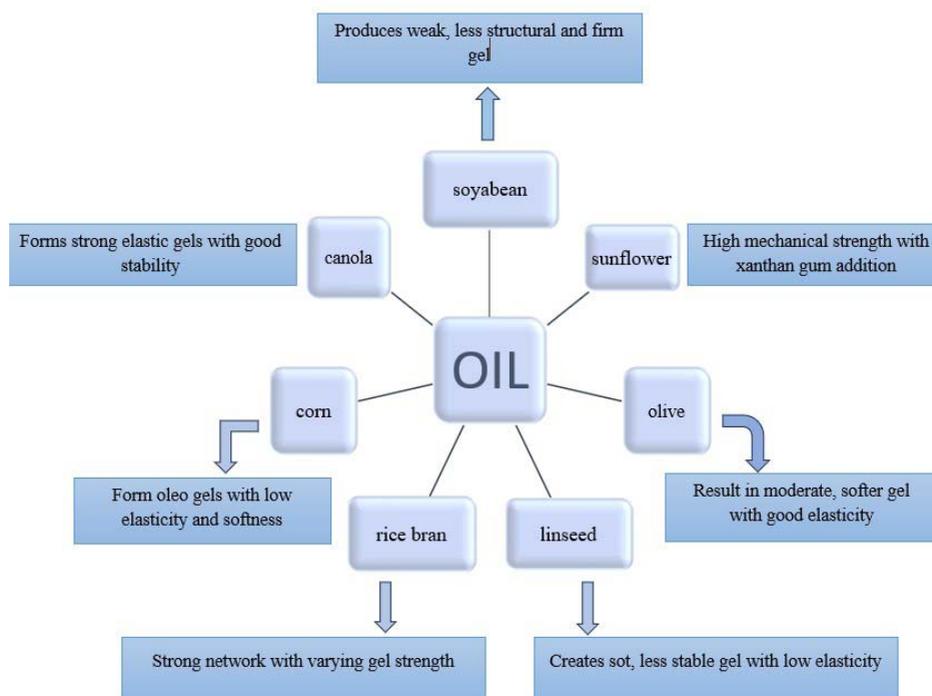


Fig. 3: Types of oils used in food-grade oleogels

that although all oleogels are a subset of organogels—defined by the presence of a structured organic liquid phase—not all organogels qualify as oleogels, since some may be structured with organic solvents other than edible oils.

The category of oil used also critically changes the microstructural rheological properties of OGs. Kavimughil et al., (2022) demonstrated that different edible oils, such as flaxseed oil, coconut oil, and soybean oil, influenced the development of pore networks and overall gel texture. In a broader comparative study, Ropciuc et al., (2024) evaluated OGs formulated with walnut, sunflower, olive, grape seed, and rice bran oils in combination with natural wax-based gelators including beeswax, sunflower wax, rice bran wax, candelilla wax, carnauba wax, and berry wax. The inclusion of these waxes significantly altered solid fat content and rheological behavior, underscoring the importance of gelator–oil interactions in achieving desirable textural and functional characteristics.

5.1.3 Oxidative stability

The assimilation of oil into a structured gel network has

been shown to significantly reduce the rate of lipid oxidation in oleogels (OGs) compared to unstructured, bulk oils. This structural entrapment restricts oxygen diffusion and limits the mobility of pro-oxidant molecules, thereby enhancing oxidative stability. Given that unsaturated fatty acids are inherently more prone to oxidative degradation than their saturated counterparts, the development of OGs presents a viable strategy to deliver unsaturated, health-promoting lipids in a more stable form. Consequently, evaluating the oxidative stability of OGs is critical not only for ensuring product quality and shelf life but also for maintaining the nutritional integrity of food systems incorporating these materials. Although the use of OGs inherently improves oxidative resistance, there are instances where the addition of antioxidants may be warranted to further suppress oxidative reactions and mitigate potential adverse health effects associated with lipid peroxidation. Nonetheless, recent research has demonstrated that many food products formulated with OGs maintain acceptable oxidative stability without the incorporation of additional antioxidant agents, underscoring the inherent protective capacity of the gel matrix (Hwang et al., 2022).

5.1.4 Sensory properties

Sensory analysis plays a critical role in validating the commercial viability of oleogels. Consumer acceptance depends on how closely oleogel-based products replicate the sensory characteristics of conventional fats. Newly published findings have explored the sensory-related acceptability of food items formulated with oleogels (OGs). For instance, a notable investigation involving sensory analysis by over 100 trained panelists evaluated margarine samples containing high-oleic sunflower oil-based OGs structured with a combination of monoglycerides (MG) and candelilla wax (CRW). The findings indicated that while the OG-based margarine formulations received slightly lower scores than their commercial counterparts in attributes such as color, aroma, appearance, texture and overall impression, consumer purchase intent remained comparable (de Silva et al., 2019). These results suggest that, with further optimization, OG-based formulations have the potential to be accepted in mainstream food markets.

5.1.5 Thermal properties

Thermal analysis of oleogels is typically performed using Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA). These techniques evaluate melting behavior, crystallization patterns, and thermal stability, which are crucial for predicting performance under processing and storage conditions. Among these, DSC is especially valuable for providing thorough insights into the thermal transitions of oleogels, including quantification of solid fat content and the peak, onset, and completion of melting and crystallization events. These thermal transitions are critical for understanding the functional performance of OGs in food applications, particularly under varying temperature conditions. The oleogelation process is typically characterized through cooling cycles and repeated heating and, which facilitate a comprehensive evaluation of thermal stability and structural formation (Pu^oca^o, Mure^oan et al., 2021). Furthermore, assessments of oil-binding capacity and resistance to oil leakage are essential for determining the structural robustness of OGs under elevated temperatures. Research indicates

that OGs generally maintain their matrix integrity even when exposed to heat, demonstrating strong oil retention capabilities. DSC thermograms of saturated oils used in OG formulations reveal distinct melting and recrystallization behaviors, underscoring the pivotal role of oil type in influencing the thermal and crystallization dynamics of oleogels (Wang, X. et al., 2020). These findings highlight the necessity of thermal analysis not only for optimizing OG formulation but also for tailoring their functionality to specific food processing and storage conditions.

5 Applications in food

Oleogels are gaining significant attention in the food sector as a healthier replacement to traditional solid fats. By replacing trans and saturated fats with structured liquid oils, oleogels help maintain the desired sensory attributes, texture, and stability of food products while improving their nutritional profile. Below are key applications of oleogels in various food categories:

Bakery Products

By integrating oleogels into bakery products, manufacturers can develop healthier alternatives without sacrificing sensory qualities, catering to consumer demand for functional and nutritious baked goods.

Biscuits & Cookies: Traditional biscuits and cookies rely on butter and shortening to achieve their characteristic crispness and rich flavor. However, replacing 50% of butter with candelilla wax–olive oil oleogels effectively maintains the crisp texture while reducing saturated fat content by 40%. This is particularly beneficial for heart health, as high saturated fat consumption is linked to cardiovascular diseases. Moreover, the inclusion of β -glucan-rich oleogels enhances the fiber content of these baked goods without compromising their texture, making them more suitable for individuals seeking improved digestive health and cholesterol management.

Cakes: Cakes typically require solid fats like shortening to create a tender crumb structure. Research by Puscar et al. (2020) shows that using beeswax–canola oil oleogels allows for a 70% reduction in shortening, leading to a softer crumb texture and 30% fewer calories. This

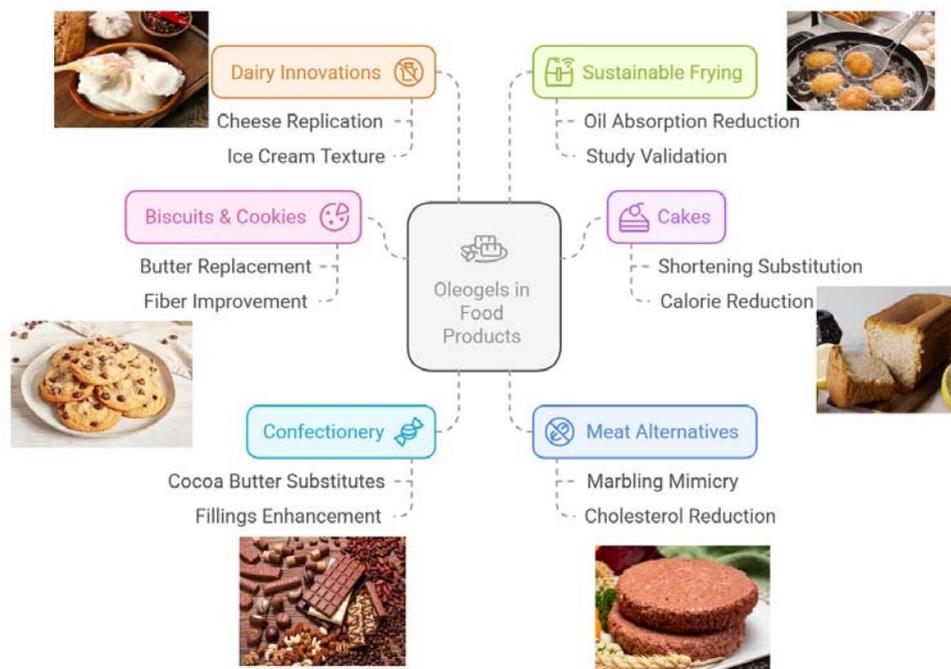


Fig 4: Application of oleogels in food products

substitution not only promotes calorie reduction but also improves the nutritional profile by incorporating healthier unsaturated fats, which can support better metabolic health and weight management.

Confectionery

Chocolate: Cocoa butter is essential for the smooth texture and melting behavior of chocolate, but its high saturated fat content raises health concerns. Using shea butter oleogels structured with sunflower wax, manufacturers can achieve a 35% reduction in saturated fat while preserving the melt-in-mouth properties that consumers expect. This reformulation supports heart health without compromising the indulgent experience of chocolate consumption.

Fillings: Oil separation is a common issue in nut-based spreads, affecting both texture and shelf stability. By incorporating rice bran wax–almond oil oleogels, hazelnut spreads gain superior heat resistance, preventing oil migration and maintaining a consistent, smooth texture during storage (Martins et al., 2018). This innovation ensures product integrity and extends shelf life while offering a healthier fat composition.

Meat alternatives

Plant-Based Meats: One of the challenges in plant-based meat development is replicating the marbling effect found in conventional meat. Oleogels formulated with algae oil and citrus fiber successfully mimic marbling, enhancing juiciness and increasing omega-3 content. This not only improves the sensory appeal of vegan burgers but also provides essential fatty acids beneficial for cardiovascular health.

Frankfurters: Traditional frankfurters rely on pork fat for texture and flavor, but excessive consumption of animal fats is linked to various health risks. By using ethyl cellulose–flaxseed oil oleogels, pork fat can be entirely replaced, leading to a healthier fatty acid profile and a 50% decline in cholesterol oxidation (Manzoor et al., 2022). This reformulation minimizes the formation of harmful oxidative compounds while offering a more nutritionally balanced alternative.

Dairy innovations

The use of oleogels in dairy innovations aligns with the shift toward healthier and plant-based alternatives,

allowing for the reduction of saturated fats while maintaining desirable texture and stability.

Cheese: Traditional full-fat cream cheese relies on dairy fats for its smooth, creamy consistency. However, excessive consumption of saturated fat is linked to cardiovascular issues. Using fermented oat-based oleogels, researchers have successfully replicated the creaminess of full-fat cream cheese while reducing saturated fat by 80% (Cui et al., 2023). This innovation offers a plant-based, heart-healthy alternative that caters to the growing demand for dairy-free and functional food products.

Ice Cream: Achieving the rich mouthfeel of traditional ice cream without dairy fats is a major challenge in plant-based formulations. Oleogels structured with candelilla wax, hemp seed oil, and olive oil serve as an effective fat replacement in new plant-based ice cream formulations (Ropciuc et al., 2024). These alternatives maintain creaminess, improve nutritional composition, and enhance the stability of frozen desserts, offering consumers a health-conscious yet indulgent option.

Sustainable frying

Deep-Fried Foods: Conventional frying oils tend to be absorbed in large quantities by food products, leading to high fat content. Studies have shown that using oleogels as a frying medium can decrease oil absorption by up to 27.7% compared to conventional oils (Chauhan et al., 2022). This reduction not only contributes to lower calorie fried products but also helps in improving lipid profiles, making fried foods a healthier option without compromising their crispness and flavor.

6 Future trends & innovations

Nutraceutical delivery:

Oleogels encapsulate fat-soluble bioactives like curcumin and vitamin D3, enhancing stability and bioavailability. Their unique properties, including high stability, tunable rheology, and low microbial growth potential, make them suitable for various pharmaceutical applications (Karmakar et al., 2023).

3D-printed foods:

Tailored oleogel matrices enable the printing of customized textures for personalized nutrition, such as low-calorie, high-protein snacks (Park et al., 2020)

Climate-resilient oils:

Oleogels using drought-resistant oils (e.g., moringa or camelina oil) support sustainable agriculture. A number of studies demonstrated oleogels' viability in margarine, reducing land use by 30% compared to palm oil (Abdolmaleki et al., 2022).

Circular economy:

Agro-industrial byproducts like fruit peels and seed shells are being valorized as low-cost gelators. For example, pectin-based oleogels from apple pomace show promise in vegan cheese.

7 Challenges & considerations

One of the main challenges in making oleogels more acceptable to consumers is overcoming their waxy mouthfeel. Researchers are working on ways to improve the texture, such as using enzymes like lipase to modify the structuring agents, which helps create a smoother and more pleasant sensory experience. In addition to consumer preferences, regulatory approval is another hurdle. New gel-forming ingredients must receive Generally Recognized as Safe (GRAS) certification, which can slow down their entry into the market. To make oleogels more practical for large-scale production, scientists are optimizing continuous manufacturing techniques, such as extrusion-cooling, to ensure they can be efficiently produced on an industrial scale.

