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INVERSE DETERMINATION OF ABSORPTION AND SCATTERING COEFFICIENTS IN HIGHLY DIFFUSIVE MEDIA USING SLIPI-1P AND KUBELKA–MUNK MODELING

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ABSTRACT

The accurate determination of absorption and scattering coefficients in highly diffusive media remains a challenging task due to the strong coupling between these two parameters. In this study, we propose an original inverse approach for estimating the absorption coefficient (μ_a) and the scattering coefficient (μ_s) from a single measurement of the extinction coefficient (μ_e) obtained using the Structured Laser Illumination Planar Imaging (SLIPI-1p) technique.

The method combines the Beer–Lambert law with the Kubelka–Munk model in order to formulate a nonlinear inverse problem. A multi-thickness transmittance reconstruction strategy is introduced to generate additional constraints from a single experimental measurement. The resulting system is solved using numerical optimization techniques, allowing the simultaneous estimation of μ_a and μ_s without imposing empirical assumptions on their ratio. The proposed approach estimates the absorption and scattering coefficients without prescribing an empirical fixed ratio between them, by fitting the Kubelka–Munk model to transmittance values reconstructed from the experimentally measured extinction coefficient.

The approach was applied to diluted milk solutions at a wavelength of 450 nm, representative of highly diffusive media. The obtained results reveal a strong dominance of scattering over absorption, in agreement with the known optical

behavior of such media. The estimated values are in good agreement with the orders of magnitude reported in the literature, thereby confirming the validity of the proposed method.

Although the method relies on reconstructed transmittance data, it provides a simple and physically consistent framework for extracting optical properties from limited experimental measurements. This work highlights the potential of combining SLIPI-based measurements with inverse modeling techniques for the quantitative characterization of complex scattering media.

Keywords: SLIPI-1p; Kubelka–Munk; Inverse Problem; Optical Properties; Scattering Media; Extinction Coefficient.

1 INTRODUCTION

The characterization of the optical properties of scattering media represents a major challenge in numerous fields such as biomedical imaging, optics of complex media, food science, and industrial processes. In particular, the determination of the absorption coefficient (μ_a) and the scattering coefficient (μ_s) is essential for describing light–matter interactions and for properly interpreting radiative propagation phenomena in such media. However, in highly scattering media, these two parameters are strongly coupled, making their simultaneous estimation particularly difficult [1,2].

The extinction coefficient ($\mu_e = \mu_a + \mu_s$) is generally experimentally accessible through transmission measurements based on the Beer–Lambert law. However, this classical approach becomes insufficient in media where multiple scattering is predominant, since it does not allow the respective contributions of absorption and scattering to be separated [3]. Several methods have been proposed to overcome this limitation, including techniques based on radiative transport, diffuse scattering, and Kubelka–Munk-type approaches, which are widely used to model light propagation in homogeneous scattering media [4,5].

Kubelka–Munk theory provides a simplified analytical framework that relates absorption and scattering coefficients to measurable quantities such as reflectance and transmittance. This approach has been successfully applied in various contexts, particularly for the characterization of scattering materials and the analysis of biological media [6,7]. Nevertheless, the use of this theory generally requires several independent measurements (reflection and transmission, or different thicknesses), which may complicate its experimental implementation.

In this context, advanced imaging techniques such as Structured Laser Illumination Planar Imaging (SLIPI) have attracted increasing interest. The SLIPI method significantly reduces the effects of multiple scattering by isolating the ballistic or quasi-ballistic component of the detected light signal [8,9]. It therefore provides access to more reliable measurements of the extinction coefficient in optically dense media. However, as with conventional methods, the measurement of μ_e alone does not directly allow the separation of μ_a and μ_s.

To overcome this limitation, several inverse approaches have been developed, based either on the solution of nonlinear systems or on the introduction of empirical assumptions regarding the relationship between absorption and scattering. Although these methods can provide useful estimates, they often remain dependent on specific experimental conditions or on parameters adjusted a priori [10].

In this work, we propose an alternative approach for simultaneously estimating the absorption and scattering coefficients from a single measurement of the extinction coefficient obtained using SLIPI-1p. The method relies on the combination of the Beer–Lambert law and the Kubelka–Munk model, together with a transmittance reconstruction strategy for multiple virtual thicknesses. This approach leads to the formulation of a nonlinear inverse problem solved using numerical optimization techniques, without relying on empirical assumptions regarding the μ_a/μ_s ratio [5,6,11].

The originality of this contribution lies in the exploitation of a single experimental measurement enriched by an adapted physical modeling framework, making it possible to overcome the classical indeterminacy of the problem. The approach is applied to diluted milk solutions selected as highly scattering model media, and the obtained results are compared with orders of magnitude reported in the literature in order to evaluate the relevance of the proposed method [7,12].

2 MATERIALS AND METHODS

2.1 Studied samples

The experiments were carried out on diluted milk solutions, selected as highly scattering model media. These media exhibit an optical behavior dominated by multiple scattering, making them particularly suitable for validating methods for extracting optical properties.

