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Optical Characterization of Shea Butter Oil Used for Frying by SLIPI-1p at 450 nm

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Abstract

Shea butter oil (*Vitellaria paradoxa*) is widely used in West Africa as a frying medium, particularly for cooking plantain bananas. During repeated frying cycles, this oil undergoes significant physicochemical transformations that alter its optical properties. In this study, the optical behavior of shea butter oil subjected to successive frying operations was investigated using the single-phase Structured Laser Illumination Planar Imaging technique (SLIPI-1p). Ten oil samples, labeled E_1 to E_{10}, were collected at successive frying stages under controlled and identical conditions, with E1 corresponding to the oil after the first two frying cycles and E10 after twenty cycles. The samples were analyzed at a wavelength of 450 nm. The SLIPI-1p technique enabled the reduction of multiple scattering effects, while a dedicated image-processing workflow was applied to extract the extinction coefficient reliably from the transmitted laser sheet. The results show that the extinction coefficient increases progressively from 0.3475 to 0.4854, reflecting the accumulation of absorbing and scattering species generated during thermal degradation. This evolution indicates a cumulative degradation mechanism in which optically active species increase with each frying cycle. These findings demonstrate that SLIPI-1p is a powerful, non-destructive tool for characterizing dense edible oils. The method shows strong potential for real-time monitoring of frying oil degradation, although further validation against standard chemical indicators, such as peroxide value and total polar compounds, is required. Future work will include correlation with these chemical indicators to strengthen the interpretation of optical measurements.

Keywords

Shea Butter Oil, Frying, SLIPI-1p, Extinction Coefficient, Optical Characterization, Oil Quality Monitoring, Cumulative Degradation

1. Introduction

Shea butter oil extracted from the nuts of *Vitellaria paradoxa* is widely used in West Africa for culinary, cosmetic, and pharmaceutical applications. In many regions, it constitutes a traditional frying medium for plantain bananas and other foods due to its availability, distinctive flavor, and relatively high oxidative stability. However, like most vegetable oils, shea butter oil undergoes significant physicochemical transformations when exposed to the high temperatures involved in frying processes. These transformations include oxidation, hydrolysis, and polymerization reactions that progressively modify the molecular composition and physical properties of the oil [1] [2].

During frying, the formation of oxidized triglycerides, polar compounds, and polymerized products leads to the accumulation of degradation by-products and suspended particles. These compounds alter the optical properties of the oil by increasing both light absorption and scattering phenomena. As a result, the optical behavior of the oil evolves during successive frying cycles, which makes optical methods particularly suitable for monitoring its degradation state. Previous studies have shown that changes in optical parameters, such as extinction coefficient and optical density, can provide valuable information about the physicochemical evolution of edible oils during thermal processing [3] [4].

Conventional analytical techniques used to evaluate the quality of frying oils, including chemical assays, UV-visible spectrophotometry, and chromatographic methods, often require complex sample preparation and may be destructive or time-consuming. Moreover, these techniques may become less reliable when applied to highly absorbing or strongly scattering media such as degraded edible oils. In such cases, the presence of suspended particles and turbid structures limits the accuracy of classical spectrophotometric measurements [5] [6].

To overcome these limitations, advanced optical imaging techniques have been developed to improve the characterization of dense and scattering media. Among these methods, the Structured Laser Illumination Planar Imaging (SLIPI) technique has proven particularly effective for suppressing the contribution of multiple light scattering and enhancing the accuracy of optical measurements in turbid media [7] [8]. By using spatially modulated laser illumination, SLIPI enables the extraction of signals dominated by single scattering, allowing more reliable estimation of optical parameters such as the extinction coefficient [9].

The single-phase implementation of this method, known as SLIPI-1p, offers a simplified experimental configuration while preserving the capability to characterize optically dense liquids. This technique has been successfully applied in several studies involving complex scattering media, including sprays, biological fluids, and dense liquid suspensions [7] [10]. However, despite the economic and nutritional importance of shea butter oil in West African food practices, very few studies have investigated its optical behavior during frying using advanced imaging techniques.