8 Conclusion

The development of advanced oleogelators is revolutionizing the food industry by offering healthier replacements to conventional solid fats. The combination of traditional wax-based oleogels with modern polymeric and plant-based systems provides tailored solutions for diverse applications, ranging from bakery products to frying oils. Future investigations should focus on

optimizing these systems for large-scale food production while ensuring regulatory compliance and consumer acceptance.

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Bio-Gasoline from waste cooking oil: A sustainable fuel alternative

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Abstract

The rising demand for sustainable energy solutions has sparked global interest in converting waste materials into clean fuels. Among various renewable feedstocks, **waste cooking oil (WCO)** has emerged as a promising candidate for producing bio-gasoline which is a potential alternative to fossil-derived gasoline. Recent advancements in **thermochemical technologies** including catalytic pyrolysis, hydro processing has opened new possibilities for efficiently transforming WCO into usable fuel. These processes not only offer an effective way to manage waste but also present an opportunity to reduce greenhouse gas emissions and reliance on fossil resources. By turning a common environmental pollutant into a sustainable energy source, WCO-derived bio-gasoline holds immense promise for supporting global energy transitions and promoting reduction in environmental pollutants. This review encompasses the current state of research, highlights key technological developments, and identifies the critical challenges and opportunities for future exploration.

Keywords: waste cooking oil (WCO), Bio-Gasoline, Thermochemical Conversion, Sustainable Fuel, Waste Valorization

1. Introduction

Once relegated to waste streams, WCO has become a renewable and affordable feedstock for the production of sustainable fuels, especially bio-gas and renewable diesel. This aligns with the goals of the circular economy and reduces environmental pollution caused by improper disposal (Manikandan et al., 2023; Caliskan, et al., 2023).

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WCO is produced in millions of tons worldwide from homes, eateries, and the food industry and its potential is being unlocked more and more by policies that support it, such as the United States' Renewable Identification Numbers (RIN) and the European Union and China's low-carbon fuel standards (Becker, 2024; Reuters, 2024a; Reuters, 2024b). When paired with catalysts like Ni/AlO_f and HZSM-5, thermochemical conversion technologies such as catalytic pyrolysis, hydrocracking and decarboxylation are ideal for creating gasoline-range hydrocarbons. WCO poses difficulties for the transesterification of biodiesel because it is mainly made up of broken-down triglycerides and increased free fatty acids (FFA) from repeated heating. WCO, which was previously relegated to waste streams, is now a cheap and renewable feedstock for the manufacturing of sustainable fuels, particularly bio-gas and renewable diesel. This lessens environmental pollution brought on by inappropriate disposal and is consistent with the objectives of the circular economy (Manikandan et al., 2023; Caliskan, Yildiz, & Mori, 2023). WCO is produced in millions of tons worldwide from homes, eateries, and the food industry and its potential is being unlocked more and more by policies that support it, such as the United States' Renewable Identification Numbers (RIN) and the European Union and China's low-carbon fuel standards (Becker, 2024; Reuters, 2024a; Reuters, 2024b). Thermochemical conversion technologies like catalytic pyrolysis, hydrocracking, decarboxylation, and supercritical or microwave-assisted processes are well-suited for producing gasoline-range hydrocarbons when combined with catalysts like Ni/Al, O_f and HZSM-5. WCO, which is primarily composed of degraded triglycerides and elevated free fatty acids (FFA) from

repeated heating, present challenges for biodiesel transesterification. According to lifecycle assessments, feedstock valorization and reduced carbon footprint can result in up to 75% reductions in GHG emissions when compared to fossil fuels (Szeto & Leung, 2022; Yaqoob et al., 2021; Manikandan et al., 2023). However, the need for pretreatment to lower moisture and FFA content, logistical challenges in collection and storage, and inconsistent feedstock quality all impede widespread adoption (Peterson & Klare, 2024; Santos et al., 2024). Ongoing research focuses on continuous reactor design for scalable production (Caliskan et al., 2023; Conversion Study, 2024), standardized pretreatment protocols, and strong catalysts resistant to feed contaminants (Sayed & El Gharbawy, 2024). To fully realize WCO's sustainable potential, infrastructure investment and policy framework improvements are also essential (Becker, 2024; Reuters, 2025).

Bio-gasoline contains less oxygen than biodiesel, which is an oxygenated ester blend. It can be used with spark-ignition engines and distribution systems that are already in place (Johnson & Li, 2022; Kumar et al., 2021, Martinez et al., 2023; Patel et al., 2024). With its high octane ratings, clean combustion, and reduced particulate emissions, it usually consists of C5–C12 alkanes, iso-alkanes, and aromatic compounds (Chen et al., 2020; Singh & Gupta, 2021). Furthermore, bio-gasoline has favorable volatility, cold-flame ignition, and an energy density that is comparable to that of fossil fuels (Rodriguez et al., 2022; Zhao & Wang, 2024). It has a 60–80% lower carbon footprint, especially when it comes from feedstocks derived from waste (Yaqoob et al., 2021; Fernandez & Lee, 2023). There has been little effect on vehicle performance and emissions profiles when added to fuel blends at high percentages (e.g., 30%) (Smith et al., 2023; Tan et al., 2021). Supportive policies like blending requirements and carbon pricing are helping to close the gap, even though production costs are still higher than those of conventional gasoline (Johnson & Li, 2022; Kumar et al., 2021).

2. WCO

WCO, generated by households, restaurants and food

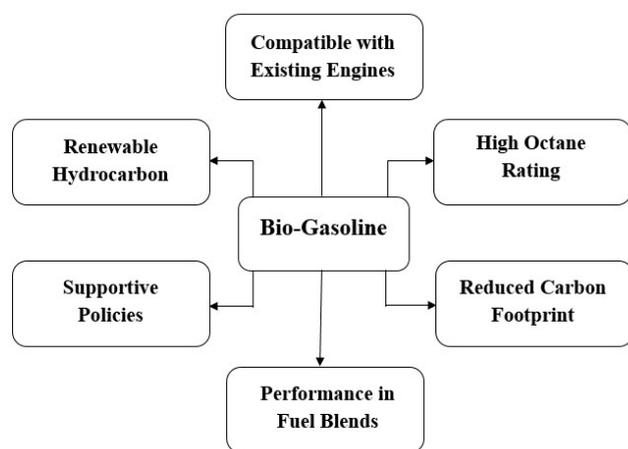
industries, has an estimated global production of 15–52 million tons per annum, (Sheinbaum Pardo et al., 2022; Hartini et al., 2023; Mannu et al., 2021). A strong demand from the industry is seen in the U.S. for Chinese WCO (for renewable diesel) with unprecedented imports. Also, China has shifted the deployment of its WCO to SAF, indicating strategic value changes. From a chemical point of view, WCO is composed mainly of triglycerides (C 16–C 18) and free fatty acids (FFA), generally as a consequence of repeated heating (Sheinbaum Pardo et al., 2022; Mannu et al., 2021; Sheinbaum Pardo et al., 2022). Its high FFA content makes it unsuitable for conventional ester derived biodiesel routes, but amenable as potential feedstock for thermochemical processes to produce paraffinic fuels and aromatics (RSC Advances, 2025). In addition to serving as a fuel, WCO is a feedstock for oleochemical products, such as bioplastics, surfactants, lubricants, and biosolvents, thus supporting its status as a player in green industrial chemistry (Sheinbaum Pardo et al.; RSC Sustainability; MDPI Polymers, 2022; PMC, 2023; 2025).

Life Cycle Assessments (LCA) demonstrate that the WCO based fuels can reach 75% of greenhouse gas reduction as compared to the fossil fuels (Yaqoob et al., 2021; Fernandez & Lee, 2023). However, a lot of challenges are associated with it such as poor quality, moisture content and other contaminants greatly differ depending on the cooking routine (RSC Sustainability, 2025; Mannu et al., 2021). There are, furthermore, logistical challenges in collection, transport and verification (Hartini et al., 2023; PMC, 2023). Emergent blockchain-based tracking systems in cities such as Barcelona illustrate this potential, with evidence of positive impacts in terms of traceability and yield of WCO (PMarketResearch, 2024). Ongoing research focuses on robust purification techniques, such as water washing and clay treatment, to reduce impurity levels before conversion (RSC Sustainability, 2025). Advanced heterogeneous catalysts and continuous reactor designs are being refined for improved conversion efficiency and scalability (RSC Advances, 2025; MDPI Polymers, 2022). Additionally, policy attention is pivoting toward comprehensive circular frameworks encompassing

collection infrastructure, standardization, and economic incentives (Hartini et al., 2023; Becker, 2024).

3. Bio-gasoline

The adoption of bio-gasoline is on the rise, as it can be used in existing petrol engines and fuel infrastructure without any special modifications needed (Martinez et al., 2023; Patel et al., 2024). Typical production processes include catalytic hydrodeoxygenation, which uses catalysts such as NiMo/Al₂O₃ to hydrogenate biomass-derived oils like WCO or pyrolysis oils to remove oxygen and convert them into gasoline-range hydrocarbons (Denson et al., 2024; Wang et al., 2024). Bio-gasoline is particularly interesting because like petrol, gasoline also contains fuels C₅–C₁₂ alkanes and aromatics guaranteeing high energy density along with greatly reduced sulfur emissions (Rodriguez et al., 2022; Singh & Gupta, 2021). Furthermore, when it is produced from waste materials, its carbon footprint can be up to 90% lower than fossil gasoline. Cited claim here lower emphasizing the potential for bio-gasoline to help curb the greenhouse effect gases emissions (Fernandez & Lee, 2023). As Smith, Tan and co-workers have shown, regular fuel up to thirty percent blend not detrimental to vehicle performance (Smith et al., 2023; Tan et al., 2021; Johnson & Li, 2022; Kumar et al., 2021).



4. Conversion technologies of producing bio-gasoline from WCO

Transforming WCO into bio-gasoline requires the application of various thermochemical processes, which

convert WCO's triglycerides and free fatty acids into gasoline-like hydrocarbons. One of the best researched methods is catalytic pyrolysis, which involves heating WCO in an oxygen-free atmosphere together with solid catalysts like zeolites or metal oxides. This method helps in significantly cleaving long-chain molecules to lighter hydrocarbons (Ali et al., 2023). Other widely used methods, hydrocracking and hydroprocessing, utilize high-pressure hydrogen with bifunctional catalysts such as NiMo or CoMo on alumina. They are aimed at oxygen removal and cracking oil molecules into C₅–C₁₂ alkanes to produce high quality gasoline-like fuels (Denson et al., 2024). Another promising approach is decarboxylation and deoxygenation that removes carboxyl and hydroxyl groups from hydrocarbons without full hydrogenation, greatly improving efficiency and selectivity for gasoline fractions (Xu et al., 2023).

4.1 Catalytic pyrolysis

Catalytic pyrolysis is one of the most common method for transforming WCO into bio-gasoline and involves thermal cracking and catalysis in one-step processing. This method transforms long-chain triglycerides into smaller hydrocarbons using solid catalysts which increase both fuel yield and quality by driving molecular changes to gasoline-range (C₅–C₁₂) fractions (Yaqoob et al., 2022; Ali et al., 2023). In a typical catalytic pyrolysis system, pre-treated WCOs are loaded into fluidized or fixed bed reactors along with an inert gas (N₂) heated to reaction temperatures. Catalytic optimization of the routes is carried out with activated carbon, HZSM-5 zeolite and metal oxides catalysts like CeO₂/Al₂O₃ and ZnO/Al₂O₃. These types of catalysts enhance cracking and decarboxylation while suppressing coke formation (Ali et al., 2023; Banchapattanasakda & Asavatesanupap, 2023; Xu et al., 2023). Above is a simplified schematic showing the condensate fuels as well as lighter/dry gas by-products formed from gaseous WCO upon contact with catalysts.

Selection and integration of catalysts significantly impacts results. For instance, the use of activated carbon catalysis at a temperature of 400 °C with a mass ratio of 1:40 catalyst to WCO resulted in bio-oil yields of up to 83.5 wt% with improved composition resembling

gasoline fractions (Banchapattanasakda & Asavatesanupap, 2023). Similarly, using CeO₂/Al₂O₃ catalysts at 500 °C gave approximately ~93 weight percent fuel C₁₀–C₁₅ fuel's yield with low oxygen and sulfur contaminant hydrocarbon valued at ~54 MJ/kg (Cho et al., 2022). One distinct advantage attributed to catalytic pyrolysis is that it can be done at lower temperatures compared to purely thermal processes. The presence of a catalyst lowers temperature requirements leading to reduced energy costs and slower delay in coke build-up (Yaqoob et al., 2022; Banchapattanasakda & Asavatesanupap, 2023). Concerning WCO feedstocks, both temperature settings (350–500 °C) as well as certain properties of the catalyst bed such as acid character and pore structure are tailored for maximization of gasoline range aromatics and isoalkanes which positively influence octane ratings (Wang et al., 2020; Xu et al., 2023).

Although these benefits are notable, difficulties still exist. Coke formation or carbonaceous residue on the surface of catalyst leads to deactivation over time. Catalyst regeneration through burning off coke helps, but balancing pore structure and catalyst acidity is critical for long-term performance (Yaqoob et al., 2022; Xu et al., 2023). In addition, controlling hydrogen content (balance wt% O) has a direct impact on hydrocarbon yields as well as the amount of hydrogen required. Catalytic pyrolysis also enables other designs for hybrid processes, like coupling pyrolysis with hydrotreatment or gas upgrading to improve fuel quality. These integrated approaches seem promising for large scale industrial applications (Nature Perspective, 2023).