The different solutions were prepared by progressive dilution in order to obtain a wide range of extinction coefficients. Measurements were performed at a wavelength of 450 nm.

The obtained solutions are described in Table 1 below [13]. The photograph of the samples is presented in Figure 1[13].

Table 1: Milk sample preparation process

Solutions	Milk dilutions	Concentrations
1	$V1$ = 5 ml of milk + 495 ml of distilled water	C_1
2	V_2 = 67.5 ml of $solution$ 1 + 7.5 ml of distilled water	$C_2 = 0.9 \times C_1$
3	V_3 = 60.0 ml of $solution$ 1 + 15.0 ml of distilled water	$C_3 = 0.8 \times C_1$
4	V_4 = 52.5 ml of $solution$ 1 + 22.5 ml of distilled water	$C_4 = 0.7 \times C_1$
5	V_5 = 45.0 ml of $solution$ 1 + 30.0 ml of distilled water	$C_5 = 0.6 \times C_1$
6	V_6 = 37.5 ml of $solution$ 1 + 37.5 ml of distilled water	$C_6 = 0.5 \times C_1$
7	V_7 = 30.0 ml of $solution$ 1 + 45.0 ml of distilled water	$C_7 = 0.4 \times C_1$
8	V_8 = 22.5 ml of $solution$ 1 + 52.5 ml of distilled water	$C_8 = 0.3 \times C_1$
9	V_9 = 15.0 ml of $solution$ 1 + 60.0 ml of distilled water	$C_9 = 0.2 \times C_1$
10	V_{10} = 7.5 ml of $solution$ 1 + 67.5 ml of distilled water	$C_{10} = 0.1 \times C_1$

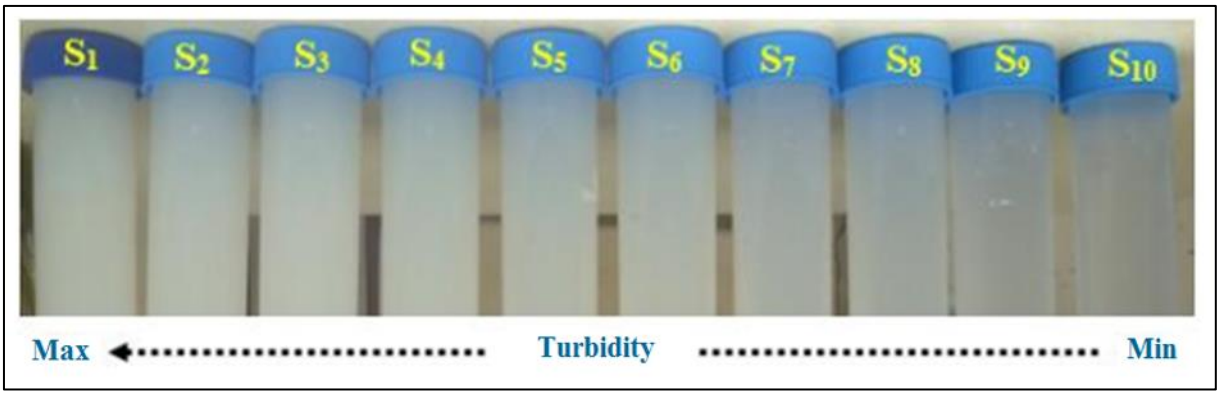


Figure 1: photograph of samples of milk solutions classified in increasing order of turbidity from right to left

2.2 SLIPI-1p Experimental Setup

A continuous-wave (CW) laser beam at 450 nm or 638 nm is used as the illumination source. The intensity of the incident beam is controlled using a neutral density filter wheel in order to optimize the signal-to-noise ratio while avoiding any saturation of the detection system. The beam is then expanded by a factor of 10 using a telescope system consisting of two converging spherical lenses. An aperture is used to select the central part of the beam, corresponding to a region where the spatial intensity profile is sufficiently homogeneous. A converging cylindrical lens with a focal length of 200 mm is then used to generate a laser light sheet in the experimental tank.

In order to spatially modulate this laser sheet, a 2 lp/mm Ronchi grating is directly mounted on the tank. This configuration makes it possible to reduce undesirable near-field diffraction effects, also known as the Talbot effect [14]. Imaging is performed using a camera oriented at 90° with respect to the direction of light propagation, allowing

observation in a perpendicular detection configuration. The camera used is an Andor Luca® CCD camera, equipped with an electron-multiplying system and a 14-bit resolution. The final image is obtained by accumulating more than 100 acquisitions in order to improve the signal-to-noise ratio. The exposure time is adjusted between 0.001 and 0.1 s to optimize the measurement dynamic range. Figure 3 illustrates the schematic diagram of the experimental setup.