Therefore, the objective of the present study is to investigate the optical properties of shea butter oil used for frying plantain bananas using the SLIPI-1p technique at a wavelength of 450 nm. In particular, the study aims to determine the extinction coefficient and optical density of several oil samples obtained after frying under controlled conditions. By combining optical measurements with statistical analysis, this work seeks to demonstrate the potential of SLIPI-1p as a non-destructive tool for monitoring the degradation of traditional vegetable oils and for improving the understanding of their optical evolution during thermal processing.

2. Materials and Methods

2.1. Sample Preparation

Shea butter oil (*Vitellaria paradoxa*) was used as the frying medium for plantain bananas, a common culinary practice in West Africa. The oil was subjected to controlled frying cycles in order to reproduce realistic cooking conditions while ensuring experimental reproducibility.

In order to ensure quantitative reproducibility, the frying protocol was defined using fixed operating parameters. A constant oil volume of 1.5 L was used in each experiment. For each frying cycle, approximately 200 g of plantain banana slices of similar ripeness and mass were introduced into the oil and fried for 6 minutes at a temperature of 180˚C ± 5˚C, which corresponds to typical frying conditions reported in food processing studies [1] [2]. This controlled approach minimizes variations in heat transfer and degradation kinetics.

Ten oil samples were collected sequentially during the frying process. Oil samples were collected after every two frying cycles, corresponding to a cumulative heating time of approximately 11 minutes per sampling interval. Each sample, therefore, corresponded to a specific stage of oil use. Immediately after collection, the samples were filtered using laboratory filter paper with an estimated pore size of 10 - 20 μm in order to remove residual food particles and large suspended solids. This filtration step ensured that the measured optical variations were mainly related to chemical degradation products and small colloidal particles formed during frying [4].

After filtration, the samples were stored in airtight amber glass bottles at room temperature and protected from ambient light until optical measurements were performed. This precaution was necessary to prevent additional photo-oxidation processes that could modify the optical properties of the samples before analysis [11].

2.2. SLIPI-1p Experimental Setup

Optical measurements were performed using a Structured Laser Illumination Planar Imaging (SLIPI-1p) system designed for the characterization of optically dense and scattering liquid media [7].

The experimental setup consisted of the following main components as illustrated in **Figure 1**:

- a continuous wave laser source emitting at 450 nm, chosen because the blue spectral region is particularly sensitive to absorption changes induced by oxidized compounds in edible oils [3];
- a spatial modulation system based on a sinusoidal grating, used to structure the laser illumination;
- an optical system for generating a thin laser sheet that propagates through the oil sample;
- a transparent sample cuvette containing the oil;
- a CCD camera positioned perpendicular to the propagation direction of the laser sheet to record the transmitted and scattered light intensity.

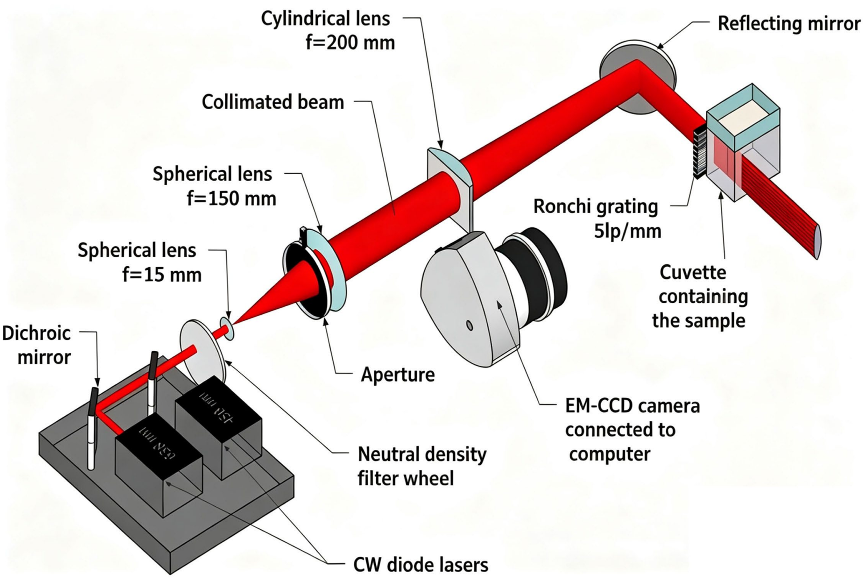

Figure 1. SLIPI-1p setup.