4.2 Hydrocracking and hydroprocessing

Hydrocracking and hydroprocessing are the main methods for converting WCO into energy such as bio-gasoline. These are catalytic processes that occur under high pressure of hydrogen and moderate-to-high temperatures that allow cracking of heavy triglyceride molecules and also remove oxygen, sulfur, and nitrogen impurities from the feedstock. In the hydroprocessing procedure, pre-treated WCO is supplied into a reactor of fixed bed or trickle bed where it is reacted in the presence of hydrogen gas and catalysts like NiMo/Al,

CoMo/Al, or Pt. The reaction and conditions—usually about 350–400 °C and 60–100 bar hydrogen pressure—are adjusted to lead to hydrogenation, deoxygenation, and breaking of carbon–carbon bonds, which yields the saturated hydrocarbons, including paraffinic and naphthenic compounds that are good for transportation fuels (Siddiqui et al., 2023; Zhao et al., 2024; Gaur et al., 2022).

The catalytic activity would be critically dependent on the selection and structure of the catalyst. For instance, bifunctional catalyst when employed, having hydrogenation and acidic cracking activities is capable of selectively preparing C₁₀–C₁₅ gasoline range hydrocarbons. Previous studies reported good levels of diesel and jet fuel proportions (Gao et al., 2018) via the hydroprocessing of WCO at 80wt.% with little sulfide and oxide addition (Mao et al., 2022; Zhang et al., 2023). Also, other modified carriers such as the mesoporous alumina or bentonite based catalysts increase surface area and acidity resulting in increased cracking activity and resistance against coke formation (Alves et al., 2024, Sharma and Das, 2023).

Hydrocracking is a further hydrotreating process in which both the saturation of multiple bonds and the breaking of long carbon chains occur, thereby achieving the greatest possible production of light hydrocarbon fractions. It can be used effectively for the conversion of triglycerides and free fatty acids into gasoline-like fuels in WCO. The hydrogen-rich environment encourages the elimination of oxygen and reduces coking, for the cleaner fuel and longer life of the catalyst (Lee, et al., 2023; Tan, et al., 2022). Studies on process optimization have shown that high-octane bio-gasoline (Bai et al., 2023, Rodrigues et al., 2021) can be obtained by increasing the hydrogen/oil ratio and regulating the space velocity. Nonetheless, its high hydrogen consumption and operating pressures make it an energy demanding pathway.

However, hydroprocessing has benefits in stability of the product, ease of integration with existing refinery equipment and meeting of fuel standards. Catalytically upgraded bio-gasoline obtained from WCO resins showed trace amount of oxygenates and impurities, with

heating value similar to that of commercial gasoline (43 MJ/kg) and can be directly used in spark-ignition engines or mixed with existing fuels with no engine modifications (Kumar et al., 2024; Fernandez & Wang, 2023; Singh et al., 2022). Integration of the hydroprocessing with pre-treatment and fractionation system also was studied to increase the yield of the products and improve their performance and environmental impact for the disposal of wasted oil.

4.3 Decarboxylation and deoxygenation

Hydrocracking and hydroprocessing are commonly used methods for upgrading WCO to practical hydrocarbon fuels, such as bio-gasoline. These are done through catalytic reactions under high hydrogen-pressure and low-to-high temperatures leading to simultaneous cracking of heavy triglyceride molecules, and elimination of impurities like oxygen, sulfur and nitrogen. In a standard hydroprocessing system, pre-treated WCO is reacted in a fixed-bed or trickle bed reactor using hydrogen gas and catalysts such as NiMo/Al₂O₃ or CoMo/Al₂O₃ to carry out the reactions. The operating conditions—usually between 350 and 400°C and a hydrogen pressure of 60 to 100 bar—are optimized in order to permit hydrogenation, deoxygenation, and carbon-carbon bond dissociation, and leads to the product of saturated hydrocarbons, such as paraffins and naphthenes that can be used as transportation fuels (Siddiqui et al., 2023; Zhao et al., 2024; Gaur et al., 2022).

The appropriate catalytic activity is highly related to the selection and structure of the catalyst. For instance, selectivity towards C₁₀–C₁₅ gasoline-range hydrocarbons can be achieved by using bifunctional catalysts with both hydrogenation and acidic cracking functions. It has been demonstrated that WCO can be hydroprocessed at > 80 wt. % to transportation fuels, consisting of gasoline and jet fractions with low sulfur and oxygen content from WCO using NiMo catalysts at 380°C (Mao et al., 2022; Zhang et al., 2023). Besides, modified carrier such as mesoporous alumina or bentonite-based catalysts can increase the surface area and acidity, and crack activity and resistance to coke

deposition are both enhanced (Alves et al., 2024; Sharma & Das, 2023).

A more severe reaction, hydrocracking, does both the saturation, i.e. does a degree of hydroprocessing in addition to breaking the chains and to increase the production of lighter hydrocarbons. It is well suited for conversion of triglycerides and free fatty acids in WCO to gasoline-like fuels. The water availability in hydrogen-rich conditions can promote the removal of oxygen via water, and can inhibit coke formation, resulting in cleaner fuel production and longer catalyst lifetime (Lee et al., 2023; Tan et al., 2022). Optimization studies suggested that by increasing the hydrogen-to-oil ratio and changing the space velocity, the product distribution can be greatly directed toward high-octane bio-gasoline (Bai et al., 2023; Rodrigues et al., 2021). High hydrogen demand and operation pressure, nevertheless, render to energy-intensive process.

However, hydroprocessing offers the advantage of product stability, compatibility with existing refinery facilities, and adherence to fuel regulations. WCO-derived Bio-Gasoline, catalytically processed bio-gasoline, is reported to contain very low (or no) oxygenates and impurities and heating values (approximately 43 MJ/kg), are similar to that of conventional gasoline and thus can be used either directly in engines employing spark-ignition engines or can be mixed with the present fuel streams without need for any mods to the engines (Kumar et al., 2024; Fernandez & Wang, 2023; Singh et al., 2022). The construction of hydroprocessing to ‘front-end’ pre-treatment and fractionation or to recover hydrocarbons can also be considered in order to enhance process efficiency and product quality, and to minimize the environmental problems of waste oil disposition.

5. Comparative analysis of technologies

The thermochemical conversion of WCO into bio-gasoline can be effected by multiple routes, each having its own merits and demerits, depending on the process conditions, yield of products, catalyst type, and cost effectiveness. Catalytic pyrolysis is promising as it does not need elevated pressure and high infrastructure and

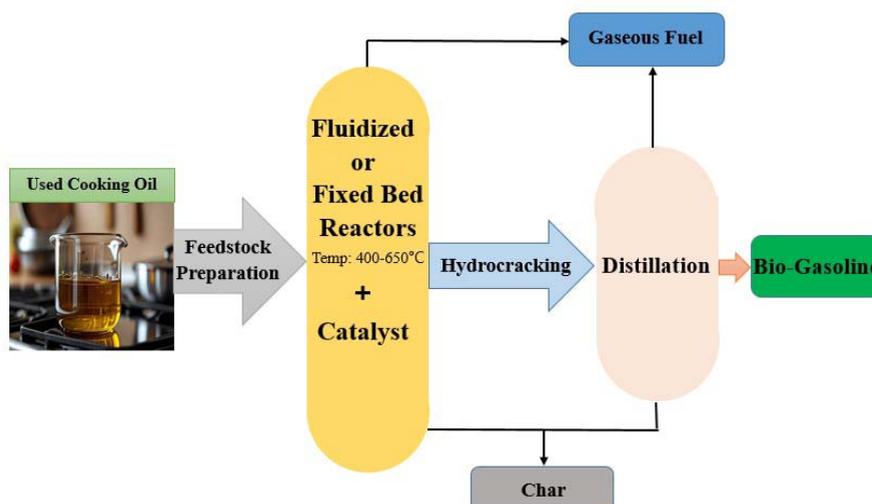


Fig. 1: Conversion of WCO into bio-gasoline

deoxygenation and fuel quality but at the expense of needing large amounts of hydrogen and huge capital investment. where decarboxylation and hydrodeoxygenation provide high selectivity towards C_5 – C_{12} alkanes but can be susceptible to catalyst deactivation and sulfur poisoning. On the other hand,

developed esterification combined with hydrorefining takes advantage of the availability of biodiesel upgrading installations for conversion, although several treatments may be required to reach final product specifications. Choosing the appropriate technology depends on the desired product profile, feedstock characteristics,

Table 1: Comparative analysis of WCO-to-bio-gasoline technologies (Bhoi et al., 2020; Atabani et al., 2012; Chen et al., 2022; Vardon et al., 2015; Zhang et al., 2021; Gholizadeh et al., 2020; Wang, L., et al. 2019).

Parameter	Catalytic Pyrolysis	Hydrocracking	Hydrodeoxygenation (HDO)
Temp. Range (°C)	350–550	300–450	100–300
Pressure (bar)	~1	30–150	10–50
Catalyst Type	Zeolites (e.g., HZSM-5), metal oxides	NiMo, CoMo on Al_2O_3	Pd/C, Pt/ Al_2O_3 , Ni-based catalysts
Hydrogen Requirement	Low	High	Medium–High
Bio-gasoline Yield (wt%)	60–80	70–90	65–85
Product Range (C-n)	Gasoline-range hydrocarbons (C_5 – C_{12})	Iso-alkanes and paraffins (C_5 – C_{12})	C_6 – C_{15} alkanes
Oxygen Removal Efficiency	Partial (~60–70%)	>90%	>90%
Coke Formation	High; regenerable	Low	Moderate; catalyst deactivation possible
Infrastructure Cost	Low–Medium	High	Medium
Scalability	Suitable for modular units	Industrial scale only	Moderate; hydrogen management needed

regional hydrogen availability, and integration potential with existing infrastructure (Bhoi et al., 2020; Atabani et al., 2012; Chen et al., 2022; Vardon et al., 2015).

6. Environmental impact & life cycle assessment (LCA)

The production of bio-gasoline from WCO presents a promising way to permanent agency alternatives, which address great both from struggle control and fossil gas dependency. From an environmental angle, the entire existence cycle - from stock inventory to gasoline combustion has proven extremely incompetent greenhouse fuel (GHG) emissions compared to gasoline too. Existence cycle assessment (LCA) device has been important in those environmental benefits. The studies document that the conversion of WCO into bio gasoline will reduce carbon emissions from WCO 60 -90% compared to general gasoline, primarily due to the waived environmental burden of disposal of older and the renewable nature of raw materials (Zhang et al., 2003; Rajendran & Murugesan, 2020). WCO -based fuels has also been favored, suggesting that more energy production chain (articone et al. 2022) than input along the production chain, EroI value for WCO fuels. Emission of NO₂, CO and small particles from whipp fuels compared to fossil fuels, making it suitable for urban transport with minor modifications in existing engines (Aatola et al., 2008; Ong et al., 2013).

But environmental benefits may differ depending on the regional availability of waste oil, transport logistics and treatment efficiency. In countries with well -known waste collection systems such as France and Germany, LCA has demonstrated that local processing reduces the environmental footprint further due to transport emissions (Hajjaji et al., 2017; Dandikas et al.), 2014). In addition, the production of biogassoline with integrated green chemical principles -such as low process quality intensity and catalyst recircitation -has been demonstrated to improve general durability (Jimenez-Gonzalez et al., 2011). Recently, catalytic-pyrilus and hydroprocessing option has been used in LCA studies, especially when heat integration and hydrogen performance is adapted. In addition, the ecological adaptation of WCO -based bio -gasoline can increase

economic feasibility and value. Although there are challenges with scale and feedstock stability, compared to normal fuels, the overall environmental impact is low, which confirms the potential of WCO -based bio -gasoline in global travel.

7. Challenges and research gaps

7.1 Feedstock collection and pretreatment

However, the reliable and quality properties of WCO are still barriers to large scale application. WCO collection is yet to be formally organized in many developing areas, with households and small-scale food eateries disposing of WCO into drains or informal selling. Decentralized sources such as these make logistics difficult, and bring in large impurities like water, food remnants, and hazardous elements, thus necessitating extensive pretreatment before thermochemical conversion can be considered (Nasrollahzadeh et al., 2021). The non-standardized collection methods and improper storage procedures result in a very wide range of triglyceride and FFA content, which may affect the reaction kinetics, catalyst longevity and product quality (Gupta et al., 2023). In addition, other pre-treatment including filtration, degumming, neutralization and drying steps significantly add not only the cost but the complexity of the process rendering it less favourable for small players, unless you find decentralised solutions.

7.2 Catalyst cost and stability

The catalysts are the key of almost all the conversion such as pyrolysis, hydrocracking, and deoxygenation, however, the expensive and short service time of effective catalysts are the main obstacle to industrial application. Precious materials such as Pt, Pd and Ru show high activity, but are associated with high costs as well as poisoning by impurities in the feed (Chen et al., 2022). Less expensive alternatives such as Ni or Co are cheaper but suffer from the problem of sintering, coke formation, or leaching during extended thermal cycles (Rao et al., 2023). Further, catalyst regeneration which typically involves high temperature oxidation or solvent wash, further increases the operational complication as well as environmental risk. One of the ongoing challenges is the development of selective,

recyclable and thermally stable catalysts, which can be preferably highly scalable and also tolerant towards WCO impurities.

7.3 Scale-up and commercialization barriers

Although laboratory scale experiments on WCO-to-bio-gasoline conversion present promising yields and product qualities, pilot or industrial scale presents substantial challenges. Heat and mass transfer limitations, fouling of catalysts, integration of energy, and real-time process control are all problems that present differently at scale (Zhao et al., 2024). Most of the proposed processes—particularly those requiring high-pressure hydrogenation or rapid pyrolysis—need advanced reactors and safety measures, which can discourage investment and policy support early on. Additionally, there are few reported successful demonstrations of continuous-flow systems processing real-world WCO at scale for regular gasoline-range product yield, indicative of a gap in commercialization between lab success and market uptake.