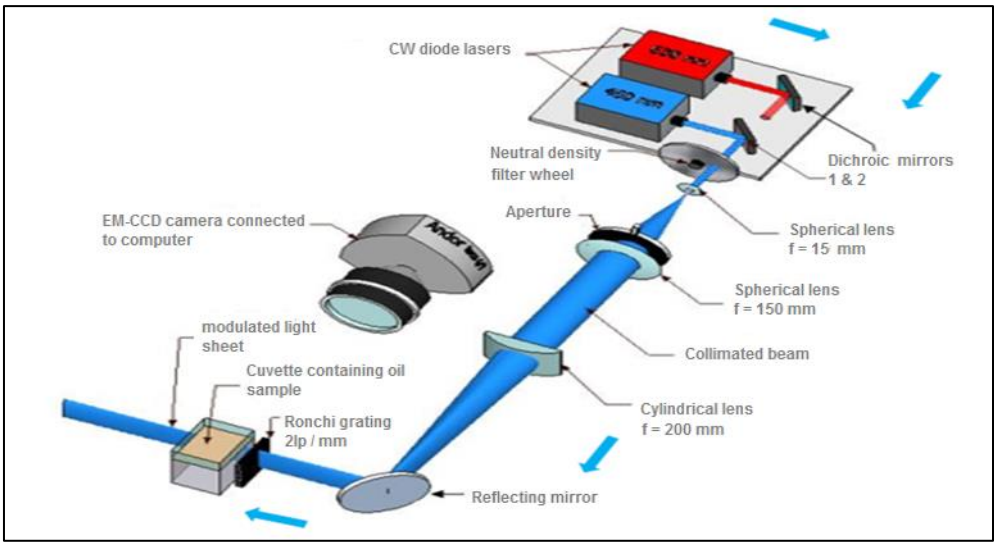


Figure 2: Schematic diagram of the SLIPI-1 experimental setup [13]

2.3 Measurement of the extinction coefficient using SLIPI-1p

The extinction coefficient μ_e was measured using the Structured Laser Illumination Planar Imaging (SLIPI-1p) technique. This method is based on structured illumination, which consists of modulating and experimentally projecting a grating pattern onto a given sample, and then numerically extracting the regions of the sample that have preserved the modulation signature. The data processing principle of SLIPI-1p can be easily explained by considering a 1D signal described by Equation (1) :

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

where $I_s$is the amplitude of the modulated intensity of the ballistic light, corresponding to the structured component of the illumination, and $I_{MS}(x)$ represents the unwanted unmodulated contributions detected, such as multiple light scattering or any other surrounding light source. ν denotes the spatial modulation frequency (expressed in mm^{-1}), corresponding to the number of intensity variation cycles per unit length, and φ is an unknown random spatial phase. The objective of the data processing is to extract I_s and reject $I_{MS}\ (x)$. The approach used in SLIPI-1p to achieve this is synchronous detection.

In the SLIPI-1p framework, the detected signal is considered as the sum of a spatially modulated component and an unmodulated or slowly varying background contribution. The first term, $I_s \, sin(2\pi\nu x + \varphi)$, represents the component carrying the imposed illumination modulation and is associated with the ballistic or quasi-ballistic contribution. The term $I_{MS}\ (x)$ represents contributions that do not preserve the imposed spatial modulation, including multiply scattered light and other slowly varying background components. Over the spatial analysis window, $I_{MS}\ (x)$is assumed to vary on a spatial scale significantly larger than the modulation period $1/\nu$. Consequently, synchronous demodulation followed by low-pass filtering isolates the modulation frequency component while suppressing the unmodulated or slowly varying contribution. This property is the basis for the reduction of multiple-scattering contamination in SLIPI-1p [8,9,13]. Residual multiply scattered contributions that preserve part of the modulation may not be completely rejected and therefore constitute a limitation of the method.

The signal $I(x)$ is multiplied by two reference signals R_1 and R_2, numerically generated with a relative phase shift of $\pi/2$:

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

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

Two distinct expressions of $I(x)$ are then obtained :

$$I_1(x) = \frac{1}{2} I_S(cos(\varphi) - cos(4\pi\vartheta x + \varphi)) + I_{MS}\, sin(2\pi\nu x) \quad (4)$$

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

The modulated components at 2ν and ν are removed using a low-pass filter in the Fourier domain. $I_1(x)$ and $I_2(x)$ then become :

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

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

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

$$\tilde{I}_S = 2\sqrt{\tilde{I}_1^{\,2} + \tilde{I}_2^{\,2}} \quad (8)$$

An illustration of the SLIPI-1p data processing principle is shown in Figure 3. This method effectively reduces the contribution of multiple scattering by isolating the ballistic and quasi-ballistic component of the light signal.

The transmitted intensity through a sample of thickness d is described by the Beer–Lambert law:

$$T_{exp}(\mathrm{d}) = \mathrm{e}^{-\mu_e d} \quad (9)$$

where T_{exp} is the experimental transmittance and μ_e is the measured extinction coefficient. The measurements were performed for a thickness d = 16 mm.

The extinction coefficient μ_e is the sum of the absorption coefficient μ_a and the scattering coefficient μ_s, as given in Equation (10) :

$$\mu_e = \mu_a + \mu_s \quad (10)$$

In this study, the aim is therefore to determine the absorption coefficient μ_a and the scattering coefficient μ_s from SLIPI measurements alone.

