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Quantitative Determination of Extinction Coefficients in Highly Scattering Liquids Using SLIPI-1p: Application to Thermally Degraded Shea Butter Oil

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Abstract

Accurate determination of optical properties in highly scattering and absorbing media remains a significant challenge for conventional optical techniques due to the strong contribution of multiple light scattering. In this work, an experimental method based on single-phase Structured Laser Illumination Planar Imaging (SLIPI-1p) is proposed for the reliable extraction of the extinction coefficient in optically dense liquids. The method relies on spatially modulated laser sheet illumination combined with a synchronous detection algorithm to suppress multiply scattered light and isolate the singly scattered component. This approach enables robust estimation of optical attenuation parameters even in strongly turbid media where classical transmission-based measurements become limited. The performance of the method is demonstrated through its application to a series of dense liquid samples consisting of shea butter oil subjected to controlled thermal degradation. Ten samples corresponding to successive heating stages were analyzed at a wavelength of 450 nm. The extracted extinction coefficients exhibit a progressive increase from 0.347 to 0.485 mm^{-1} across the analyzed samples (E1 - E10), highlighting the sensitivity of the method to monitor the relative evolution of optical properties from the first sampled degradation stage (E1). Statistical analysis shows good repeatability, with a coefficient of variation of approximately 10%, confirming the reliability of the experimental protocol. The results demonstrate that the SLIPI-1p approach provides a non-destructive and accurate tool for quantitative optical characterization of highly scattering media. This method opens promising perspectives for real-time monitoring of complex liquid systems and for applications requiring precise optical diagnostics in optically dense environments.

Keywords

SLIPI-1p, Extinction Coefficient, Structured Illumination, Scattering Media, Optical Diagnostics

1. Introduction

Accurate optical characterization of highly scattering and absorbing media remains a major challenge in experimental physics. In such media, the presence of multiple light scattering significantly limits the applicability and accuracy of conventional optical techniques, including standard transmission spectroscopy and classical Beer-Lambert approaches. These limitations become particularly critical when dealing with optically dense liquids, where scattering and absorption processes are strongly coupled and difficult to separate [1] [2].

In many practical situations, complex liquid systems undergo physicochemical transformations that directly affect their optical properties. For instance, thermally stressed liquids progressively generate absorbing species, suspended particles, and colloidal structures, leading to a simultaneous increase in light absorption and scattering. Monitoring these changes requires robust and non-destructive diagnostic tools capable of operating reliably in highly turbid environments [3]-[6].

Among advanced optical diagnostic techniques, Structured Laser Illumination Planar Imaging (SLIPI) has emerged as a powerful approach for overcoming the limitations imposed by multiple scattering. By using spatially modulated illumination combined with appropriate signal processing, SLIPI enables the selective extraction of singly scattered light while efficiently suppressing multiply scattered contributions. This capability significantly improves the accuracy of quantitative optical measurements in dense and complex media [7]-[9].

The single-phase implementation of this technique, referred to as SLIPI-1p, offers a simplified experimental configuration while maintaining the ability to provide reliable measurements of optical parameters. Previous studies have demonstrated its effectiveness in a wide range of applications involving strongly scattering systems, such as sprays, biological media, and dense liquid suspensions [7] [10]. In particular, SLIPI-based approaches have been shown to enable accurate estimation of extinction coefficients in situations where conventional spectrophotometric methods fail due to turbidity effects [9].

Despite these advances, the experimental validation of such methods on realistic dense liquid systems undergoing progressive physicochemical changes remains an important issue. In this context, complex organic liquids subjected to thermal degradation provide relevant model systems, as they exhibit continuous evolution of their optical properties due to the formation of absorbing and scattering species [1] [4].

The objective of the present work is therefore to develop and apply an experimental SLIPI-1p-based approach for the determination of the extinction coefficient in highly scattering dense liquids. The proposed method relies on structured laser sheet illumination and synchronous detection to extract the modulated signal component associated with singly scattered light. The performance and robustness of the method are demonstrated through its application to a series of liquid samples subjected to controlled thermal degradation.