7.4 Integration into existing fuel infrastructure

Another key challenge is the compatibility of bio-gasoline with current fuel supply chains and engine systems. Although bio-gasoline replicates the petroleum gasoline C...-C•, hydrocarbon fraction, it could still have variance in terms of vapor pressure, oxygenate level, or cold flow properties, which might affect fuel

blending, storage, or combustion characteristics (Singh et al., 2022). Regulatory clearances, fuel certification, and infrastructure adaptations (e.g., corrosion-resistant pipelines or tank linings) are frequently necessary, slowing down deployment. Additionally, current refineries are not necessarily capable of co-processing WCO-derived oils without extra retrofitting or catalyst modifications, thus necessitating a multi-sectoral approach involving technology developers, oil refiners, and government agencies.

8. Comparison of Biodiesel and Bio-Gasoline, synthesized using Waste Cooking Oil

Two separate methods of converting are the conversion of waste cooking oil (WCO) into fuel are conversion into biodiesel and bio-gasoline. Because of its oxygenated ester structure, transesterified biodiesel typically has a lower calorific value (~37–40 MJ/kg), which lowers the energy yield per unit mass (Gui, Lee, & Bhatia, 2008; Rajendran & Murugesan, 2020). On the other hand, bio-gasoline produced by hydroprocessing, catalytic pyrolysis, or decarboxylation of WCO has oxygen content that is less than one weight percent and heating values that are more comparable to those of conventional gasoline, usually in the range of 42–46 MJ/kg (Rodriguez, Perez, & Martinez, 2022; Kumar, Jaiswal, & Agarwal, 2024; Zhao & Wang, 2024). Due to the higher calorific value, bio-gasoline

Table 2. Comparative properties of biodiesel and bio-gasoline derived from WCO

Property	Biodiesel (FAME from WCO)	Biodiesel (FAME from WCO)
Energy Density (MJ/kg)	37–40	37–40
Oxygen Content (wt.%)	~10–12 wt.% (oxygenated esters)	~10–12 wt.% (oxygenated esters)
Viscosity (@ 40 °C)	4–6 (mm ² /s)	4–6 (mm ² /s)
Engine Compatibility	Diesel engines (compression ignition); limited blends (B20–B30)	Diesel engines (compression ignition); limited blends (B20–B30)
Cold Flow Properties	Poor; higher pour/cloud point	Poor; higher pour/cloud point
Greenhouse Gas reduction as compared to fossil fuel	~60–70%	~60–70%
Key Limitations	Cold flow issues, blending limits, oxidative stability	Cold flow issues, blending limits, oxidative stability

can be used in spark-ignition engines and existing gasoline infrastructure without requiring significant changes, while biodiesel is mostly used in compression-ignition engines and is frequently used in blends of 20–30% because of problems with viscosity and cold flow (Atadashi, Aroua, & Aziz, 2012; Ong et al., 2013). WCO-derived bio-gasoline offers greater energy per unit mass, lower oxygen content, and wider compatibility as a drop-in fuel alternative but biodiesel production is less capital-intensive and technically simpler (Balasubramanian, Vinu, & Madras, 2021; Fernandez & Lee, 2023). Apart from this, biodiesel generally exhibits higher viscosity as compared to bio-gasoline, affecting fuel atomization and cold-flow performance (Atadashi, Aroua, & Aziz, 2012; Ong et al., 2013).

9. Future Prospects and roadmap

WCO-derived bio-gasoline is ready for major expansion, spurred by heightened environmental consciousness, world energy security, and the demand for decarbonisation. In the future, the emphasis will migrate from fundamental research to applied practice and large-scale integration into current energy systems. Perhaps the most hopeful potential is in the streamlining and standardization of WCO collection networks, particularly from decentralized sources like households and small restaurants. Through structural collection and encouraging segregation at source, feedstock supply can be made stable to meet constant fuel production. Improved catalyst design will be key to improving conversion efficiency, selectivity, and longevity. The future direction includes the creation of low-cost non-noble metal catalysts that are robust against impurities, need less frequent regeneration, and provide high yields of gasoline-range hydrocarbons. Concurrently, improvements in processes such as continuous flow catalytic pyrolysis, microwave-assisted deoxygenation, and hybrid hydroprocessing units may minimize energy input and maximize throughput.

At the industrial and policy level, integration into refineries via co-processing routes and policymaking support for blending mandates on biofuels will be critical. Modular and scalable conversion units for deployment in urban and rural areas will also increase the viability

of decentralized production of bio-gasoline. In the long run, integrating bio-gasoline production with green hydrogen, carbon capture, and circular economy principles can build a clean fuel system that solves both energy and waste management problems. The path forward involves interdisciplinary convergence of engineers, chemists, policymakers, and entrepreneurs to scale this vision and unlock the entire potential of WCO-based bio-gasoline.

10. Conclusion

The conversion of WCO into bio-gasoline is a promising step towards sustainable energy alternatives consistent with circular economy and waste valorization. With state-of-the-art thermochemical methods like catalytic pyrolysis, hydrocracking, and deoxygenation, WCO which was previously an environmental burden can be converted effectively into gasoline-range hydrocarbons compatible with current engines and infrastructure. These technologies not only respond to the twin challenges of fossil fuel exhaustion and waste reduction but also provide fuels with less carbon burden and better combustion efficiency. Yet, while appreciable advances have been made at the laboratory level, some challenges remain such as unstable feedstock supply, catalyst restraints, scalability of the process, and integration hurdles. Improving catalyst systems, reaction conditions, and decentralized and modular processing units will be the focus of future work. Further, robust policy structures, public acceptance, and stakeholder involvement are critical to commercialize these technologies from pilot to commercial scale. In total, bio-gasoline from WCO is a sustainable and viable alternative to traditional fuels, with the potential to make a significant contribution to global cleaner energy transition.

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Alterations in oil quality during deep-frying: A study on blended vegetable oils

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Abstract

This study aimed to enhance the oxidative stability of groundnut oil and sunflower oil by blending them with rice bran oil (RBO) to create triple oil blends. The physical and chemical properties of pure oils and their blends—including refractive index, free fatty acid content, iodine value, peroxide value, saponification value, and fatty acid composition—were analyzed. Results indicated that rice bran oil exhibited superior oxidative stability compared to groundnut and sunflower oils. Furthermore, blending RBO with the other two oils significantly improved the oxidative stability of the resulting mixtures. The optimal formulation was identified as a blend containing 60% rice bran oil, 20% groundnut oil, and 20% sunflower oil.

Key words : Oxidative Stability, Rice Bran Oil Blends, Vegetable Oil Composition, Thermal Stability, Fatty Acid Profile

1. Introduction

Rice bran oil (RBO) is currently one of the most widely used oils and has become a popular ingredient in the global food industry. Food processing industries prefer rice bran oil due to its relatively high level of saturated fat, which offers stability and greater resistance to oxidation when heated at high temperatures¹. Most vegetable oils contain a high level of polyunsaturated fatty acids (PUFAs), which are more susceptible to oxidative changes. These oxidative changes in PUFAs can produce various oxidation products, including trans fatty acids (TFAs).

RBO has gained attention from consumers due to its abundance of health-promoting compounds such as tocopherols, tocotrienols, phytosterols, and gamma-oryzanol. It is recognized as one of the healthiest cooking

oils because of its balanced fatty acid profile. Oleic acid constitutes about 40–50%, linoleic acid about 28–29%, and palmitic acid about 16–21% of its composition. RBO may help reduce inflammation due to its antioxidant properties, lower cholesterol levels, and promote cardiovascular health. Gamma-oryzanol has been associated with increasing good cholesterol (HDL) and reducing bad cholesterol (LDL) and triglycerides.

Refined sunflower oil, especially the high oleic variety, is also very versatile. Due to its natural flavour and heat stability, it can be used in various culinary applications such as frying, cooking, or as an ingredient. High oleic sunflower oil is known for its excellent oxidative stability and superior fatty acid composition, particularly its high oleic acid content. Oleic acid, an unsaturated fatty acid, is more stable to oxidation than other fatty acids. Because it is richer in oleic acid than linolenic acid, sunflower oil is less prone to oxidative breakdown and produces fewer harmful aldehydes during cooking or storage. However, oils rich in oleic acid may still undergo oxidative rancidity during prolonged frying or storage.²⁻³

Sunflower oil is predominantly composed of triglycerides and contains a variety of fatty acids, including monounsaturated fats (oleic acid about 20–30%), polyunsaturated fats (linoleic acid around 60–70%), and saturated fats. Additionally, sunflower oil may contain minor components such as tocopherols (Vitamin E), sterols, and other antioxidants, which contribute to its stability and health benefits. The fatty acid composition, along with the physical and chemical properties, plays an important role in determining oil quality.⁴

Groundnut oil, also known as peanut oil, is a widely used vegetable oil derived from peanuts. It has a mild flavor and a high smoke point, making it suitable for various

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cooking methods, including frying and sautéing. Groundnut oil is composed primarily of monounsaturated fats, particularly oleic acid (approximately 57%), followed by polyunsaturated fats like linoleic acid (around 20%), and saturated fats such as palmitic acid (about 16%) . It is also a rich source of vitamin E, providing about 15 mg per 100 grams, which is 100% of the daily recommended intake.

Due to its resistance to oxidation and minimal deterioration, rice bran oil (RBO) is a popular choice for cooking and baking purposes, owing to its excellent stability. The blending of non- conventional RBO with traditional oils (such as sunflower oil and groundnut oil) can result in a more stable cooking oil, reducing the overall demand for traditional oils. RBO is rich in unsaturated fatty acids.⁵ However, oils with lower unsaturation are more suitable for cooking because they oxidize at a much slower rate compared to oils high in polyunsaturated fatty acids (PUFAs). The fatty acid profile of an oil is a key factor influencing its oxidation stability and the formation of undesirable compounds.⁶⁻⁷ During prolonged exposure to high temperatures, oxidation stability becomes one of the most important characteristics that a frying oil should possess, as its physico-chemical and nutritional properties can undergo significant changes during heating. Globally, there is increasing demand for the production of blended oils for culinary uses due to their improved thermal stability, enhanced nutritional benefits, and cost- effectiveness compared to pure vegetable oils.^{8 to 10}

Antioxidants present in rice bran oil, sunflower oil and groundnut (peanut) oil

Rice bran oil, sunflower oil and groundnut (peanut) oil

are rich in natural antioxidants (Table 1to3) that contribute to their health benefits and stability during cooking.¹¹⁻¹⁵Groundnut oil contains tocopherols, particularly gamma-tocopherol, and resveratrol, which offer antioxidant properties and support heart health. Sunflower oil is abundant in tocopherols, especially alpha- tocopherol, and may contain beta-carotene, which supports immune function and skin health. Rice bran oil stands out with its unique antioxidant profile, including γ -oryzanol, tocopherols, tocotrienols, and phytosterols. α -oryzanol, a mixture of ferulic acid esters of sterols and triterpenoids, is particularly effective in reducing oxidative stress, lowering cholesterol levels, and providing anti-inflammatory effects. Tocotrienols, less commonly found in other oils, possess unique antioxidant properties that can help protect against chronic diseases like heart disease and certain types of cancer. Phytosterols in rice bran oil can help lower cholesterol levels and have antioxidant properties. The combination of these antioxidants makes rice bran oil beneficial for heart health, lowering cholesterol levels, and providing antioxidant protection. Incorporating these oils into your diet can provide diverse health benefits, especially when used in moderation as part of a balanced diet.

This study aimed to enhance the oxidative stability of groundnut oil and sunflower oil by blending them with rice bran oil (RBO) to create triple oil blends. The physical and chemical properties of pure oils and their blends including refractive index, free fatty acid content, iodine value, peroxide value, saponification value, and fatty acid composition were analyzed.

Table -1 Antioxidants present in rice bran oil

Antioxidant	Type	Function
γ -Oryzanol	Polymeric mixture (mainly erulic acid esters)	Scavenges free radicals; inhibits lipid peroxidation
Tocopherols	Vitamin E compound	Fat-soluble antioxidant; protects cell membranes
Tocotrienols	Vitamin E compound	More potent antioxidant than tocopherols
Phytosterols	Plant sterols	Compete with cholesterol absorption
Squalene	Triterpene hydrocarbon	Quenches singlet oxygen and free radicals
Ferulic Acid	Phenolic compound	Strong free radical scavenger

Table -2 Antioxidants present in sunflower oil

Antioxidant	Type	Function
Vitamin E	Tocopherol	Protects fats from oxidation
Phytosterols	Sterol compounds	Antioxidant, cholesterol-lowering
Phenolic compounds	Polyphenols	Antioxidant, mostly in unrefined oil
Squalene	Triterpene	Antioxidant, skin-protective

Table 3 Antioxidants present in ground nut oil

Antioxidant	Type	Function
Tocopherols (mainly α - and γ -tocopherol)	Vitamin E compounds	Protects lipids from oxidation, stabilizes oil during storage
Resveratrol	Polyphenolic compound	Scavenges free radicals, modulates enzymes
Phytosterols	Plant sterols	Compete with cholesterol for absorption
Phenolic acids (e.g., p-coumaric acid)	Phenolic compounds	Act as antioxidants and anti-inflammatory agents
Coenzyme Q10 (minor)	Quinone compound (trace amounts)	Involved in cellular energy production and antioxidant defence

2. Materials & methods:

The study investigates the physicochemical properties of refined, bleached, and deodorized (RBD) sunflower, groundnut, and rice bran oils during deep frying, employing standard analytical methods to assess oil quality.

2.1 Materials:

- **Oils:** RBD sunflower, groundnut, and rice bran oils were procured from the local market.
- **Potatoes:** Used for frying experiments; average moisture content was approximately 75%.
- **Chemicals:** All chemicals used were of analytical reagent (AR) grade.

2.2 Methods:

The key analytical methods for assessing the quality of edible oils are as follows:¹⁶

- **Refractive Index:** Measured using an Abbe refractometer at 30°C. The formula for temperature correction is:

$$R = R_2 + K(T' - T)$$

Where R_2 is the measured refractive index, K is a constant (0.000385 for oils), T_2 is the actual temperature, and T is the standard temperature (30°C).