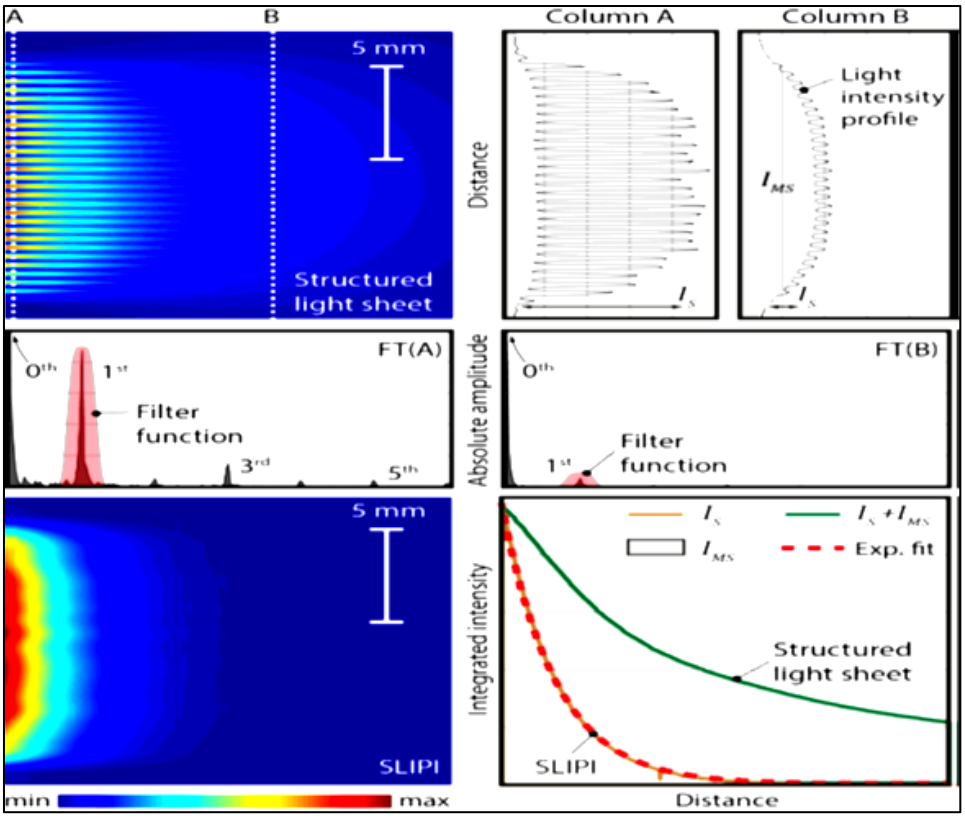


Figure 3: Principle of the SLIPI data processing method [13].

The example shown in Figure 3 illustrates the signal of a structured laser light sheet, with cross-sections extracted at two different depths, labeled A and B. A decrease in amplitude from column A to column B is observed. The one-dimensional (1D) Fourier transforms of curves A and B show a reduction in the peak strength of the first order (modulation frequency). This frequency is then isolated by frequency filtering (red region) after applying the synchronous detection algorithm.

2.4 Modeling using Kubelka–Munk theory

In order to separate the absorption and scattering contributions, the Kubelka–Munk theory was used. Within this framework, the absorption coefficient (μ_a) and the scattering coefficient (μ_s) are related to an auxiliary parameter γ defined by the Kubelka–Munk two-flux model, which constitutes an approximation of radiative transfer in homogeneous scattering media [5,15].

The characteristic attenuation parameter γ is defined according to the classical Kubelka–Munk two-flux formulation as

$$\gamma = \sqrt{\mu_a\,(\mu_a + 2\mu_s)} \tag{11}$$

The first occurrence of μa in this expression is essential and should not be confused with μs. This parameter results directly from the eigenvalue solution of the coupled forward- and backward-flux equations of the Kubelka–Munk model [5,17].

The theoretical transmittance of a homogeneous planar medium of thickness d can be obtained from the classical Kubelka–Munk two-flux equations, which describe the coupled propagation of forward and backward diffuse fluxes in a scattering medium [15,17].

$$\alpha = \frac{\beta(\mu_a + 3\mu_e)}{\cosh(\gamma d) + \frac{\mu_a}{\beta}\sinh(\gamma d)} \tag{12}$$

This formulation has been extensively used for the optical characterization of strongly scattering materials [17].

2.5 Reconstruction of transmittance at virtual thicknesses

Since only one experimental thickness (d_0=16 mm) was measured, no independent experimental transmittance data are available at other thicknesses. To formulate the inverse problem, additional transmittance values are therefore generated mathematically from the experimentally determined extinction coefficient. These values must be regarded as virtual or synthetic thickness data and not as independent experimental measurements.

From the measured transmittance at d_0=16 mm, $T_{exp}(d_0) = \exp(-\mu_e d_0)$,

the transmittance corresponding to an arbitrary virtual thickness d_i is reconstructed according to

$$T_{exp}(d_i) = \left[T_{exp}(d_0)\right]^{d_i/d_0} = \exp(-\mu_e d_i) \tag{13}$$

In the present study, the virtual thicknesses were selected as $d_i \in \{4,8,12,16\}$ mm.