By combining advanced optical imaging with quantitative data processing, this study aims to demonstrate the potential of SLIPI-1p as a reliable and non-destructive diagnostic tool for optical characterization of complex media. The proposed approach provides new perspectives for experimental investigations requiring accurate measurements in optically dense and highly scattering environments.

2. Materials and Methods

2.1. Experimental Design and Sample Preparation of Thermally Degraded Oil

Shea butter oil (*Vitellaria paradoxa*) was used as the frying medium for plantain bananas, representing a widely practiced culinary process in West African food preparation. In this study, the oil was subjected to controlled and repeatable frying cycles in order to simulate realistic cooking conditions while ensuring high experimental reproducibility.

To guarantee quantitative consistency throughout the experiment, a strictly controlled frying protocol was implemented. A fixed oil volume of 1.5 L was used during a single continuous frying experiment.

For every frying cycle, approximately 200 g of plantain banana slices with similar ripeness and uniform mass distribution were introduced into the oil and fried for 6 minutes at 180 ± 5˚C. These operating conditions are consistent with typical deep-frying parameters reported in food processing studies [1] [2]. This standardized procedure minimized variations in heat transfer dynamics and reduced uncertainties associated with non-uniform thermal degradation.

A total of ten oil samples (E1 - E10) were collected sequentially from the same oil batch during this single continuous frying experiment carried out under controlled operating conditions. Consequently, the samples represent successive stages of thermal degradation of the same oil rather than independent frying experiments. Sampling was performed after every two frying cycles, corresponding to an average cumulative heating time of approximately 11 minutes between two successive samples. Each collected sample therefore represents a well-defined stage in the progressive thermal degradation of the oil.

Since fresh (unused) oil was not analyzed, the present study evaluates the relative evolution of the optical properties from sample E1 onward. Accordingly, sample E1 represents the first sampled degradation stage and serves as the reference for assessing the subsequent evolution of the extinction coefficient throughout the frying process.

Immediately after collection, all samples were filtered using laboratory-grade filter paper with a pore size of approximately 10 - 20 μm to remove residual food particles, charred debris, and large suspended solids. This filtration step ensured that subsequent optical measurements primarily reflected the intrinsic chemical degradation products and fine colloidal particles generated during thermal processing [4].

Following filtration, the samples were stored in airtight amber glass bottles at room temperature and protected from direct exposure to light. This precaution minimized additional photo-oxidation and secondary chemical reactions that could otherwise alter the optical properties prior to analysis [11].

2.2. SLIPI-1p Experimental Setup

In this section the SLIPI-1p approach is briefly described in sections. The details can be found in [12], [13] and [14].

2.2.1. Experimental Device and Image Acquisition

A 450 nm or 638 nm continuous-wave (CW) laser beam is used as the illumination source. Although the experimental setup is compatible with both wavelengths, only the 450 nm laser was used in the present study, since the objective was to evaluate the sensitivity of the SLIPI-1p method in the blue spectral region, where thermally degraded oils exhibit stronger optical attenuation. The 638 nm laser is included in the experimental setup for future multi-wavelength investigations and was not employed in the experiments reported here.

The incident laser intensity is adjusted using a neutral density filter wheel in order to optimize the signal-to-noise ratio while avoiding detector saturation. The laser beam is then expanded by a factor of 10 using a telescope composed of two positive spherical lenses. An aperture is used to select the central portion of the beam, where the spatial intensity profile is sufficiently homogeneous. A positive cylindrical lens with a focal length of 200 mm is used to generate a laser sheet inside the sample basin.

To spatially modulate the laser sheet, a 2 line pairs per millimeter (2 lp/mm) Ronchi grating is placed directly against the basin. This configuration minimizes the adverse effects of near-field diffraction, commonly referred to as the Talbot effect [15]. The scattered light is recorded by an Andor Luca® CCD camera positioned at 90˚ with respect to the laser propagation direction. The camera is equipped with a 14-bit electron-multiplying CCD (EMCCD) sensor. For each measurement, more than 100 consecutive images are accumulated to produce a single averaged image, thereby improving the signal-to-noise ratio. The exposure time is adjusted between 0.001 s and 0.1 s to optimize the dynamic range. **Figure 1** presents the annotated schematic diagram of the SLIPI-1p setup.