- **Specific gravity:** Determined by weighing a 10 ml specific gravity bottle filled with distilled water and then with the oil sample at 30°C. The formula is:

$$\text{Specific Gravity} = \frac{\text{Weight of oil}}{\text{Weight of water}}$$

$$\text{Temperature correction: } S = S' + 0.00041(T_1 - T)$$

Where S_2 is the measured specific gravity, T_1 is the measured temperature, and T is the standard temperature (30°C).

- **Acid Value:** Quantifies free fatty acids in the oil. Determined by titration with standard sodium hydroxide using phenolphthalein as an indicator. The formula is:

$$\text{Acid Value} = \frac{(56.1 \times N \times V)}{W}$$

Where N is the normality of NaOH, V is the volume

(ml) of NaOH used, and W is the weight (g) of the oil sample.

- **Iodine value:** Determined using the Wijs method with iodine monochloride in acetic acid. The formula is:

$$\text{Iodine Value} = (12.69 \times (B - S) \times N) / W$$

Where B is the volume (ml) of sodium thiosulfate used in blank, S is the volume (ml) of sodium thiosulfate used in sample, N is the normality of sodium thiosulfate, and W is the weight (g) of the sample.

- **Peroxide value:** Measures primary oxidation products (peroxides) in the oil. Determined by titration with sodium thiosulfate after reaction with acetic acid–chloroform mixture and potassium iodide. The formula is:

$$\text{Peroxide Value} = ((S - B) \times N \times 1000) / W$$

Where S is the volume (ml) of sodium thiosulfate for sample, B is the volume (ml) of sodium thiosulfate for blank, N is the normality of sodium thiosulfate, and W is the weight (g) of the oil sample.

- **p-Anisidine value:** Indicates secondary oxidation products in the oil. Determined by measuring the increase in absorbance at 350 nm after reaction with p-anisidine in isooctane. Higher values indicate greater secondary oxidation, affecting oil quality and flavor.

- **Fatty acid composition**

Fatty acid composition was analyzed using gas–liquid chromatography (GLC) after converting the oils to fatty acid methyl esters (FAMES).

Preparation of methyl esters (FAME):

Approximately 10 g of oil was refluxed with 50 ml of 78% alcoholic KOH in ethanol for 3 hours. The mixture was transferred to a separatory funnel containing 50 ml of cold distilled water. Unsaponifiables were extracted twice using 50 ml of petroleum ether. The soap solution was acidified with 2N sulphuric acid to obtain free fatty acids, which were extracted with five

10 ml portions of diethyl ether. The ether extracts were dried over anhydrous sodium sulphate, filtered, and concentrated under vacuum. The fatty acids were esterified by refluxing with acidified methanol (100 ml methanol + 1 ml concentrated H₂SO₄) for 4 hours. Methyl esters were extracted using diethyl ether, washed with sodium bicarbonate and distilled water, dried, and recovered under vacuum.

Gas-liquid chromatography (GLC):

A stainless-steel column (3 mm × 2 m) packed with 15% DEGS was used. Nitrogen served as the carrier gas, and hydrogen was used as the flame ionization detector (FID) fuel. Flow rates were 30 ml/min for both gases. The injector temperature was set at 225°C, and the oven temperature at 190°C. A 0.4 µL sample of a 10% solution of methyl esters in diethyl ether was injected using a micro syringe. Fatty acid percentages were calculated using computerized integration software.

This method effectively quantifies the fatty acid composition of oils, providing insights into their nutritional and functional properties.

3. Experimental

3.1 Procurement of Potatoes and Preparation of Chips

Potatoes were procured from the local market, peeled, and sliced into elliptical shapes. The sliced potatoes were submerged in water to prevent oxidation, then dried using filter paper. The prepared potato chips were deep-fried in pure sunflower oil, pure groundnut oil, pure rice bran oil, and in blends of sunflower-groundnut oil and rice bran oil in varying proportions.

3.2 Frying Vessel and Heating Arrangements

A stainless-steel vessel was used for deep-fat frying, with a capacity of 2 litres. An 8-inch mild steel rod was welded to the side of the pan for clamping it to a vessel in the wax bath. The wax bath was constructed from mild steel and had a capacity of approximately 12 litres. Paraffin wax, purchased from the local market, was used as the heating medium in the wax bath (Fig. 1). Two immersion heaters, each rated at 1 KVA, were installed—one of which was fitted with a thermostatic

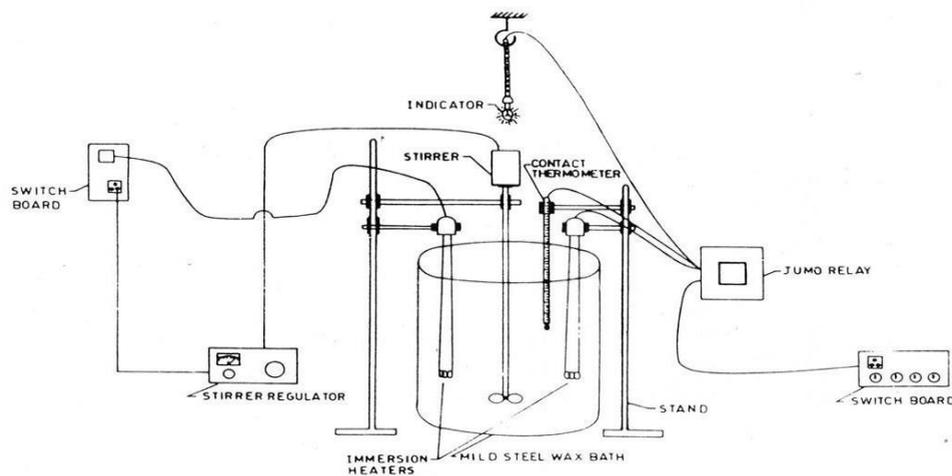


Fig.1: Assembly used in the deep-fat frying experiment

control system. A contact thermometer and a controller were integrated into the electrical circuit to regulate temperature. When the desired temperature was reached, the controller automatically switched the heater off and turned it on again if the temperature dropped below the set point. This maintained a constant temperature in the wax bath. The temperature of the frying pan was maintained at 180°C. However, due to some heat loss from the wax bath to the frying pan, the wax bath was maintained at approximately 190°C to compensate.

3.3 Stirring arrangements

Uniform temperature distribution is critical during deep-fat frying. To achieve this, an agitator was installed in the wax bath to ensure constant circulation of heat. A speed controller was attached to the agitator to regulate its speed, which was fixed at 2000 rpm throughout the experiment. Second agitator was installed in the frying pan to maintain uniform temperature in the oil. Additionally, an ordinary thermometer (0–360°C range) was inserted into the frying pan to monitor oil temperature during the frying process.

3.4 Preparation of Oil Blends

In the study, six distinct oil formulations were evaluated to assess their performance during deep-fat frying. Two of these formulations utilized pure oils: sunflower oil

and groundnut oil. The remaining four formulations were blends, each incorporating rice bran oil as the base component. These blended oils were created by varying the proportions of sunflower oil and groundnut oil mixed with rice bran oil. The resulting mixtures were then subjected to deep-fat frying under controlled conditions to analyse their thermal behaviour and stability.

Oil blend formulations

The oil blends were prepared by mixing rice bran oil (RBO), groundnut oil (GO), and sunflower oil (SFO) in the following proportions:

- **Blend 1:** 60% RBO, 20% GO, 20% SFO
- **Blend 2:** 50% RBO, 25% GO, 25% SFO
- **Blend 3:** 40% RBO, 30% GO, 30% SFO

These blends were prepared by thoroughly mixing the oils to ensure homogeneity. The proportions were chosen to evaluate the effects of varying the content of groundnut and sunflower oils in the blend on the frying performance and stability of the oil.

Blending methodology

1. **Selection of oils:** Refined rice bran oil, groundnut oil, and sunflower oil were selected for blending. These oils were chosen based on their availability,

cost-effectiveness, and individual properties such as smoke point and fatty acid.

2. **Preparation of blends:** The oils were blended in the specified proportions (60:20:20, 50:25:25, and 40:30:30) using a mechanical stirrer to ensure uniform mixing. The blends were prepared in sufficient quantities to allow for multiple frying cycles.
3. **Storage of blends:** The prepared oil blends were stored in amber-coloured glass bottles to protect them from light and prevent oxidation. The bottles were sealed and kept at room temperature until use.

3.5 Deep-fat frying

- **Oil volume & heating:** Approximately 1.2 liters of oil were used, heated to 180°C using a thermostatic control system.
- **Oil level consistency:** The oil level in the frying pan and the heating medium level in the wax bath were maintained consistently.
- **Batch preparation:** 25 g batches of potato chips, previously dried on filter paper, were prepared for frying.
- **Frying schedule:** Each batch was fried at 15-minute intervals for 4 hours per day, over six consecutive days, totalling 36 hours of frying per oil sample.
- **Oil filtration:** At the end of each 6-hour frying session, the frying medium was filtered to remove food particles.
- **Sample collection:** Oil samples were collected in clean glass bottles at the end of each session.
- **Sample storage:** Collected oil samples were stored in a cool, dark place (refrigerator) until further analysis.

4. Results and Discussion

4.1 Fatty Acid Composition

The fatty acid compositions of RBO (Rice Bran Oil), GO (Groundnut Oil), and SFO (Sunflower Oil) were

analysed before and after deep-fat frying. The results are shown in Tables 4 to 8. Table 1 presents the initial fatty acid profiles of pure oils. RBO exhibited a higher saturated fatty acid content, predominantly palmitic acid (C16:0), whereas SFO showed the highest percentage of polyunsaturated fatty acids (PUFA), primarily linoleic acid (C18:2).

Table – 4 Fatty acid composition of RBO, GO, and SFO (Before heating)

Fatty Acid Name	RBO	GO	SFO
Saturated Fatty Acid	18.90	18.51	11.21
Myristic Acid (C14:0)	0.26	0.03	0.07
Palmitic Acid (C16:0)	15.23	9.47	6.62
Stearic Acid (C18:0)	2.06	3.53	3.27
Behenic Acid (C22:0)	0.26	2.62	0.78
Arachidic Acid (C20:0)	0.87	1.47	0.24
Lignoceric Acid (C24:0)	0.42	1.39	0.23
Mono Saturated Fatty Acid	48.99	59.39	37.02
Oleic Acid (C18:1)	44.93	59.26	30.4
Palmito Oleic Acid (C16:1)	4.06	0.13	6.62
Polyunsaturated Fatty Acid	31.19	20.46	58.30
Linoleic Acid (C18:2)	30.26	19.96	58.25
Linolenic Acid (C18:3)	0.93	0.5	0.05

Table 5 shows the fatty acid composition of various blends of RBO, GO, and SFO in ratios of 60:20:20, 50:25:25, and 40:30:30. The proportion of saturated, monounsaturated, and polyunsaturated fatty acids varied with blend ratios, with PUFA content decreasing as GO proportion increased.

Table 5 - Fatty acid composition of RBO, GO, and SFO oil blends (Before heating)

Fatty Acid Name	RBO:GO:SFO 60:20:20	RBO:GO:SFO 50:25:50	RBO:GO:SFO 40:30:30
Saturated Fatty Acid	24.30	20.60	16.199
Myristic Acid (C14:0)	0.176	0.154	0.134
Palmitic Acid (C16:0)	18.812	15.660	12.521
Stearic Acid (C18:0)	5.316	4.430	3.544
Mono Saturated Fatty Acid	84.34	69.455	55.564
Oleic Acid (C18:1)	81.754	67.295	53.836
PalmitoOleicAcid(C16:1)	2.592	2.160	1.728
Polyunsaturated Fatty Acid	65.982	54.435	43.388
Linoleic Acid (C18:2)	65.08	54.235	43.388
Linolenic Acid (C18:3)	20.90	0.2	0.015

The fatty acid composition of pure Rice Bran Oil (RBO) and its blends with Sunflower and Groundnut oils was analyzed before and after frying, as detailed in Tables 6 and 7. The results indicated a slight increase in saturated fatty acids, notably palmitic (C16:0) and stearic (C18:0) acids, over time. Conversely, polyunsaturated fatty acids (PUFAs), particularly linoleic acid (C18:2n-6), exhibited a gradual decrease, suggesting susceptibility to oxidation. Monounsaturated fatty acid (MUFA) oleic acid (C18:1n-9) remained relatively stable, indicating its oxidative resistance. These findings align with previous studies highlighting the stability of oleic acid during frying processes.

Table 6 - Fatty acid composition of RBO during heating at 180 ± 2°C

Fatty Acid Name	Duration of heating (h)			
	0	4	8	12
Saturated Fatty Acid	18.90	19.32	19.35	20.10
Myristic Acid (C14:0)	0.26	0.27	0.27	0.30
Palmitic Acid (C16:0)	15.23	15.27	15.28	15.24
Stearic Acid (C18:0)	2.06	2.27	2.29	2.28
Behenic Acid (C22:0)	0.26	0.26	0.27	0.28
Arachidic Acid (C20:0)	0.87	0.87	0.88	0.89
Lignoceric Acid (C24:0)	0.42	0.42	0.41	0.40
Mono Saturated Fatty Acid	48.99	49.35	49.38	44.40
Oleic Acid (C18:1)	44.93	45.0	45.12	44.2
PalmitoOleicAcid(C16:1)	4.06	4.10	4.11	4.15
Polyunsaturated Fatty Acid	31.19	32.9	33.10	33.27
Linoleic Acid (C18:2)	30.26	29.20	29.01	28.0
Linolenic Acid (C18:3)	0.93	0.94	0.95	0.95

Table 7 - Fatty Acid Composition of Triple Blended Oil at 180 ± 2°C

Fatty Acid Name	RBO:GO:SFO 60:20:20	RBO:GO:SFO 50:25:50	RBO:GO:SFO 40:30:30
Saturated Fatty Acid	35.84	34.14	32.44
Myristic Acid (C14:0)	1.16	0.16	1.10
Palmitic Acid (C16:0)	0.21	0.15	0.10
Stearic Acid (C18:0)	3.43	3.32	3.20
Mono Saturated Fatty Acid	51.16	52.65	53.86
Oleic Acid (C18:1)	50.95	50.05	52.50
Palmito Oleic Acid (C16:1)	0.21	0.15	0.10
Polyunsaturated Fatty Acid	13.11	13.21	13.70
Linoleic Acid (C18:2)	12.81	12.95	13.10
Linolenic Acid (C18:3)	0.30	0.30	0.26

Table 8 shows that free fatty acid (FFA) content increased in all oils after frying, with the highest increase observed in pure GO and the lowest in the 60:20:20 blended oil. This indicates better oxidative stability of the blended systems, particularly those with higher RBO content.