The principle of the SLIPI technique relies on the spatial modulation of the incident laser beam. This modulation allows the suppression of the contribution of multiply scattered photons, which normally deteriorate measurement accuracy in turbid media [8]. By isolating the component of the signal associated primarily with single scattering, the SLIPI-1p method provides a more reliable estimation of the optical attenuation within the sample [7] [9].

For each oil sample, three independent measurements were performed in order to evaluate experimental repeatability. The captured images were processed using dedicated numerical routines to extract the modulated SLIPI signal and reconstruct the intensity distribution of the transmitted laser sheet [10].

In order to ensure reproducibility of the data processing, the SLIPI-1p workflow consisted of several successive steps. First, the recorded images were corrected for background noise and camera dark signal. A region of interest (ROI) corresponding to the central part of the laser sheet was selected in order to minimize edge effects. The intensity profile along the propagation direction was then extracted.

The extracted profile was subsequently smoothed to reduce high-frequency noise and fitted using an exponential decay model based on the Beer-Lambert law. The extinction coefficient was finally obtained from the slope of the logarithmic intensity decay.

2.3. Determination of Optical Parameters

The optical attenuation of the laser sheet propagating through the oil samples was quantified using the extinction coefficient μ_e, which represents the combined effect of absorption and scattering processes within the medium [8].

The extinction coefficient is defined as:

$$\mu_e = \mu_a + \mu_s \tag{1}$$

where

- μ_a is the absorption coefficient,
- μ_s is the scattering coefficient.

Assuming an exponential attenuation of light intensity along the propagation path, the transmitted intensity $I(x)$ at a depth x in the sample follows a Beer-Lambert type relation adapted for scattering media [5]:

$$I(x) = I_0 \cdot e^{-\mu_e x} \tag{2}$$

where

- I_0 is the incident laser intensity,
- x is the optical path length in the sample.

The extinction coefficient was obtained by fitting the exponential decay of the measured intensity profile extracted from the SLIPI images.

The optical density (OD) was then calculated from the extinction coefficient according to:

$$\text{OD} = \mu_e L \tag{3}$$

where L represents the optical path length corresponding to the thickness of the sample.

These optical parameters provide quantitative information about the evolution of the absorption and scattering properties of the oil during frying.

The oil samples were placed in a transparent cuvette with an optical path length of 16 mm.

All measurements were performed at a controlled laboratory temperature of approximately 25˚C.

The extinction coefficient is expressed in mm^{-1}, corresponding to the attenuation per unit optical path length.

2.4. Statistical Analysis

A statistical analysis was conducted to evaluate the reliability and variability of the measured optical parameters.

For both the extinction coefficient and optical density, the following statistical indicators were calculated:

- mean value, representing the central tendency of the measurements;
- standard deviation, characterizing the dispersion of the data;
- coefficient of variation (CV), used to evaluate the relative variability of the measurements.

The coefficient of variation was calculated as:

$$\mathrm{CV} = \frac{\sigma}{\bar{x}} L \tag{4}$$

where

- σ is the standard deviation
- $\bar{x}$ is the mean value.

Correlation analysis between the extinction coefficient and optical density was also performed in order to evaluate the consistency between these two optical indicators.

All numerical calculations were carried out using Microsoft Excel and MATLAB, which allowed the generation of trend curves and the evaluation of regression models describing the evolution of the optical parameters during the frying process [10].

2.5. Measurement Uncertainty and Repeatability

In order to strengthen the scientific reliability of the measurements, an evaluation of experimental repeatability was performed. Each sample was measured three times under identical experimental conditions. The reported extinction coefficient for each sample corresponds to the mean value of the three independent measurements. The repeatability of the measurements was evaluated through the relative standard deviation, which ranged between 5% and 10% across all samples.