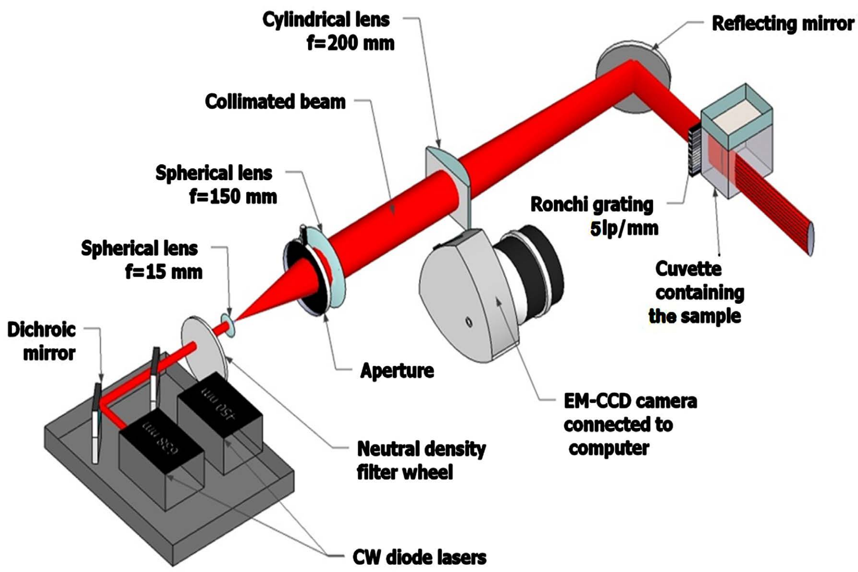

Figure 1. Annotated schematic of the SLIPI-1p experimental setup.

2.2.2. Data Processing and the Extinction Coefficient Extraction

SLIPI-1p is based on the structured illumination that consists in modulating experimentally and projecting the pattern of a grating onto a given sample; and then extracting digitally the areas of the sample that have kept the information from the modulation. It is an approach widely used in imaging in which it allows to split optically as in a super-resolved microscopy [16] [17]. It is the same approach that is used here. The principle of SLIPI-1p data processing is easily explained by considering a 1D signal described by the Equation (1).

$$I(x) = I_s \sin(2\pi\vartheta x + \varphi) + I_{MS} \tag{1}$$

with I_s as the modulated intensity of light that has the ballistic photon information; I_{MS} as the representation of any unwanted and unmodulated intensity contributions detected such as the multiple light scattering or any other surrounding light source; ϑ as the spatial frequency (mm^{-1}) modulation and φ as an unknown random spatial phase. The purpose of data processing is to extract I_s and reject I_{MS}. The approach used by the SLIPI-1p to achieve this is the synchronous detection. The signal $I(x)$ is multiplied by two reference signals R_1 and R_2, digitally created with a relative phase shift of π/2:

$$R_1(x) = \sin(2\pi\vartheta x) \tag{2}$$

$$R_2(x) = \cos(2\pi\vartheta x) \tag{3}$$

Multiplying $I(x)$ by these reference signals gives:

$$I_1(x) = \frac{1}{2} I_S \left(\cos(\varphi) - \cos(4\pi\nu x + \varphi)\right) + I_{MS} \sin(2\pi\nu x) \tag{4}$$

$$I_2(x) = \frac{1}{2} I_S \left(\sin(\varphi) + \sin(4\pi\nu x + \varphi)\right) + I_{MS} \cos(2\pi\nu x) \tag{5}$$