Table 8- Free fatty acid content of oil and blends before and After 6 Hours of Frying

Oil Formation	Before	After
RBO	0.46	1.63
GO	1.53	2.10
SFO	0.28	1.08
60:20:20	0.41	0.75
50:25:25	0.39	0.86
40:30:30	0.38	0.90

4.2 Acid value

The acid value (AV) of frying oils serves as an indicator of hydrolytic degradation, reflecting the accumulation of free fatty acids (FFAs) resulting from the breakdown of triglycerides. An increase in AV signifies a decline in oil quality and stability. According to the Codex Alimentarius, refined oils should have an AV below 0.6 mg KOH/g, while virgin and cold-pressed oils should not exceed 4.0 mg KOH/g.

In the conducted study, AV (Table -9) increased in all oil samples after frying. Notably, blended oils, especially the 60:20:20 blend, exhibited the least increase in AV, suggesting enhanced hydrolytic stability compared to pure oils. This observation aligns with findings from other studies, which reported a linear increase in AV during frying, with blended oils demonstrating better resistance to hydrolytic degradation. These results underscore the importance of selecting appropriate oil blends to maintain oil quality and prolong frying stability.

Table 9 - Acid Value of RBO, GO and SFO before and after heating (mgKOH/g)

S. No	Oil	Acid Value (Before)	Acid Value (After)
1	RBO	0.15	0.68
2	GO	2.2	4.6
3	SFO	0.263	1.941

4.3 Physical and chemical properties

Tables 10 and 11 detail the physical and chemical properties of pure and blended oils before and after frying, including free fatty acid (FFA) content, peroxide value (PV), iodine value (IV), saponification value (SV), refractive index (RI), and specific gravity. These parameters provide insights into the oils' stability and quality during the frying process.

Table 10 - Physical and chemical properties of RBO, GO and SFO

Properties	RBO Before.	After	GO Before.	After	SFO Before.	After
FFA	-	-	-	-	0.048	0.156
PV	0.38	1.08	0.787	2.21	0.39	0.49
IV	95.40	95.00	112.05	110.43	132	130
SV	191.33	198.32	189.90	191.20	191	189
RI	1.4171	1.4181	1.4673	1.4681	1.4630	1.4730

Table 11 - Physical and chemical properties of ternary blended oil

Properties	RBO: GO: SFO 60:20:20		RBO: GO: SFO 50:25:25		RBO: GO: SFO 40:30:30	
	Before.	After	Before.	After	Before.	After
FFA	0.05	0.147	0.051	0.157	0.047	0.158
PV	0.49	0.54	0.49	0.58	0.41	0.61
IV	73	71	83	80	93	90
SV	196	192	194	190	193	188
RI	1.4540	1.4560	1.4560	1.4590	1.4590	1.4610
SpecificGravity	0.948	0.925	0.885	0.823	0.932	0.897

Observations indicated that the RI and specific gravity of oils slightly increased after frying. The IV decreased after frying, indicating degradation of unsaturated bonds. SV changes were minimal, indicating only slight alterations in average molecular weight. PV increased initially, confirming early-stage oxidation.

4.4 Oxidative Stability

Table 12 - Oxidative stability test of ternary blended oil

Blended Oil	Acid Value	Peroxide Value	Anisidine Value
RBO: GO: SFO 60:20:20	0.97	1.01	3.77
RBO: GO: SFO 50:25:25	0.89	0.94	3.31
RBO: GO: SFO 40:30:30	0.76	0.91	3.29

Table 12 presents oxidative stability data (AV, PV, and p-Anisidine Value) for ternary blends. The 60:20:20 blend had higher oxidative resistance, as evidenced by

its lower anisidine value and moderate peroxide and acid values. The lower anisidine values across all blended oils indicate fewer secondary oxidation products, supporting the stability of blends during prolonged frying.

The percentage of oil uptake was evaluated in the fried potato chips during the deep fat frying process. The results indicated that oil uptake was higher in pure Rice Bran Oil (RBO) compared to the blended oils used as frying media. Additionally, oil absorption increased with successive frying cycles for both RBO and the blended oil systems.

A significant difference ($p < 0.05$) in oil uptake was observed after the 4th and 5th repeated frying cycles for both RBO and blended oils. This increase in oil absorption may be attributed to the progressive degradation of oil, which leads to changes in its viscosity and surface tension, thus enhancing oil penetration into the food matrix during frying.

5. Conclusion

Repeated deep-fat frying causes oil deterioration due to oxidation, hydrolysis, and polymerization. Key findings

include that pure RBO and SFO maintained relatively better thermal stability than GO during repeated frying cycles. Ternary blends, particularly RBO: GO: SFO in a 60:20:20 ratio, exhibited superior oxidative stability, minimal degradation in chemical properties, and better retention of fatty acid composition. Blended oils showed lower peroxide and acid values compared to pure oils, suggesting they are more suitable for repeated frying. The iodine value decreased significantly ($P < 0.05$), indicating the loss of unsaturated fatty acids, especially during frying of high-moisture foods. Anisidine values further confirmed the formation of secondary oxidation products, though they remained lower in blends. In summary, blending RBO and SFO with GO results in cooking oils with improved oxidative stability, making them more suitable for domestic and commercial frying applications than pure oils.

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1. Advances in lipidomics for disease biomarker discovery

Lipidomics, the large-scale study of cellular lipid molecules, has significantly advanced disease diagnosis and personalized medicine. By profiling lipid species in biological samples, researchers can identify unique lipid signatures associated with conditions such as cardiovascular disease, diabetes, and neurodegenerative disorders. Recent technological improvements, including ultra-high-performance liquid chromatography (UHPLC) coupled with mass spectrometry (MS), have enhanced sensitivity and specificity. For example, lipidomic analyses have revealed elevated ceramide levels in patients with insulin resistance (Wenk, 2010), establishing a connection between lipid alterations and disease pathogenesis. Additionally, lipid biomarkers like phosphatidylcholines and sphingolipids are now used to predict disease progression and therapeutic responses (Liebisch et al., 2020). As lipidomics matures, integrating it with genomics and proteomics approaches promises to deepen insights into disease mechanisms, identify novel therapeutic targets, and enable personalized treatment strategies.

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2. Lipid nanoparticles in mRNA vaccine delivery

Lipid nanoparticles (LNPs) have emerged as a critical technology in the development of mRNA vaccines, notably during the COVID-19 pandemic. These nano-sized carriers encapsulate fragile mRNA molecules, protecting them from enzymatic degradation and facilitating their delivery into host cells. Composed mainly of ionizable lipids, phospholipids, cholesterol, and polyethylene glycol (PEG)-lipid conjugates, LNPs enhance cellular uptake via endocytosis (Pardi et al., 2018). Recent research focuses on optimizing lipid

compositions to improve stability, reduce reactogenicity, and increase immunogenicity. For instance, modified ionizable lipids have shown to enhance mRNA release and translation efficiency (Zhang et al., 2020). Moreover, surface modifications of LNPs are being explored to target specific cell types, broadening vaccine applications beyond infectious diseases. These advances promise broader applications of LNPs in personalized medicine, gene therapy, and cancer immunotherapy.

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3. Lipidomics and its role in understanding cancer metabolism

Cancer cells exhibit reprogrammed lipid metabolism to support rapid proliferation, membrane synthesis, and energy demands. Lipidomics has provided insights into these metabolic shifts, revealing alterations such as increased fatty acid synthase activity and accumulation of certain lipid species, like phosphatidylinositols, which promote oncogenic signaling (Beloribi-Djefaflija et al., 2016). Lipid profiling identifies specific biomarkers associated with tumor progression, metastasis, and therapy resistance. For example, increased ceramide levels have been linked to apoptosis regulation in cancer cells (Kumar et al., 2018). Targeting dysregulated lipid pathways offers promising therapeutic avenues, with some inhibitors of lipid synthesis enzymes already entering clinical trials. Lipidomics thus serves as a critical tool to understand cancer biology and develop lipid-targeted therapies.

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4. Omega-3 fatty acids and mental health

Omega-3 fatty acids, particularly DHA (docosahexaenoic acid) and EPA (eicosapentaenoic acid), are essential for brain development and function. Their anti-inflammatory properties and role in membrane fluidity are crucial for maintaining neuronal health. Recent clinical and preclinical research highlights their therapeutic potential in mental health disorders such as depression, anxiety, and cognitive decline (Freeman et al., 2006).

Epidemiological studies have found that individuals with depression tend to have lower levels of omega-3 fatty acids in their blood. Supplementation trials suggest that omega-3s, especially EPA, can reduce depressive symptoms, particularly when used alongside conventional antidepressants (Grosso et al., 2014). The mechanisms involve modulation of neuroinflammation, enhancement of neuroplasticity, and regulation of neurotransmitter systems such as serotonin and dopamine.

Recent investigations also indicate that omega-3 supplementation might benefit individuals with schizophrenia and bipolar disorder, improving mood and cognitive functions (Marangell et al., 2003). Despite variability in study outcomes, a growing body of evidence supports incorporating omega-3 fatty acids into dietary recommendations for mental health management.

Given their safety profile and broader health benefits, omega-3s are increasingly regarded as adjunct therapies. However, standardized dosing and long-term effects require further research to optimize their clinical application.

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5. Lipid-based nanocarriers for targeted drug delivery

Lipid-based nanocarriers, including liposomes, solid lipid nanoparticles (SLNs), and nanostructured lipid carriers (NLCs), have revolutionized drug delivery systems by improving bioavailability, stability, and targeting precision. These carriers encapsulate both hydrophilic and hydrophobic drugs, protecting them from degradation and allowing controlled release at target sites (Mishra et al., 2010).

Liposomes, composed of phospholipid bilayers, are extensively used for delivering chemotherapeutic agents, imaging agents, and gene therapies. SLNs and NLCs, made of solid or mixed lipids, offer advantages such as longer shelf life, sustained release, and ease of surface modification for targeting specific tissues (Mehanna et al., 2019).

Recent developments focus on enhancing targeting efficiency via surface modifications with ligands, antibodies, or peptides, enabling precise delivery to tumor cells or inflamed tissues. Moreover, lipid nanocarriers facilitate crossing biological barriers like the blood-brain barrier, opening avenues for neurological disorder treatments.

These carriers are promising in personalized medicine, especially for cancer, infectious diseases, and neurodegenerative conditions, reducing off-target effects and maximizing therapeutic efficacy.

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6. Lipid metabolism in obesity and diabetes

Alterations in lipid metabolism are central to the development of metabolic diseases such as obesity and type 2 diabetes mellitus (T2DM). Excess caloric intake, especially diets rich in saturated fats, leads to an excessive accumulation of lipids, notably triglycerides, free fatty acids (FFAs), ceramides, and diacylglycerols. These lipids significantly contribute to insulin resistance—a hallmark of T2DM (Samuel & Shulman, 2012).

Recent lipidomic studies have identified elevated ceramide levels—bioactive sphingolipids that impair insulin signaling by disrupting Akt/PKB phosphorylation—as key mediators in insulin resistance (Holland et al., 2011). Similarly, increased diacylglycerol (DAG) concentrations activate novel protein kinase C (PKC) isoforms, which interfere with insulin receptor function.

Furthermore, adipose tissue dysregulation in obesity results in abnormal secretion of adipokines and FFAs, which induce systemic inflammation and oxidative stress—additional contributors to insulin resistance. The enzyme lipoprotein lipase (LPL), responsible for hydrolyzing triglycerides into FFAs for tissue uptake, often exhibits dysregulated activity, exacerbating lipid abnormalities.

Understanding these lipid disturbances has led to targeted therapies such as ceramide synthesis inhibitors and lifestyle interventions focusing on dietary fat quality and caloric restriction. Advances in lipidomics provide insights into lipid profiles that predict disease progression and therapeutic responses, emphasizing the importance of lipid metabolism regulation in preventing obesity and diabetes.

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7. Lipid-modulating drugs and therapeutic strategies

Lipid-modulating therapies have become a cornerstone in managing cardiovascular diseases associated with dyslipidemia. Statins, fibrates, niacin, and PCSK9 inhibitors are widely used to reduce low-density lipoprotein cholesterol (LDL-C), triglycerides, and improve overall lipid profiles (Cholesterol Treatment Trialists' Collaboration, 2010).

Recent research emphasizes novel targets within lipid metabolism, such as apolipoproteins, lipoprotein lipase (LPL), and enzymes involved in triglyceride synthesis. PCSK9 inhibitors, like evolocumab and alirocumab, substantially lower LDL-C levels by promoting receptor recycling (Sabatine et al., 2015). Fibrates activate peroxisome proliferator-activated receptors (PPARs) to reduce triglycerides and increase high-density lipoprotein (HDL).

Emerging therapies seek to address residual cardiovascular risk by targeting lipoprotein(a) and oxidized LDL. Additionally, some drugs are under investigation to modulate ceramide and sphingolipid pathways, given their role in atherosclerosis and insulin resistance.