The relative variation between repeated measurements remained below 10%, indicating acceptable experimental stability for optical measurements in highly scattering media [9].

Possible sources of uncertainty include:

- small fluctuations in laser intensity,
- camera noise and image processing errors,
- slight variations in sample positioning.

However, the use of structured illumination significantly reduces the impact of multiple scattering, which constitutes the main limitation of conventional optical measurements in turbid liquids [7].

3. Results

3.1. Extinction Coefficients at 450 nm

The extinction coefficients measured for the ten shea butter oil samples range from 0.3475 to 0.4854, indicating a significant increase in optical attenuation as the frying process progresses. This evolution reflects the progressive accumulation of absorbing and scattering compounds formed during repeated thermal exposure of the oil.

The samples E_1 to E_{10} correspond to successive frying stages. Specifically, E_1 represents the oil after the first two frying cycles, while E_{10} corresponds to the oil after twenty frying cycles. Although the fresh (unused) oil was not measured in this study, E_1 can be considered as the earliest degradation stage under thermal conditions.

Table 1. Extinction coefficients and optical density of shea butter oil samples after frying plantain bananas.

Sample	Extinction coefficient	Optical density
E_1	0.3475	2.7802
E_2	0.3926	3.1410
E_3	0.4187	3.3496
E_4	0.4511	3.6091
E_5	0.4518	3.6145
E_6	0.4619	3.6954
E_7	0.4620	3.6960
E_8	0.4632	3.7056
E_9	0.4829	3.8636
E_{10}	0.4854	3.8833

The data presented in **Table 1** show a monotonic increase in the extinction coefficient from sample E_1 to E_{10}. This trend is consistent with previous studies on edible oil degradation, which report that thermal oxidation leads to the formation of polar compounds, polymers, and suspended particles that enhance both light absorption and scattering [1] [4].

The graphical representation (**Figure 2**) highlights a quasi-linear to slightly nonlinear increase in the extinction coefficient with oil usage. This behavior suggests a cumulative degradation mechanism, where the concentration of optically active species increases progressively with each frying cycle. Similar trends have been reported in optical monitoring studies of vegetable oils, where extinction coefficients were found to correlate strongly with degradation indicators [3].

The statistical analysis yields a mean extinction coefficient of 0.4417 ± 0.0443, with a coefficient of variation (CV) of approximately 10%, indicating moderate variability and good experimental reproducibility. These results confirm the reliability of the SLIPI-1p technique for quantitative optical measurements in highly scattering media [9].