The modulated components 2ϑ and ϑ are suppressed with a low-pass filter in the Fourier domain. $I_1(x)$ and $I_2(x)$ become:

$$\tilde{I}_1(x) = \frac{1}{2} \tilde{I}_S \cos(\varphi) \tag{6}$$

$$\tilde{I}_2(x) = \frac{1}{2} \tilde{I}_S \sin(\varphi) \tag{7}$$

where tilde indicates that frequency filtering is applied. The intensity $\tilde{I}_S$ must be extracted via the Equation (8):

$$\tilde{I}_S = 2\sqrt{\tilde{I}_1^2 + \tilde{I}_2^2} \tag{8}$$

An illustration of the SLIPI-1p process is shown in (**Figure 2**). The example displays the signal from a structured laser light sheet, with effective sections extracted from two different depths, marked as A and B. A decrease in amplitude is observed from column A to column B. The 1D Fourier transforms of curves A and B show a reduction in the strength of the first-order peak (modulation frequency). This frequency is then isolated using frequency filtering (red zone) after applying the synchronous detection algorithm. Finally, the exponential decay is revealed, as indicated in the SLIPI image and the corresponding I_s curve. From a modulated image, the modulation amplitude is extracted using Equation (8). The modulated component, I_s, corresponds to the simple light diffusion that decreases exponentially with distance. By applying an exponential fit to I_s, the extinction coefficient μ_e is directly extracted as indicated by the Beer-Lambert-Bouguer law, which states that, assuming a collimated beam of a single wavelength traverses a uniform medium, the transmittance T is given by:

$$T = \frac{I_t}{I_0} = \exp(-\mu_e L) = \exp(-OD) \tag{9}$$

with T corresponding to the transmittance, which is a measure of light attenuation along the distance *L*. I_0 represents the incident light measured using a "blank" reference cuvette containing only the solvent. Then, I_t is the transmitted light, measured considering the solvent-solute mixture. Finally, μ_e is the extinction coefficient and OD is the optical path length. The extinction coefficient μ_e is the sum of the absorption coefficient μ_a and the scattering coefficient μ_s showed in the Equation (10).

$$\mu_e = \mu_a + \mu_s \tag{10}$$

For each SLIPI image, a rectangular region of interest centered on the laser sheet was selected in order to avoid edge effects and intensity distortions near the image boundaries. The SLIPI signal was averaged over the width of the laser sheet to obtain a one-dimensional intensity profile as a function of the propagation distance.

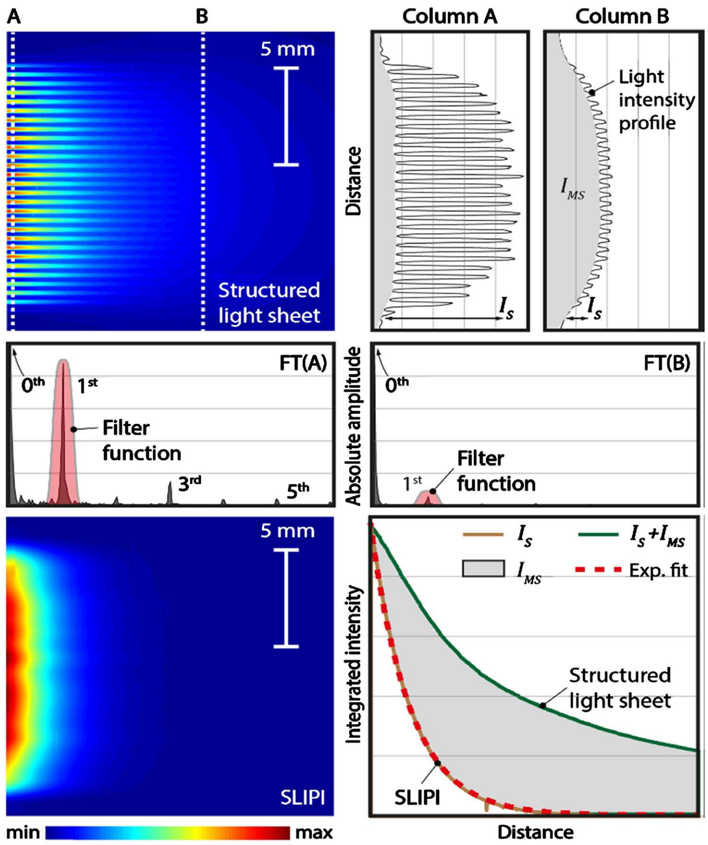

Figure 2. Principle of the SLIPI processing method. The example shows the signal from a sheet of patterned laser light, with cross sections extracted from two different depths, labeled A and B. The decrease in amplitude from column A to column B is observed. The Fourier ID transforms of the curves A and B show the reduction in the 1st order peak strength (modulation frequency). This frequency is then isolated using frequency filtering (red area) after applying the synchronous detection algorithm.