This procedure does not introduce additional experimental information. Rather, it provides a set of mathematically consistent transmittance values corresponding to different optical path lengths, all constrained by the single experimentally measured extinction coefficient. The resulting dataset is subsequently used to determine the pair (μ_a,μ_s) that provides the best agreement with the Kubelka–Munk transmittance model.

The virtual-thickness reconstruction should therefore be understood as a mathematical regularization and parameterization strategy rather than as an experimental multi-thickness measurement.

2.6 Inverse problem formulation

The objective is to simultaneously estimate μ_a and μ_s by fitting the Kubelka–Munk model to the reconstructed data.

The problem is formulated as a nonlinear least-squares optimization problem, similar to classical approaches used in optical parameter inversion in scattering media [2,10]:

$$\min_{\mu_a, \mu_s} \sum_i \left[T_{exp}(d_i) - T_{KM}(d_i, \mu_a, \mu_s)\right]^2 \tag{14}$$

where:

$T_{exp}(d_i) = \mathrm{e}^{-\mu_e d_i}$

T_{KM} is the transmittance derived from the Kubelka–Munk model.

This approach makes it possible to overcome the indeterminacy of the initial problem without introducing any a priori assumption on the relationship between absorption and scattering, which constitutes a major limitation of conventional methods based on empirical approximations [5,2].

$$(\widehat{\mu_a}, \widehat{\mu_s}) = \underset{\mu_a>0, \mu_s>0}{\arg\min} \sum_{i=1}^{N} \left[T_{exp}(d_i) - T_{KM}(d_i, \mu_a, \mu_s)\right]^2 \tag{15}$$

where $T_{exp}(d_i)$ is the reconstructed transmittance at virtual thickness di, whereas $T_{KM}(d_i, \mu_a, \mu_s)$is the transmittance predicted by the Kubelka–Munk model for the same thickness and candidate values of the absorption and scattering coefficients.

2.7 Numerical solution

The numerical solution of the inverse problem is based on a nonlinear optimization procedure that adjusts the parameters μ_a and μ_s in order to best reproduce the experimental data. This minimization is performed using iterative descent-type algorithms, in particular Nelder–Mead or Levenberg–Marquardt, which are well suited for nonlinear problems and are weakly dependent on analytical derivatives [11,18].

For each sample, the coefficients are estimated starting from positive and physically consistent initial values in order to ensure algorithm stability and avoid non-physical solutions. The optimization process is continued until a convergence criterion is reached, defined by the reduction of the quadratic error between experimental and modeled values, as well as by the stability of the solutions from one iteration to the next [18,19].

It is important to emphasize that the reconstructed transmittance values at virtual thicknesses are not statistically independent measurements. They are deterministically derived from the same experimentally measured extinction coefficient. Consequently, the multi-thickness reconstruction does not create new independent experimental information but provides multiple model-evaluation points constrained by the Beer–Lambert attenuation law. The uniqueness and stability of the estimated μ_a and μ_s therefore depend on the sensitivity of the Kubelka–Munk model to these parameters over the selected thickness range. This limitation is taken into account when interpreting the obtained coefficients.

2.8 Fundamental assumptions, validity domain, and originality of the proposed method

The method is based on several essential assumptions, including the homogeneity and isotropy of the studied medium, the validity of the Kubelka–Munk theory, and the dominance of multiple scattering phenomena [5,20]. It also assumes that interface reflection effects are either absent or negligible compared to other optical contributions. These assumptions define the framework of application and the limits of validity of the developed approach.

The proposed approach also assumes that the measured SLIPI-1p signal provides a reliable estimate of the extinction coefficient associated with the ballistic or quasi-ballistic component. The Kubelka–Munk model is subsequently applied to describe the diffuse photon transport using the estimated absorption and scattering coefficients. Interface reflections are assumed to be negligible or sufficiently controlled under the experimental conditions. Finally, the virtual-thickness reconstruction is assumed to remain valid over the selected range of thicknesses. Because the reconstructed transmittances originate from a single measurement, the resulting inverse problem may remain weakly identifiable, and the estimated coefficients should therefore be interpreted as model-dependent effective optical parameters.

Furthermore, the originality of the method lies in its distinct approach compared to classical techniques. Indeed, unlike traditional methods that require multiple independent measurements or rely on empirical assumptions regarding the μ_a/μ_s ratio, the proposed approach is based on an optimization strategy relying on multi-thickness reconstruction. This formulation makes it possible to simultaneously estimate the absorption and scattering coefficients from a single measurement of the extinction coefficient, while rigorously incorporating the physical foundations of the Kubelka–Munk model [5–3].

3 RESULTS AND DISCUSSION

3.1 Determination of optical coefficients

From the experimental measurements of the extinction coefficient (μ_e), the absorption coefficient μ_a and the scattering coefficient μ_s were estimated by considering the strongly scattering nature of the medium ($\mu_s \gg \mu_a$).