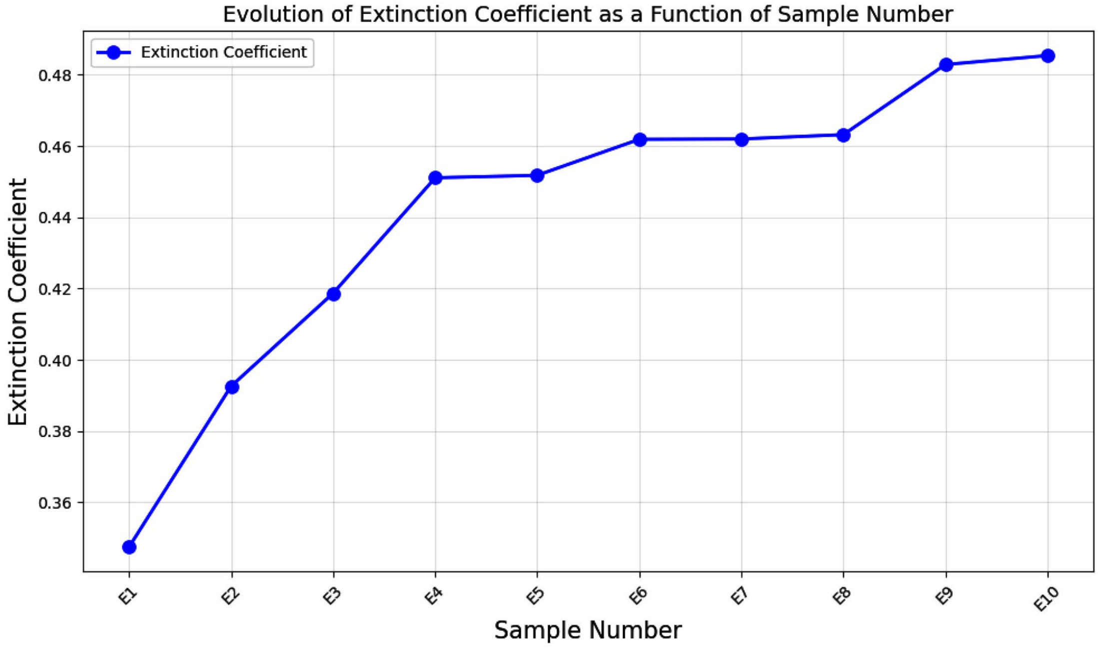

Figure 2. Evolution of the extinction coefficient of shea butter oil samples after frying plantain bananas.

3.2. Optical Density

Figure 3 below illustrates the variation of optical density as a function of the frying stage for the different shea butter oil samples.

The optical density (OD) values follow a similar increasing trend, ranging from 2.7802 to 3.8833, which confirms the progressive increase in optical attenuation within the oil samples.

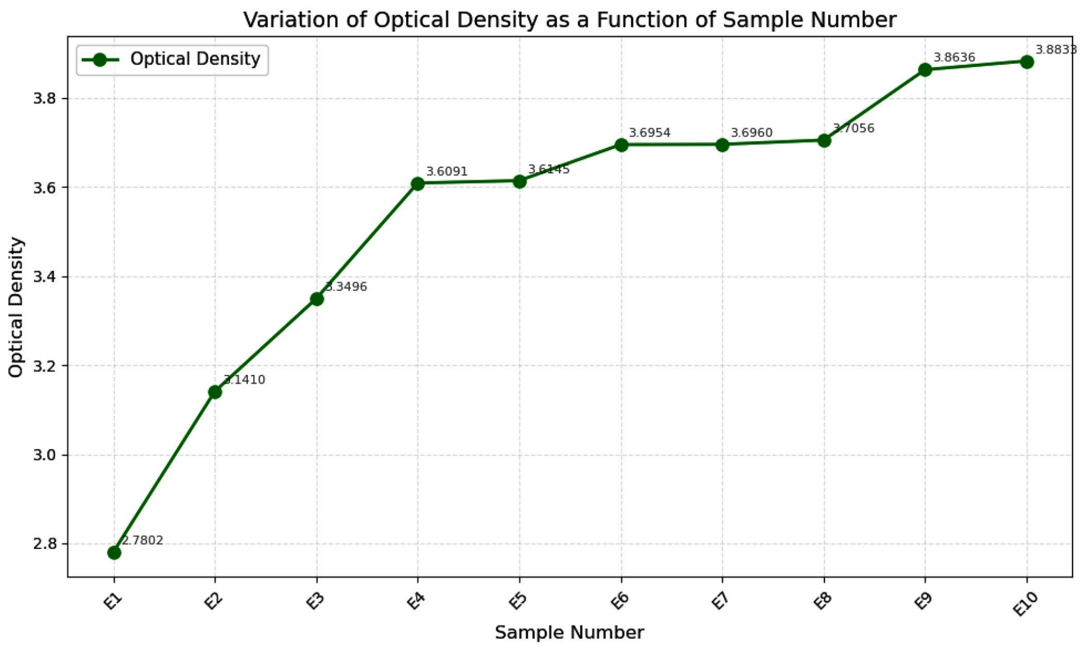

Figure 3. Variation of the optical density of shea butter oil samples after frying plantain bananas.

The increase in optical density is directly related to the increase in extinction coefficient, as described by the Beer-Lambert relation. This behavior reflects the growing concentration of degradation products, which contribute to both absorption and scattering processes within the oil [5].