The extinction coefficient was obtained by fitting this profile with the exponential function

$$I_t = I_0 \exp(-\mu_e L) \tag{11}$$

over the entire region where the SLIPI signal remained above the noise floor. Nonlinear least-squares regression was performed using MATLAB. The uncertainty associated with each extinction coefficient corresponds to the standard error of the fitted parameter returned by the regression algorithm. Each reported value represents the mean of three independent measurements.

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

$$OD = \mu_e L \tag{12}$$

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.

2.2.3. Validity of the Beer-Lambert Approach

The application of the Beer-Lambert law in the present work relies on the fact that the SLIPI processing suppresses most multiply scattered photons and isolates the singly scattered component of the detected signal. Under these conditions, the remaining intensity decreases approximately exponentially along the laser-sheet propagation direction. The validity of this approximation assumes a homogeneous medium over the analyzed region, constant optical properties, negligible fluorescence, and a dominant contribution of single scattering after SLIPI processing. Consequently, the extracted extinction coefficient should be interpreted as an effective attenuation coefficient associated with the singly scattered light component.

2.3. 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:

$$CV = \frac{\sigma}{\overline{x}} 100\% \tag{13}$$

where

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

All numerical calculations were carried out using Microsoft Excel and MATLAB. Since the optical density was directly calculated from the extinction coefficient using Equation (12), no independent correlation analysis was performed. The statistical evaluation therefore focused on descriptive parameters, including the mean value, standard deviation, coefficient of variation, minimum, maximum, and relative range, in order to assess the repeatability and the evolution of the optical measurements during the frying process [10].

2.4. Experimental Uncertainty, Repeatability and Error Analysis

To ensure the reliability and robustness of the proposed SLIPI-1p measurements, a detailed evaluation of experimental uncertainty and repeatability was performed. This step is essential in quantitative optical diagnostics, particularly in highly scattering media where measurement fluctuations can be significant.

Each sample was removed from the cuvette and reinserted before each measurement in order to account for positioning variability. Thus, the three repetitions correspond to independent image acquisitions rather than repeated processing of the same image. The extinction coefficient reported for each sample corresponds to the arithmetic mean of these three independent measurements.

Repeatability was quantified using the relative standard deviation (RSD), which ranged from 5% to 10% for all samples. This level of variation is generally considered acceptable for optical measurements performed in turbid and strongly scattering media, where residual fluctuations in sample positioning, scattering structure, and signal extraction may influence the measured values.

The overall stability of the measurements is further confirmed by the relative variation between repeated acquisitions, which consistently remained below 10%. These results demonstrate good experimental reproducibility and further validate the robustness of the SLIPI-1p method for the quantitative optical characterization of highly scattering liquids.

The main sources of experimental uncertainty can be summarized as follows:

- Optical source fluctuations, including small variations in laser intensity over time;
- Detector-related noise, such as camera readout noise, dark current, and photon shot noise;
- Image-processing uncertainties associated with Fourier filtering and synchronous detection;
- Sample positioning and alignment errors, which may slightly modify the effective optical path.

Despite these potential sources of uncertainty, the use of structured illumination significantly reduces the influence of multiple scattering, which remains the dominant source of inaccuracy in conventional transmission-based optical measurements performed in turbid media.

Overall, the repeatability analysis confirms that the SLIPI-1p technique provides stable, reproducible, and reliable measurements suitable for the quantitative optical characterization of highly scattering liquid systems [7] [9].

3. Results

3.1. Evolution of Extinction Coefficient under Thermal Degradation at 450 nm

The extinction coefficients measured for the ten shea butter oil samples range from 0.347 to 0.485 mm^{-1}, revealing a clear increase in optical attenuation with progressive frying cycles. This behavior reflects significant modifications in the optical properties of the oil induced by repeated thermal exposure.

Such an increase is attributed to the continuous formation and accumulation of absorbing and scattering species within the medium. During frying, chemical reactions such as oxidation, polymerization, and thermal decomposition lead to the generation of complex molecular structures and suspended colloidal particles, which progressively enhance light attenuation.