The obtained results are presented in the following table :

Table 2: Values of extinction, absorption, and scattering coefficients of milk solutions at 450 nm.

Solution	μ_e	T_{exp}	μ_a	μ_s
1	2.0467	$5.99\ 10^{-15}$	0.1023	1.9444
2	1.8870	$7.69\ 10^{-14}$	0.0944	1.7926
3	1.7677	$5.24\ 10^{-13}$	0.0884	1.6793
4	1.5883	$9.19\ 10^{-12}$	0.0794	1.5089
5	1.3626	$3.39\ 10^{-10}$	0.0681	1.2945
6	1.1676	$7.71\ 10^{-9}$	0.0584	1.1092
7	0.9502	$2.50\ 10^{-7}$	0.0475	0.9027
8	0.7125	$1.12\ 10^{-5}$	0.0356	0.6769
9	0.5032	$3.18\ 10^{-4}$	0.0252	0.4780
10	0.2561	$1.66\ 10^{-2}$	0.0128	0.2433

3.2 Analysis of the results

The figure below shows the evolution of μ_a and μ_s as a function of μ_e.

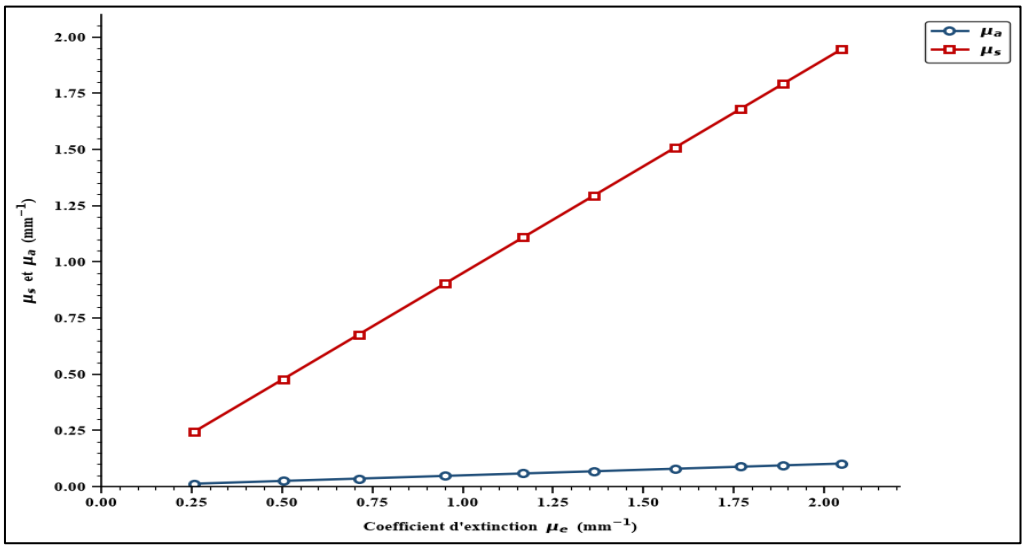


Figure 4: Evolution of the absorption and scattering coefficients as a function of the extinction coefficient.

The results clearly show that the scattering coefficient is significantly higher than the absorption coefficient. This behavior is fully consistent with the optical nature of milk, in which light propagation is mainly dominated by scattering phenomena caused primarily by casein micelles and fat globules. Furthermore, both optical coefficients vary approximately linearly with the extinction coefficient. The scattering coefficient closely follows the variations of μ_e, while the absorption coefficient represents only a small fraction of the total extinction. These observations confirm that the extinction coefficient is essentially dominated by scattering contributions, leading to the approximation $\mu_e \approx \mu_s$.

Moreover, when concentration decreases, both extinction and scattering coefficients decrease significantly, whereas the absorption coefficient shows only a slight reduction. This behavior indicates that scattering strongly depends on the concentration of scattering particles in the medium, while absorption remains weak due to the low presence of absorbing chromophores at 450 nm.

Figures 5 and 6 below shows the transmittance curve of the 10 milk samples.