The mean optical density is 3.5338 ± 0.3552, with a coefficient of variation similar to that of the extinction coefficient (~10%). This consistency further supports the robustness of the measurements.

3.3. Evolution of the Extinction Coefficient with Frying Stage

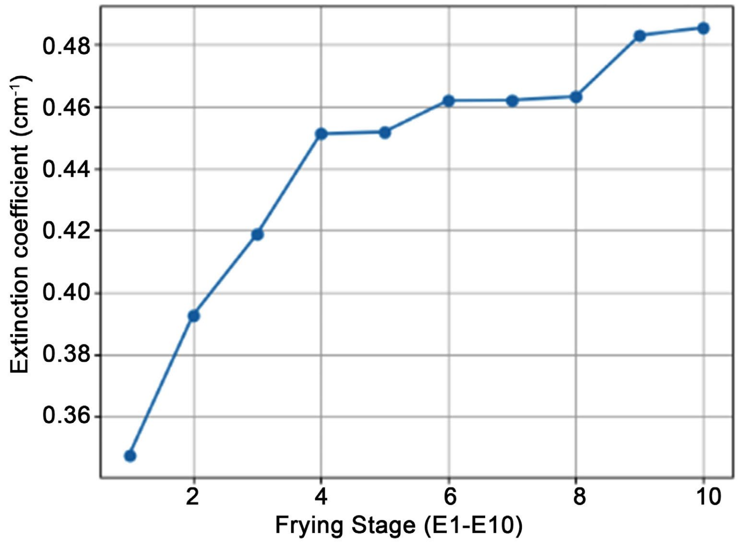

Figure 4. Evolution of the extinction coefficient of shea butter oil as a function of frying stage (E_1 - E_{10}).

The extinction coefficient was analyzed as a function of the frying stage (E_1 - E_{10}) (**Figure 4**). The results reveal a progressive increase with cumulative heating time, highlighting the strong dependence of optical attenuation on the level of oil degradation. This evolution suggests that the extinction coefficient can be used as a direct indicator of frying oil degradation.

This evolution suggests that the extinction coefficient can serve as a direct indicator of frying oil degradation.

3.4. Statistical Summary of Optical Parameters

Table 2 summarizes the main statistical parameters of the extinction coefficient and optical density, including the mean values, standard deviations, coefficients of variation, and measurement ranges.

Table 2. Statistical parameters of extinction coefficient and optical density.

Parameter	Mean	Standard deviation	CV (%)	Min	Max
Extinction coefficient	0.4417	0.0443	10.03	0.3475	0.4854
Optical density	3.5338	0.3552	10.05	2.7802	3.8833

The statistical summary confirms that both parameters exhibit:

- progressive increase with oil usage,
- moderate dispersion (CV ≈ 10%),
- and high measurement consistency.

These results demonstrate that the experimental protocol and SLIPI-1p method provide stable and reproducible measurements, even in highly scattering media such as degraded frying oils.

4. Discussion

The results obtained in this study clearly demonstrate that shea butter oil undergoes significant optical transformations during repeated frying cycles. The progressive increase in the extinction coefficient reflects a continuous modification of the physicochemical structure of the oil under thermal stress.

From a physicochemical standpoint, this evolution can be attributed to the formation of oxidized triglycerides, free fatty acids, and high-molecular-weight polymerized compounds generated during frying. These degradation products increase the concentration of chromophoric species, which enhances light absorption, particularly in the blue spectral region (450 nm). At the same time, the formation of suspended particles and colloidal aggregates contributes to increased light scattering within the medium [1] [4].

The extinction coefficient μ_e, which accounts for both absorption and scattering contributions, therefore increases as a direct consequence of these combined effects. This observation is consistent with previous studies on edible oils, where thermal degradation was shown to induce a significant rise in optical attenuation due to the accumulation of polar compounds and insoluble materials [2] [11].

Compared to classical optical techniques, SLIPI-1p offers a significant advantage by enabling reliable measurements in highly scattering environments. In conventional transmission measurements, multiple scattering leads to an overestimation of transmitted intensity and consequently to an underestimation of the extinction coefficient. By contrast, the structured illumination approach used in SLIPI suppresses multiply scattered photons and enhances measurement accuracy, as demonstrated in previous works on complex liquid systems and sprays [8] [10].