The samples E1 to E10 correspond to successive frying stages under controlled conditions. Specifically, E1 represents the oil after the first two frying cycles, while E10 corresponds to the oil after twenty frying cycles. Since fresh (unused) oil was not analyzed, the present study evaluates the relative evolution of the optical properties from sample E1 onward. Consequently, all reported changes in the extinction coefficient correspond to the relative degradation of the oil with respect to the first sampled degradation stage (E1), rather than to fresh oil.

The data presented in **Table 1** clearly show a monotonic increase in the extinction coefficient from E1 to E10, confirming a progressive enhancement of optical attenuation with frying duration. This trend is consistent with previous studies on edible oil degradation, which report that thermal oxidation promotes the formation of polar compounds, polymerized molecules, and suspended particles, all contributing to increased absorption and scattering [1] [4].

The graphical representation in **Figure 3** further highlights this evolution, showing a quasi-linear to slightly nonlinear increase in the extinction coefficient as a function of oil usage. This behavior suggests a cumulative degradation mechanism in which optically active species progressively accumulate with each frying cycle.

Such a trend indicates that the degradation process is not instantaneous but rather progressive and continuous, governed by the gradual transformation of the chemical composition of the oil under repeated thermal stress. Similar behaviors have been reported in optical monitoring studies of vegetable oils, where extinction coefficients have been shown to correlate strongly with degradation indicators [3].

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

Sample	Extinction Coefficient	Optical Density
E_1	0.347	2.780
E_2	0.393	3.141
E_3	0.419	3.350
E_4	0.451	3.610
E_5	0.452	3.614
E_6	0.462	3.695
E_7	0.462	3.697
E_8	0.463	3.706
E_9	0.483	3.864
E_{10}	0.485	3.883

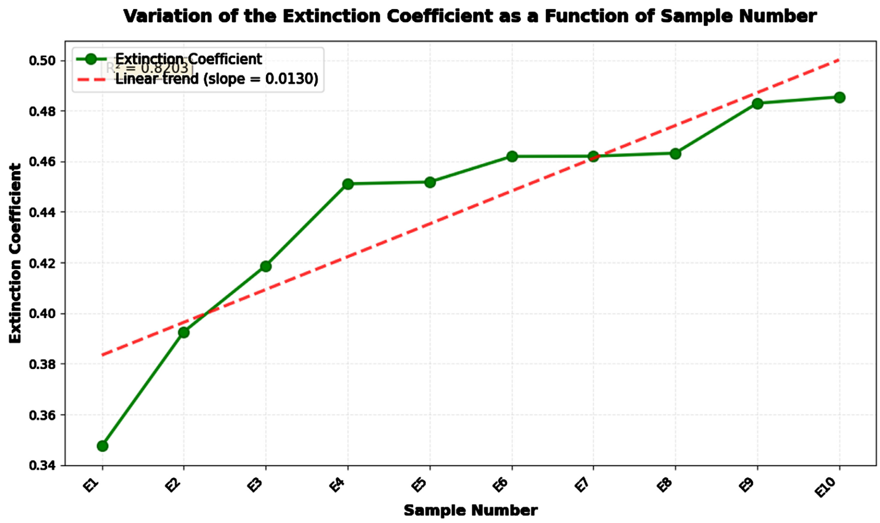

Figure 3. Evolution of the extinction coefficient of shea butter oil samples after frying plantain bananas.

3.2. Trend Analysis of Extinction Coefficient

A monotonic increase in the extinction coefficient is observed from sample E1 to E10, indicating the relative progression of oil degradation throughout the successive frying stages.This behavior reflects continuous physicochemical transformations occurring in the medium, including oxidation reactions, polymerization of triglycerides, and formation of high-molecular-weight compounds.

These processes contribute simultaneously to an increase in both absorption and scattering, which explains the gradual rise of the extinction coefficient measured by the SLIPI-1p method.

The statistical analysis yields a mean extinction coefficient of:
$\mu_e = 0.442 \pm 0.044\ \text{mm}^{-1}$ with a coefficient of variation: CV ≈ 10.03%.