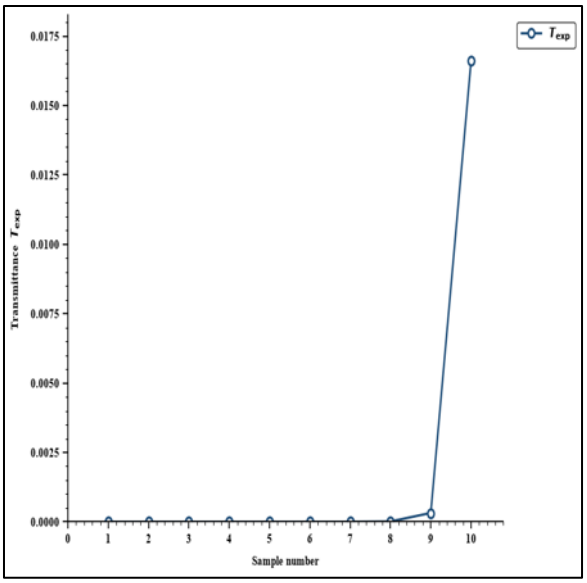


Figure 5: Transmittance of the milk samples

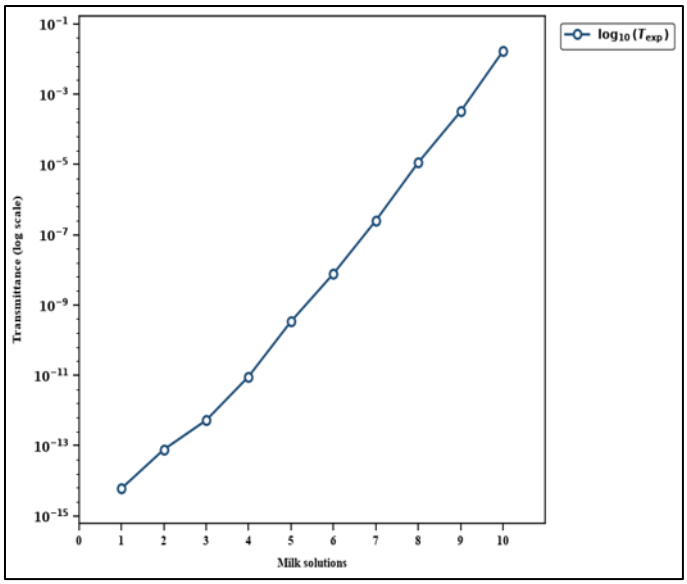


Figure 6: Semi-logarithmic transmittance curve of milk solution

The transmittance curve obtained for the ten milk solutions at an optical thickness of d = 16mm reveals a pronounced attenuation of light propagation within the studied medium. The general behavior of the curve shows that the transmittance remains extremely low for the most concentrated samples and progressively increases as the milk solutions become more diluted. This evolution reflects the strong dependence of optical attenuation on the concentration of scattering particles present in the medium [3,21,22].

For the first solutions, the transmittance values are nearly zero, indicating that only a very small fraction of the incident light is transmitted through the sample. This behavior demonstrates that the medium is highly turbid and strongly scattering. In milk, light scattering is mainly caused by casein micelles and fat globules, which act as efficient scattering centers in the visible spectral range [21,22]. As photons propagate through the medium, they undergo multiple scattering events, leading to a substantial loss of directional light intensity before reaching the detector [2,23].

The exponential decrease in transmitted intensity is fully consistent with the generalized Beer–Lambert law used in this study [24]. The very low transmittance values obtained for large extinction coefficients confirm that the optical attenuation is extremely strong when the concentration of scattering particles is high. Under these conditions, the transport of light no longer follows a simple ballistic regime but rather a multiple diffusive regime, where photons experience numerous interactions inside the medium [2,25]. This phenomenon is characteristic of strongly scattering biological and colloidal media [2,23].

As the dilution increases from one solution to another, the extinction coefficient decreases progressively, resulting in a gradual increase in transmittance. This behavior indicates that the reduction in particle concentration decreases the probability of photon scattering events, allowing a larger portion of light to propagate through the sample.

Another important observation concerns the shape of the curve. The transmittance increase is not linear but exponential, which is physically expected from radiative attenuation laws [24]. Small reductions in the extinction coefficient produce significant increases in transmitted light, especially for the least concentrated samples. This explains the sudden rise observed for the last solutions of the series.

The obtained results also provide strong evidence that scattering dominates absorption in the studied milk samples. If absorption were the dominant mechanism, the attenuation behavior would be primarily governed by molecular absorption effects. However, the observed optical behavior, together with the previously determined values of μ_a and μ_s , confirms that the extinction coefficient is mainly controlled by the scattering contribution, leading to the approximation : $\mu_e \approx \mu_s$.

This conclusion is fully consistent with the known optical properties of milk reported in the literature for visible wavelengths around 450 nm [21,22,26].

Furthermore, the use of a relatively large optical path length (d = 16mm) amplifies the attenuation effects and highlights the sensitivity of the SLIPI-1p technique for investigating highly scattering media. The extremely low transmittance values measured for concentrated samples demonstrate the capability of the proposed method to analyze optically

dense environments where conventional Beer–Lambert approaches often become insufficient because of multiple scattering effects [2,23].

Overall, the transmittance curve confirms the physical consistency of the experimental measurements and supports the validity of the proposed inversion method used to estimate the absorption and scattering coefficients from extinction measurements. The observed trends are in good agreement with the theoretical principles of light transport in turbid media and with previous studies reported in the scientific literature [2,25].

3.3 Physical analysis, bibliographic validation, and scientific contribution of the proposed method

The obtained results show that at 450 nm, milk behaves as a weakly absorbing and strongly scattering medium. This behavior is directly related to its complex colloidal structure, mainly composed of lipid globules and casein micelles, which act as efficient scattering centers. In this spectral regime, light–matter interaction is dominated by multiple scattering, while absorption remains limited due to the low presence of absorbing chromophores in the visible range, particularly around 450 nm [3,2].