Lifestyle interventions, including dietary modification with plant-based unsaturated fats, omega-3 fatty acids, and physical activity, complement pharmacotherapy in lipid management. These strategies collectively aim for comprehensive lipid profile optimization and reduction of cardiovascular events.

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8. Lipids and neurodegenerative diseases

Lipids are essential for maintaining neuronal structure, membrane integrity, and signaling within the central nervous system. Disruption in lipid homeostasis has been implicated in neurodegenerative diseases such as Alzheimer's disease (AD), Parkinson's disease (PD), and multiple sclerosis (MS). In AD, abnormal accumulation of sphingolipids, especially ceramides, has been observed, where elevated ceramide levels promote amyloid-beta aggregation, neuroinflammation, and neuronal apoptosis (Mielke et al., 2010).

Lipidomics studies reveal that specific lipid signatures could serve as early biomarkers. For example, decreased phosphatidylcholine (PC) and increased ceramide levels correlate with disease progression in AD (Mapstone et al., 2014). Additionally, abnormal cholesterol metabolism influences amyloid precursor protein (APP) processing, affecting plaque formation. Oxidized lipids, such as oxidized phospholipids, induce oxidative stress, damaging neuronal membranes and accelerating neurodegeneration (Gamba et al., 2015).

In PD, lipid imbalances in alpha-synuclein interactions and membrane composition have been linked to protein aggregation and neuronal toxicity. Therapeutic strategies targeting lipid pathways, such as sphingolipid modulators, are under investigation for neuroprotection (Mencacci et al., 2018).

Given the critical role of lipids in brain health, modulating lipid metabolic pathways and developing lipid-based biomarkers may facilitate early diagnosis and targeted therapies for neurodegenerative diseases.

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9. Sustainable development in lipid extraction and processing

With increasing global demand for edible oils, sustainability in lipid extraction and processing has gained prominence. The traditional extraction methods, such as solvent extraction with hexane, pose environmental and health concerns, prompting shifts toward greener technologies. Supercritical carbon dioxide (scCO₂) extraction is emerging as an eco-friendly alternative, offering high efficiency with no residual solvents (Rao et al., 2018).

Lipid processing also emphasizes waste valorization. By-products like seed hulls and residual biomass are increasingly used to produce biodiesel, animal feed, and biofertilizers, promoting a circular economy. Enzymatic hydrolysis and interesterification techniques are being refined to produce healthier fats with tailored fatty acid profiles, including omega-3-enriched oils.

Regulatory pressures and consumer demand for organic and natural products also influence processing practices. Innovations in biotechnology, such as genetic modification of oilseed crops, aim to enhance oil yield and quality sustainably.

Overall, integrating advanced extraction technologies, waste utilization, and biodegradable packaging will pave the way for sustainable lipid technology, reducing environmental impact while meeting global nutritional needs.

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10. Lipid-based biotechnology for sustainable oil production

Biotechnology has revolutionized the pursuit of sustainable lipid production by harnessing engineered microorganisms and genetically modified crops. Microbial lipids, produced by oleaginous yeasts, algae, and bacteria, present a promising alternative to traditional plant oils, especially since these microbes can be cultivated on non-arable land, utilizing wastewater and industrial effluents, thus minimizing environmental impact (Li & Zhang, 2017). Engineering microbial metabolic pathways to boost lipid biosynthesis enables the production of tailored lipids with specific fatty acid compositions, including omega-3 fatty acids, which could meet both nutritional and industrial demands.

On the plant-based front, genetic modification of oilseed crops such as soybean, canola, and oil palm has been undertaken to increase oil yield, improve stress resistance, and alter fatty acid profiles for healthier and more stable oils. For example, overexpressing desaturase enzymes in transgenic crops has resulted in

oils with higher omega-3 content, promoting healthier fats (Ruiz-Lara et al., 2019). These approaches aim to reduce dependency on imported oils and mitigate monoculture-related environmental issues.

Additionally, advances in biotechnological tools like CRISPR-Cas9 are enhancing precision editing of lipid biosynthetic pathways. Coupling these tools with sustainable feedstock utilization and eco-friendly extraction processes paves the way for a more environmentally sustainable and economically viable lipid production industry.

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Medium chain triglyceride (MCT) oil: A comprehensive guide

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In the world of health and nutrition, Medium Chain Triglyceride (MCT) oil has become a popular supplement among athletes, keto enthusiasts, and individuals seeking better metabolic health. But what exactly is MCT oil, and why is it gaining so much attention? This article explores the science, benefits, risks, and practical uses of MCT oil, backed by peer-reviewed research.

What are medium chain triglycerides (MCT):

Medium-chain triglycerides (MCTs) are a unique type of fat molecule. To understand them, it's helpful to compare them to the more common fats found in our diet: long-chain triglycerides (LCTs). All triglycerides are composed of a glycerol backbone to which three fatty acid molecules are attached. The key differentiator for MCTs lies in the length of these fatty acid chains. While LCTs have fatty acid chains with 13 or more carbon atoms, MCTs have fatty acid chains with 6 to 12 carbon atoms. The most common types of MCTs found in supplements and natural sources are caprylic acid (C8, with 8 carbon atoms) and capric acid (C10, with 10 carbon atoms), though caproic acid (C6) and lauric acid (C12) are also present.

This shorter chain length significantly impacts how MCTs are digested and absorbed by the body. Unlike LCTs, which require bile salts and pancreatic enzymes for digestion and are then absorbed into the lymphatic system before entering the bloodstream, MCTs can be absorbed directly into the portal vein and transported to the liver. This bypasses the lymphatic system, leading to a much faster and more efficient absorption process. Once in the liver, MCTs are rapidly metabolized. They are either quickly oxidized for energy through a process called beta-oxidation or converted into ketone bodies. Ketones can serve as an alternative fuel source for the brain and muscles, especially when carbohydrate availability is low (as in a ketogenic diet).

While MCT oil is a concentrated form, MCTs are naturally found in various foods, primarily:

- I. Coconut oil: This is the richest natural source of MCTs, particularly lauric acid (C12).
- II. Palm kernel oil: Similar to coconut oil, it's also a good source.
- III. Dairy products: Smaller amounts of MCTs are found in milk fat, butter, and full-fat yogurts, especially from grass-fed animals.

In essence, medium-chain triglycerides are a readily available and efficiently utilized form of fat that can provide a quick source of energy and contribute to ketone production, making them of interest in various health and dietary contexts.

How MCTs are metabolized:

The metabolism of Medium-Chain Triglycerides (MCTs) is a fascinating process that sets them apart from the more common Long-Chain Triglycerides (LCTs) found in most dietary fats. This unique metabolic pathway contributes to their rapid energy delivery and other potential health benefits. Unlike LCTs, which require extensive digestion by pancreatic lipases and bile salts in the small intestine, MCTs are much more easily hydrolyzed. Lingual and gastric lipases (enzymes present in the mouth and stomach) can begin to break down MCTs even before they reach the small intestine.

The most significant difference lies in their absorption. While LCTs are broken down, re-esterified into triglycerides, and then packaged into chylomicrons that enter the lymphatic system before eventually reaching the bloodstream, MCTs have a much more direct route. Their shorter chain length and more hydrophilic nature allow them to bypass the lymphatic system almost entirely. Instead, once broken down into medium-chain fatty acids (MCFAs) and glycerol, they are directly

absorbed into the portal vein, which leads straight to the liver. This direct route means they enter the bloodstream much faster than LCTs.

Once in the liver, MCFAs are quickly taken up by liver cells. Crucially, they do not require carnitine to enter the mitochondria for energy production. LCTs, on the other hand, need the carnitine shuttle system to transport them across the mitochondrial membrane. This carnitine-independent transport further contributes to the rapid metabolism of MCTs.

Inside the liver mitochondria, MCFAs undergo rapid beta-oxidation, a process that breaks them down into acetyl-CoA. This acetyl-CoA can then enter the Krebs cycle (also known as the citric acid cycle) to produce ATP (energy). However, due to the rapid influx and oxidation of MCFAs, the liver often produces an excess of acetyl-CoA. When this happens, the liver converts the surplus acetyl-CoA into ketone bodies (acetoacetate, beta-hydroxybutyrate, and acetone).

Ketone bodies are water-soluble molecules that can be used as an alternative fuel source by various tissues, including the brain, heart, and skeletal muscles, especially when glucose (carbohydrate) availability is low. This is why MCT oil is a popular supplement for individuals on ketogenic diets, as it can help them achieve and maintain a state of ketosis. The rapid production and utilization of ketones from MCTs make them a highly efficient energy source, potentially providing a quick mental and physical boost.

Hence, one can say, MCTs are metabolized with remarkable efficiency and speed. Their unique digestion and absorption pathway, bypassing the lymphatic system and directly entering the liver, combined with their carnitine-independent entry into mitochondria, allows for rapid energy production and the significant generation of ketone bodies, offering a distinct metabolic advantage over LCTs.

Proven health benefits of MCT oil:

MCT oil has been the subject of numerous studies, and while some of its purported benefits still require more extensive research, several areas have shown promising or proven health advantages:

Epilepsy management: One of the most well-established and clinically supported uses of MCT oil is in the management of drug-resistant epilepsy, particularly in conjunction with ketogenic diets. By promoting the production of ketone bodies, MCT oil can provide an alternative energy source for the brain, which may help reduce seizure frequency and severity. Studies have shown significant reductions in seizure rates in some patients supplementing with MCT oil.

Fat malabsorption disorders: Due to their unique and rapid digestion and absorption pathway (bypassing the lymphatic system and not requiring bile salts for absorption), MCTs are particularly beneficial for individuals with conditions that impair fat absorption. This includes conditions like pancreatic insufficiency, short bowel syndrome, cystic fibrosis, and other digestive disorders, where MCT oil can help prevent malnutrition and ensure adequate calorie and nutrient intake.

Weight management (Modest effect): Some research suggests MCT oil may play a modest role in weight management. Such as, MCT oil has been shown to increase feelings of fullness (satiety), which can lead to a reduced overall calorie intake. Also, studies have indicated that MCTs can increase energy expenditure (thermogenesis) and promote fat oxidation (burning fat for fuel), particularly when replacing long-chain triglycerides in the diet. This effect, while present, may not be dramatic for significant weight loss. However, it's important to note that very high doses of MCT oil on top of a high-fat diet have been linked to fat accumulation in the liver in animal studies, highlighting the need for balanced consumption.

Cognitive function (particularly in glucose hypometabolism): The ability of MCTs to produce ketones, which can serve as an alternative brain fuel, has led to interest in their potential for cognitive support, especially in conditions where the brain's ability to use glucose is impaired (e.g., Alzheimer's disease). Some studies have shown short-term cognitive improvements in individuals with mild cognitive impairment or Alzheimer's disease. Ketones may help compensate for reduced glucose metabolism in the brain. Research in healthy individuals also suggests potential for enhanced cognitive performance (e.g., working memory, executive function), with effects often seen with doses

of 6 to 40 grams per day. However, more robust, larger, and longer-term studies are needed to definitively confirm and characterize these cognitive benefits, especially for prevention or long-term improvement in neurological conditions.

Potential risks and side effects:

While MCT oil offers several potential health benefits, it's crucial to be aware of its potential risks and side effects, especially when consumed in large quantities or by individuals with certain health conditions. Here are the key potential risks and side effects of MCT oil:

Digestive issues: This is by far the most common side effect. Because MCTs are absorbed so rapidly, consuming too much too quickly can overwhelm the digestive system, leading to: diarrhoea, stomach cramps, nausea, vomiting, gas and bloating. It's highly recommended to start with a small dose (e.g., 1 teaspoon) and gradually increase it over time to allow your body to adjust. Taking MCT oil with food can also help mitigate these effects.

High saturated fat intake and potential impact on cholesterol: MCT oil is a concentrated source of saturated fat. While MCTs are metabolized differently than LCTs (long-chain triglycerides, the saturated fats found in most foods), and some studies suggest they may not negatively impact cholesterol as much as other saturated fats, high doses still contribute significantly to overall saturated fat intake. In some individuals, particularly "hyper-responders," high saturated fat intake, including from MCT oil, can lead to increased LDL ("bad") cholesterol. While not universally observed, some studies have shown an increase in LDL cholesterol with high MCT oil consumption in a subset of the population. This could potentially increase the risk of heart disease over the long term. Hence, it's essential to monitor cholesterol levels, especially if one has pre-existing cardiovascular concerns or a family history of heart disease and discuss MCT oil use with your doctor.

Caloric density and weight gain: Although MCT oil is often promoted for weight management, it's still pure fat and therefore very calorie-dense (approximately 115 calories per tablespoon). If MCT oil is added to the diet without adjusting overall calorie intake, it can lead to

weight gain rather than weight loss.

Fat build-up in the liver (rare, high doses): While MCTs are generally less likely to be stored as fat in the liver compared to LCTs and some studies even suggest they might help reduce liver fat, consuming very high doses of MCT oil consistently over time has been linked to fat accumulation in the liver in some animal studies. This is a rare occurrence in humans with typical supplemental doses but highlights the importance of moderation.

Diabetes and ketone buildup: In people with diabetes, especially Type 1 diabetes, high doses of MCTs can lead to an excessive build-up of ketones, a condition known as ketoacidosis. While the ketones from MCTs are generally safe for healthy individuals and those on a controlled ketogenic diet, uncontrolled ketone levels can be dangerous for diabetics. Individuals with diabetes should consult their doctor before using MCT oil.

Liver problems: Since MCTs are processed by the liver, individuals with pre-existing severe liver conditions (e.g., cirrhosis, liver disease, high blood pressure inside the liver, brain/nervous system complications from liver damage) should avoid using MCT oil as it could exacerbate their condition.

Allergic reactions: Though rare, some individuals may experience an allergic reaction to MCT oil, presenting with symptoms like hives, difficulty breathing, or swelling.