The moderate coefficient of variation (~10%) obtained for the optical parameters indicates good repeatability and experimental stability. This level of variability is acceptable for measurements performed in optically dense and heterogeneous media, where small fluctuations in particle distribution and optical path can influence the recorded signal. The reproducibility of the results further confirms the robustness of the experimental protocol and the reliability of the SLIPI-1p method for quantitative optical characterization.

In addition, the progressive increase of the extinction coefficient suggests a cumulative degradation mechanism, where the concentration of optically active species increases with each frying cycle. This behavior is consistent with kinetic models of oil degradation reported in the literature, which describe a gradual accumulation of oxidation products and polymerized compounds during prolonged thermal exposure [3].

When compared to other vegetable oils studied under similar conditions [12], shea butter oil appears to exhibit relatively high extinction coefficients. This can be explained by its specific chemical composition, which includes a high content of unsaturated fatty acids and natural antioxidants. While these components initially confer a certain oxidative stability, their degradation leads to the formation of strongly absorbing and scattering species, thereby significantly altering the optical properties of the oil.

However, it should be noted that the optical measurements were not directly compared with standard chemical indicators of oil quality, such as peroxide value or total polar compounds. Therefore, the present results should be interpreted as a preliminary validation of the optical approach.

Despite these limitations, this study demonstrates that the SLIPI-1p technique constitutes a powerful and non-destructive tool for the characterization of optically dense edible oils. By enabling accurate measurement of extinction coefficients in highly scattering media, it offers new perspectives for real-time monitoring of oil degradation and for improving food quality control in both traditional and industrial contexts.

5. Conclusions

This study demonstrated the effectiveness of the Structured Laser Illumination Planar Imaging (SLIPI-1p) technique for the optical characterization of dense edible oils, particularly shea butter oil subjected to successive frying cycles.

The experimental results revealed a progressive increase in the extinction coefficient as a function of the number of frying cycles, reflecting a continuous degradation of the physicochemical properties of the oil. This evolution was interpreted as a consequence of the formation and accumulation of oxidized, polymerized, and particulate compounds, which are responsible for the simultaneous increase in light absorption and scattering phenomena within the medium.

The low statistical variations recorded indicate good reproducibility of the method and confirm the robustness of the experimental protocol.

One of the major contributions of this work lies in demonstrating the ability of the SLIPI-1p technique to provide reliable measurements in highly scattering media, where conventional optical methods face significant limitations due to multiple scattering. This approach, therefore, represents a powerful and non-destructive alternative for the analysis of optically complex media.

These observations are consistent with international recommendations for controlling the quality of food oils, which advocate monitoring both optical and chemical parameters to prevent advanced degradation of frying oils [13].

However, some limitations were identified, including the use of a single wavelength and the absence of direct correlation with standard chemical quality indicators of oils.

Overall, this study shows strong potential for oil quality monitoring, although further validation against standard chemical methods is required. Future work will include correlation with peroxide value and total polar compounds.

Overall, this study confirms the potential of the SLIPI-1p technique as an innovative tool for monitoring the degradation of frying oils. It opens promising perspectives for food quality control applications, both in traditional and industrial contexts, with the possibility of real-time and non-invasive monitoring of the properties of the studied media.

Author Contributions

Serge Martial Adepo: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Validation, Writing - original draft, Writing - review & editing; **Jocelyne Mamaket Bosson**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Writing - original draft, Writing - review & editing; **Anicet Kouabenan Kouakou**: Conceptualization, Data curation, Resources, Methodology, Writing - original draft; **Guy-Oscar Regnima**: Data curation, Resources, Methodology, Writing - original draft; **Jérémie T. Zoueu**: Methodology, Project administration, Supervision, Funding acquisition, Writing - original draft, Writing - review & editing.

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Data Availability Statement

This work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere.

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Conflicts of Interest

The authors declare no conflicts of interest.

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