This relatively low dispersion confirms the stability, reliability, and good experimental reproducibility of the SLIPI-1p measurements despite the highly scattering nature of the medium. These results further demonstrate the robustness of the technique for quantitative optical measurements in turbid environments [9].

The observed trend suggests that μ_e can be used as a reliable quantitative indicator of oil degradation level during thermal processing. In particular, the gradual increase in μe across frying stages highlights its sensitivity to cumulative structural changes in the oil.

3.3. Statistical Reliability and Consistency Analysis of Optical Parameters

A comprehensive statistical analysis was performed to quantify the overall behavior and stability of the optical parameters measured by the SLIPI-1p technique during the progressive thermal degradation of shea butter oil. This analysis provides a global view of both the central tendency and the dispersion of the extinction coefficient and optical density across all experimental stages.

The statistical results (**Table 2**) reveal a coherent and physically consistent evolution of the optical properties of the oil throughout successive frying cycles. Both the extinction coefficient and optical density exhibit a clear monotonic increase, confirming the progressive accumulation of absorbing and scattering species induced by thermal degradation processes.

Table 2. Statistical parameters of optical properties of shea butter oil during frying degradation.

Parameter	Mean	Standard Deviation	CV (%)	Min	Max	Relative Range (%)
Extinction Coefficient	0.442	0.044	10.03	0.347	0.485	31.22
Optical Density	3.534	0.355	10.05	2.780	3.883	31.23

The relatively similar coefficients of variation (≈10%) observed for both parameters indicate a homogeneous level of dispersion across all measurements. This level of variability is generally considered acceptable for optical diagnostics in highly scattering media, where intrinsic heterogeneities, particle formation, and local structural fluctuations can introduce unavoidable variations in the measured signal.

Since the optical density was directly calculated from the extinction coefficient using Equation (12), the statistical comparison between both parameters is limited to descriptive statistics rather than correlation analysis. The similar coefficients of variation simply reflect the mathematical relationship linking these two quantities. This consistency further supports the reliability of the SLIPI-1p measurement approach and the robustness of the data processing procedure.

In addition, the relative range (~31%) highlights a significant amplitude of variation in the optical properties across the frying stages. This result confirms a pronounced cumulative degradation effect, despite the moderate dispersion observed in repeated measurements, thereby reinforcing the sensitivity of the optical parameters to progressive thermal aging of the oil.

4. Discussion

The results demonstrate a progressive relative evolution of the optical properties from sample E1 onward, reflecting the cumulative effects of repeated frying cycles. Since fresh oil was not included in the measurements, the observed changes should be interpreted as relative degradation with respect to the first sampled stage. The progressive increase in the extinction coefficient reflects continuous physicochemical modifications of the oil under cumulative thermal stress, confirming that optical attenuation is highly sensitive to degradation processes in complex liquid systems.

From a physicochemical perspective, these changes can be attributed to the combined effects of oxidation, hydrolysis, and polymerization reactions occurring during frying. These processes lead to the formation of oxidized triglycerides, free fatty acids, and high-molecular-weight polymerized compounds. Such species contribute to an increased concentration of chromophoric molecules, which enhances light absorption, particularly in the blue spectral region (450 nm). In parallel, the generation of suspended particles and colloidal aggregates increases the scattering cross-section of the medium, thereby amplifying the overall optical attenuation [1] [4].

The extinction coefficient, which inherently includes both absorption and scattering contributions, therefore increases as a direct consequence of these coupled mechanisms. This behavior is consistent with previous investigations on thermally degraded edible oils, where a progressive increase in optical attenuation has been associated with the accumulation of polar compounds and insoluble degradation products [2] [11].

From a methodological standpoint, the SLIPI-1p approach provides a significant advantage over conventional transmission-based optical techniques. In classical measurements, multiple scattering effects can distort transmitted intensity measurements, potentially leading to an underestimation of the extinction coefficient. In contrast, the structured illumination strategy employed in SLIPI selectively suppresses multiply scattered photons and enhances the contribution of singly scattered light. This improves the fidelity of the reconstructed signal and enables more accurate optical characterization in highly turbid media, as previously demonstrated in complex liquid systems and spray diagnostics [8] [10].