Interaction with medications: While research on direct drug interactions with MCT oil is limited, it's always prudent to consult a healthcare provider if you are taking any medications, as MCT oil could potentially affect nutrient absorption or the metabolism of certain drugs.

In nutshell, while MCT oil can be a valuable supplement for certain purposes, responsible and informed use is key to minimizing potential risks and side effects.

How to use MCT oil:

MCT oil is incredibly versatile due to its neutral taste and liquid form at room temperature. However, proper usage is key to maximizing its benefits and minimizing potential side effects. Commercially available MCT

products in market are mentioned in the Table 1. A suggestion on how to use MCT oil effectively:

Start low and go slow: This is the most crucial tip to avoid digestive upset (diarrhea, nausea, stomach cramps). Start with just 1 teaspoon (5 ml) per day for the first few days. If you tolerate it well, increase to 1.5 teaspoons, then 2 teaspoons, and so on, over a week or two. Most people find 1 to 2 tablespoons (15-30 ml) per day to be an effective and well-tolerated dose. Some individuals may go higher, but always increase slowly and listen to your body. Consuming MCT oil with meals can significantly reduce the likelihood of digestive issues.

Ways to incorporate MCT Oil into diet: This is perhaps the most popular way to use MCT oil. Blend 1-2 tablespoons of MCT oil with hot coffee and a pat of grass-fed butter or ghee. This creates a creamy, frothy drink that can provide sustained energy and satiety. Else, add a tablespoon or two to your morning protein shake or fruit smoothie. It blends easily and adds a creamy texture without altering the taste. Replace some or all of the olive oil in your homemade salad

dressings with MCT oil. Also, stir a teaspoon or tablespoon into your yogurt, oatmeal, or chia pudding.

Important Considerations for Usage: MCT oil has a relatively low smoke point compared to many other cooking oils (around 320°F/160 °C). Heating it to high temperatures can cause it to break down, lose its beneficial properties, and potentially create harmful compounds. Hence, avoid frying, sautéing, or deep-frying with MCT oil. Use it for low-heat cooking, or better yet, add it *after* cooking.

While beneficial, MCT oil should not completely replace other healthy fats in your diet (e.g., olive oil, avocado oil, nuts, seeds, fatty fish). A balanced intake of different types of fats is crucial for overall health.

Look for MCT oil that is 100% capric acid (C8) and/or caprylic acid (C10), as these are the most efficiently metabolized MCTs for energy and ketone production. Avoid products that contain a high percentage of lauric acid (C12), as it behaves more like a long-chain triglyceride in the body. Ensure it's responsibly sourced and free from fillers or additives.

Table 1: Commercially available MCT products in market (Source: J Food Science and Technology, 2022 Jun 22; 60(8):2143–2152. doi: 10.1007/s13197-022-05499-w)

SI No.	MCT oil brand	Application	Producer
1.	MCT oil	Act as a fuel to brain and body	Nature way, USA
2.	Powdered MCT Oil	Ketogenic diet	Quest Nutrition USA
3.	MCT Oil (mixture of C8 and C10)	Food applications like bakery and confectionary	AAK Kamani, India
4.	Joymix MCT Oil	For weight management	Malaysia
5.	Keto products	Source of energy	360 Nutrition, USA
6.	Keto organic MCT Oil	Used for weight loss	Ancient Nutrition, USA
7.	MCT powder	Help to control cardiovascular diseases	Organika, Canada
8.	Liquid MCT Oil	Supplement to be used in food formulation	Supplement manufacturer, UK
9.	Spring valley oil	Management of weight and for athletes	Spring Valley, USA
10.	Soft gel (MCT Oil)	Improved fat metabolism	Carlson Lab, USA
11.	Melrose MCT powder and MCT oil	Energy for brain and body	Melrose, Australia
12.	MCT Oil	Source of energy	Bioglan, Australia
13.	Max-C8	Proper metabolism, digestion, energy, weight management	Zenwise health, Germany
14.	Pure tricaprylin oil	Weight management	Weight world, UK
15.	Diet MCT Oil	Nutraceutical fat and source of energy	Diet works, USA

Who should be cautious or consult a Doctor:

Individuals with Diabetes, especially Type 1 diabetics, as excessive ketone production could lead to ketoacidosis. Since MCTs are processed by the liver, those with severe liver disease should avoid it. Pregnant or breastfeeding women must consult a doctor before use. Anyone on medications, to avoid potential interactions, must discuss with healthcare provider.

Market size:

The wide acclaim of MCT oil in rapidly increasing keto-friendly and low-carb diets has caused a surge in its popularity as it enhances fat metabolism and provides a quick source of energy. Additionally, the rising adoption of dietary supplements and sports nutrition fuels consumption MCT oil among athletes and fitness enthusiasts. With the evolving preferences of organic and non-GMO products, companies are now introducing flavored variants which further expand product innovation. Also, other industries like personal care, pharmaceutical, and skincare are now recognizing the antimicrobial and moisturizing effects of the MCT oil that leads to its multifunctional usage in everyday products. As a result, the MCT oil demand is significantly increasing due to it being incorporated in energy bars, coffee creamers, and meal replacement products.

On a regional scale, North America and Europe are still the leading countries because of the high construction of public health. However, rapidly increasing disposable income and the general shift towards wellness in the Asia-Pacific makes it a lucrative emerging region (Table 2).

Table 2: MCT Oil Market across the world (Global market insights).

MCT OIL Market	
Global Forecast (2025-2034)	
MARKET STATISTICS	SEGMENT STATISTICS
Market Value (2024) \$905.3 MN	Caprylic acid segment Market Size (2024): \$447.7 MN
Market Value (2034) \$1.9 BN	Coconut oil segment Market Size (2024): \$394.3 MN

CAGR (2025-2034) 7.5%	Food and beverages segment Market Size (2024): \$458.1 MN
	Dry segment Market Size (2024): \$817.5 MN
REGIONAL STATISTICS	
Asia Pacific:	Market Size (2024): \$319 MN

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Title (English): *Divine Scientist*

Title (Marathi): *Gurunam Guruh*

Author: *Aneeta Patil*

Publisher: *Sundaram Digital Publication House, Mumbai*

Price: ₹ 995 per copy (available at www.sundarampublication.com)

Reviewer: *Professor Ganapati D. Yadav, Bhatnagar Fellow & National Science Chair, Emeritus Professor of Eminence and Former Vice Chancellor, Institute of Chemical Technology, Mumbai*

I had the privilege of reading this compelling biography of Padma Vibhushan Professor Man Mohan Sharma, FRS, first in its original draft in Marathi version and then in its English translation. Aneeta Patil requested me to go through it and provide missing links or corrections if any. As someone who has had the good fortune of knowing Prof. Sharma for over five decades, initially as his student, later as a colleague at UDCT (now ICT Mumbai), and as a close family friend, I found this work to be profoundly moving and inspiring. He has been my mentor, the Maha Guru and philosopher who has influenced my life. I was also fortunate to get to know many of his family members during my Ph.D. days. Every word written in the book raises the curiosity to know more and more about this saintly persona.

The biography is thoughtfully structured into 29 chapters, yet rather than summarizing each, I prefer to highlight its most striking elements. Once you begin reading, it becomes impossible to put down. Whether you are a student, colleague, admirer, or someone unfamiliar with Prof. Sharma, you will inevitably find yourself wishing you had met him or had the honour of being his student or acquaintance. His presence has always been mesmerizing.

The book teaches profound lessons in humility, curiosity, integrity, and quiet confidence. It celebrates a life dedicated wholly to science, education, industry, government policy and national service, free from the lure of power, position, or privilege. He wanted his students to surpass his achievements and never took anybody else's credit although he may be the generator of the idea. What scientists call now as a 'nano' was studied by him in 1969 in his theoretical work with P.A. Ramachandran and was mentioned by the great Chemical Engineering Professor T.K. Sherwood of MIT

in 1975! Ramachandran's entire thesis was theoretical.

Author Aneeta Patil deserves great credit for capturing the essence of this extraordinary yet deeply humble man in such lucid prose. Over a year of research, she interviewed numerous individuals including his famous students whose lives were touched by Prof. Sharma, friends, classmates, students, colleagues, and industrialists alike. Three of his most renowned and accomplished students, namely, Dr. R.A. Mashelkar, Prof. J.B. Joshi, and Prof. G.D. Yadav (the author of this review), all elected Fellows of the Indian National Science Academy (INSA), International Members of the US National Academy of Engineering, Fellows of The World Academy of Sciences (TWAS), and recipients of Padma awards, shared personal and insightful stories about their beloved Guru. Aneeta's work unveils the inner world of a man revered across academia, whose influence continues to span generations.

I was honoured to speak at the book's release on June 6, 2025, before a large and enthusiastic audience. On that occasion, I remarked that Prof. Sharma is like a Jain Muni, detached from worldly ambition, glitter and materialist pleasure. He turned down top positions including Secretary, DST; Chairman, UGC; DG, CSIR; and Director, IIT Kanpur. Instead, he chose to remain a professor at his alma mater, the UDCT, becoming the youngest professor in the University of Mumbai's history and later its longest serving one. I was deeply moved when he specifically acknowledged me in his speech, praising my invaluable efforts to remove the shanties along the footpaths surrounding the ICT campus, even at the great risk of my own life and that of my family. Such is his magnanimity.

You will always wonder, is such a person amongst us as a beacon of knowledge and humility?

His list of accolades is staggering. But what truly defines him is his generosity of spirit. He is a mentor of mentors, a sculptor of minds, a sage counsellor to many in different walks of life and the nation at large. These facets are beautifully brought out in the book.

The foreword, written by Bharat Ratna Prof. C.N.R. Rao, FRS, is a heartfelt tribute to Prof. Sharma's intellect, integrity, and enduring friendship. Despite not always being fully recognized by his own university, where even his election to the Royal Society in London was met with cold indifference, Prof. Sharma never

uttered a word of protest. He accepted such moments with equanimity and grace. He was once denied the prestigious Bhatnagar Fellowship by the university, yet he bore it with humility rather than resentment.

His academic lineage, over 1500 Ph.D. scholars, directly and through his students, has created a towering banyan tree of knowledge and innovation. Long before “translational research” became a buzzword, he practised it. His Ph.D. research led to a patent sold to Shell for £1,000 in 1963, a princely sum then. Among those inspired and mentored by him is industrialist Mukesh Ambani, who, at the book release function, announced a historic donation of ₹ 151 crore with no conditions attached. It was an unparalleled moment in the annals of Guru-Shishya (teacher-student) tradition and made headlines the following day. What a legacy he has created!

Prof. Sharma has forged lifelong friendships across age groups and professions, academicians, scientists, bureaucrats, and industrialists, driven by a shared commitment to national development. The book recounts several such episodes that reveal his vast influence. He has a phenomenal memory and recollects many forgotten instances when he meets old timers.

A devout and disciplined individual, he observes a fast every Tuesday in honour of Lord Ram and visits a Hanuman temple every Saturday as far as possible, no matter where he is. His spiritual discipline is matched by his intellectual brilliance. He is an avid reader of Ram Charit Manas. Often called a “walking-talking encyclopaedia,” his memory and command over data, policy, history, and even old Hindi film songs are legendary. A true Brahmarshi of the modern era.

He has served on elite panels selecting IIT directors, secretaries to the government, CSIR lab directors, Director Generals, and more. The list is long. His mastery of English, although having been educated in Hindi, deep grasp of global chemical markets, and precise articulation have shaped policy at the highest levels. As a member of the Scientific Advisory Committee to the Prime Minister, along with some of the most revered scientists, his ideas helped shape institutions like IITs, IISERs, and AcSIR.

His rapport with the former and the late Prime Minister Dr. Manmohan Singh (when he was the Chairman UGC), his longstanding chairmanship of the Petroleum Ministry’s scientific committee, and his role in the

Empowered Committee of the MHRD are part of institutional memory. That committee, after a decade of selfless service, voluntarily disbanded, an act of rare ethical leadership. Some of the most visionary decisions for university and college research raised the level of research in India.

As Chairman of the IIT Council, he championed doctoral research and institutional excellence. The number of PG and Ph.D. students in major IITs swelled to more than 50%. He was the Chairman of the BOG of IIT Madras, where his visionary ideas helped them to propel in leaps and bounds. His vision for institutional autonomy, especially for his *karmabhoomi* UDCT, and other universities, left a lasting mark on technical education in India. His influence spans CSIR’s industrial linkages, chemical and pharma sectors, and even the functioning of the Ministry of Chemicals and Fertilizers.

At every step, his late wife Sudha remained his quiet strength. Her affectionate nickname for him, *Gyaan Pipaasu*, a thirster of knowledge, perfectly captured his insatiable intellectual curiosity. Their children and grandchildren spoke movingly at the book release, underlining how deeply family and values are embedded in his life.

The book is rich with anecdotes and reflections that underscore his generosity, brilliance, and humility. He fondly recalls his mentors, Dr. G. P. Kane, Prof. P. V. Danckwerts of Cambridge, and Prof. G. M. Nabar, acknowledging their lasting impact on his life.

The biography quickly became a bestseller. On his 88th birthday (June 4), followed by the felicitation in Mumbai on June 6, countless admirers attended in person or online. His autograph on the sold copies was a hallmark, and those who met him and received his blessing were the happiest. His relatives, too, were moved to rediscover their connection to such a towering figure, at once a *Dnyan Yogi* and *Karma Yogi*.

This book is a collector’s item and deserves a place in every personal and institutional library. Sundaram Digital Publication House has done an outstanding job, with plans to release Hindi and Gujarati translations soon. Given Prof. Sharma’s multilingual abilities and close ties with families from Maharashtra and Gujarat, these editions are sure to resonate deeply.

Let me conclude with a prayer from the *Atharva Veda*:

ॐ त्र्यम्बक्यै नमः

May he live to see a hundred autumns.

Journal of lipid science and technology

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Dr HB Singh
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