This dominance of scattering implies that light transport in the medium cannot be described by a simple ballistic regime, but rather by a multiple diffusive regime in which photons undergo numerous interactions before being detected. This behavior is typical of turbid biological media, where light propagation is strongly influenced by the size, density, and distribution of suspended particles [1]. In this context, the scattering coefficient plays a dominant role in the overall attenuation of the incident beam, which justifies the experimentally observed relationship between μ_e and μ_s.

The values obtained in this study are in good agreement with those reported in the scientific literature. In particular, Arthur C. Eckbreth showed that in scattering media in the visible range, multiple scattering is the dominant mechanism over absorption [12]. Similarly, Emil Kristensson demonstrated, through SLIPI techniques applied to complex media, that the contribution of the scattering coefficient μ_s is largely predominant in optically dense environments [9].

Bibliographic data generally indicate high values of μ_s, typically ranging between 1 and 10 mm^{-1} for strongly scattering media, while the absorption coefficient μ_a remains low, often below 0.1 mm^{-1} [1,7]. In this study, the obtained values lie within the ranges $\mu_s \in [0.24; 1.94]$ mm^{-1} and $\mu_a \in [0.01; 0.10]$ mm^{-1}, confirming satisfactory physical consistency with the orders of magnitude reported in the literature. The observed discrepancies may be attributed to variations in concentration, the specific nature of the milk samples studied, and the experimental measurement conditions.

Another important aspect concerns the relationship between μ_e, μ_s and μ_a. The results show that the extinction coefficient is essentially governed by scattering, leading to the approximation $\mu_e \approx \mu_s$. This approximation is theoretically justified in weakly absorbing and strongly scattering media, where absorption represents a secondary contribution to overall attenuation [2,1]. This observation reinforces the validity of the model used and confirms the relevance of the approach based on the separation of optical contributions.

The proposed method also presents several significant advantages. It relies on a single experimental measurement obtained using the SLIPI-1p technique, which considerably reduces the complexity of the experimental protocol while ensuring a consistent estimation of optical parameters. Unlike classical methods requiring multiple measurements or simplifying assumptions on the μ_a/μ_s ratio, the developed approach enables simultaneous reconstruction of both coefficients within a unified physical framework based on the Kubelka–Munk model [5,10].

This approach is particularly well suited to strongly scattering media, where conventional methods based on the Beer–Lambert law quickly become limited due to multiple scattering effects. However, the validity of the proposed separation relies on the condition $\mu_s \gg \mu_a$, which is a central assumption of the model. Therefore, the method is mainly applicable to scattering media and may lose accuracy in strongly absorbing media, where absorption mechanisms dominate light propagation.

From a scientific standpoint, this approach provides optimized exploitation of SLIPI-1p data by enabling reliable extraction of intrinsic optical properties of scattering media. It also strengthens the link between experimental measurement and theoretical modeling by relying on a coherent formulation of radiative transport phenomena. The obtained results thus demonstrate good consistency with the fundamental principles of light–matter interaction and with trends reported in the literature, confirming the robustness and scientific relevance of the developed method.

4 CONCLUSION

In this work, a method for estimating the optical properties of strongly scattering media was developed based on the Structured Laser Illumination Planar Imaging (SLIPI-1p) technique. This approach relies on the use of the experimentally measured extinction coefficient μ_e to separately access the absorption and scattering coefficients.

To overcome the indeterminacy inherent in the relation $\mu_e = \mu_a + \mu_s$ a strategy combining the Beer–Lambert law and the Kubelka–Munk model was implemented. A synthetic reconstruction of the transmittance at several virtual thicknesses was used to formulate the nonlinear inverse problem. These reconstructed values do not represent additional independent measurements but provide a mathematically consistent set of model-evaluation points derived from the experimentally measured extinction coefficient. The resulting estimates of μ_a and μ_s should therefore be interpreted within the validity and identifiability limits of the combined SLIPI-1p, Beer–Lambert, and Kubelka–Munk framework. This approach provides an interesting alternative to classical methods requiring multiple independent measurements or strong empirical assumptions.

The application of the method to diluted milk solutions yielded optical coefficients consistent with the physics of strongly scattering media. The results show a clear dominance of the scattering coefficient over the absorption coefficient, in agreement with the known optical properties of milk in the visible range. The obtained orders of magnitude are also in good agreement with those reported in the literature, which constitutes an initial validation of the relevance of the approach.

However, it should be noted that reconstructing transmittance from a single measurement of the extinction coefficient introduces a functional dependency that may limit the uniqueness of the inverse problem solution. Thus, although the proposed method provides physically consistent estimates of μ_a and μ_s, its application is particularly suitable for media in which scattering strongly dominates absorption.

Possible improvements include the integration of additional experimental measurements, such as diffuse reflectance or acquisitions at different real thicknesses, in order to enhance the robustness of the inversion. Furthermore, extending the method to more complete radiative transfer models, as well as experimental validation on complex biological media, would further strengthen its applicability domain.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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The authors declare no conflicts of interest.

Author Contributions

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

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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