The relatively moderate coefficient of variation (~10%) obtained for both the extinction coefficient and optical density indicates good experimental repeatability and stability of the measurement procedure. Considering the highly heterogeneous nature of thermally degraded oils, such variability remains within an acceptable range for optical diagnostics in dense scattering media. The reproducibility of the results further confirms the robustness of both the experimental setup and the SLIPI-1p signal processing algorithm.

Moreover, the monotonic increase in the extinction coefficient across frying stages suggests a cumulative degradation mechanism. This indicates that optically active species progressively accumulate with repeated thermal exposure, leading to a quasi-irreversible evolution of the optical properties. This interpretation is consistent with kinetic models of oil degradation reported in the literature, which describe a continuous buildup of oxidation products and polymerized compounds during prolonged heating [3].

When compared with other vegetable oils studied under similar thermal conditions [18], shea butter oil exhibits relatively high extinction coefficient values. This behavior can be linked to its specific chemical composition, particularly its fatty acid profile and natural antioxidant content. While these constituents initially enhance oxidative stability, their degradation under repeated heating leads to the formation of strongly absorbing and scattering species, significantly altering the optical response of the medium.

It should also be noted that the present optical measurements were not directly correlated with conventional chemical quality indicators, such as peroxide value or total polar compounds. Therefore, the current study should be regarded primarily as an optical validation of the SLIPI-1p methodology rather than as a complete physicochemical characterization of oil degradation.

Despite this limitation, the present work demonstrates that SLIPI-1p constitutes a powerful, non-destructive, and reliable tool for the optical characterization of highly scattering edible oils. By enabling accurate determination of extinction coefficients in optically dense media, the technique opens promising perspectives for real-time monitoring of oil degradation and for advanced optical diagnostics in both laboratory and industrial food quality control applications.

5. Conclusions

In this work, an experimental approach based on single-phase Structured Laser Illumination Planar Imaging (SLIPI-1p) has been developed and applied for the quantitative determination of the extinction coefficient in highly scattering dense liquids. The proposed method addresses a major limitation of conventional optical techniques, namely the strong influence of multiple light scattering, which significantly affects measurement accuracy in turbid media.

By combining spatially modulated laser sheet illumination with a synchronous detection algorithm, the SLIPI-1p approach enables efficient suppression of multiply scattered light and reliable extraction of the singly scattered signal component. This capability allows accurate estimation of optical attenuation parameters under conditions where classical transmission-based methods become limited or no longer applicable.

The experimental results obtained from samples E1 to E10 demonstrate a clear and reproducible increase in the extinction coefficient, reflecting the relative evolution of the optical properties from the first sampled degradation stage rather than from fresh oil. The good repeatability of the measurements, characterized by a coefficient of variation of approximately 10%, confirms the robustness of both the experimental setup and the data processing procedure.

Beyond the specific application presented in this study, the proposed method offers a versatile and non-destructive tool for optical diagnostics in a wide range of complex media. It can be extended to various systems involving strong scattering effects, including biological fluids, colloidal suspensions, and industrial liquids, where accurate optical characterization remains challenging.

Some limitations of the present work should be noted, including the use of a single wavelength, the absence of direct correlation with standard physicochemical indicators, and the lack of measurements on fresh (unused) oil. Consequently, the reported extinction coefficients describe the relative evolution of optical degradation from the first sampled frying stage (E1) rather than an absolute degradation scale. Future studies should include measurements of fresh oil to establish an absolute degradation baseline, as well as multi-wavelength investigations coupled with complementary analytical techniques to further validate and generalize the proposed approach.

Overall, this study demonstrates that the SLIPI-1p technique constitutes a powerful experimental tool for reliable optical measurements in highly scattering environments, opening new perspectives for real-time, non-invasive monitoring and advanced characterization of optically dense media.

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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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Author Contributions

Anicet Kouabenan Kouakou: Formal analysis, Investigation, Methodology, Resources, Validation, Writing—original draft, Writing—review & editing; **Serge Martial Adepo**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Writing—original draft, Writing—review & editing; **Amara Kamate**: 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.

Conflicts of Interest

The authors declare no conflicts of interest.

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