Study on Optical Properties of Milk based on Light Propagation Theory

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Abstract. The light propagation in milk based on experimental and theoretical analysis is reviewed. The review is done on light propagation theory which consists of light absorbance, reflection, and scattering. The study covers on types of milk, milk quality and modelling methods based on Mie scattering and Monte Carlo algorithm. The experiments consist of spectrometry methods where visible (VIS) and near infra-red (NIR) are used. Many spectrometry experiments and theoretical modelling are discussed to observe and analyse optical properties of milk.

1. Introduction
The dairy industry is one of the important industries among food and beverages industries. People around the world consume milk and dairy products to sustain a healthy and nutritious diet as part of their daily life. It is crucial to monitor and control milk production quality and process handling to ensure the quality of milk is comparable to other nutritious food consumptions.

2. Light Propagation
Light propagation is a phenomenon that occurs whenever the light transmits its energy from one point to another point [1]. This phenomenon leads to the occurrence of light absorption, transmission, and reflectance. The absorption of light is defined as the process of particles absorbing their light and converting it into energy, which is most likely turned into heat. On the contrary, the transmission of light is the ability of light to pass through any particles or object without being absorbed or scattered [2].

Meanwhile, a reflection of light occurs whenever light bounces back after hitting on an object [3]. It results in changes of the reflected angle depending on types of objects that had been hit. The smooth and shiny surface helps the smoother and sharper reflection angle of the light, while the rougher and denser surface produces an uneven reflection angle, causing loss of energy [3].

Research on light propagation escalates in many applications. Light propagation theory can be used to analyze optical properties of milk. Our previous studies applied light propagation theory to investigate milk quality through the fat composition [4] and different condition of milk [5].

Light scattering is a phenomenon that occurs whenever the light hits a small object (particle or molecule), resulting in a change of direction. The scattering process is initiated as the photon is absorbed
by the inhomogeneous medium, redirected away from the incident direction. The scattered light angular distribution is high due to the scattering regime and anisotropy factor \( g \) of the medium [6]. The scattered energy might differ or similar to its energy propagation. It is classified into elastic and inelastic scattering, differentiated into two different regimes: the scatterers’ size and light wavelength. Rayleigh’s scattering is an example of elastic scattering, happens when the particle size is smaller than the wavelength of light. The light is distributed consistently in all directions, and the two scatterings depend on the wavelength. Mie scattering is highly non-uniform in angular distribution but is non-wavelength-dependent, where its scattering pattern focuses on the forward direction. Secondary peaks are observed based on angular distribution due to the scattered waves interference [7]. Mie theory is used to investigate the milk quality as the optical properties of milk based on backscattering intensity can be used to study fat and protein concentrations [8].

The efficiency of extinction, \( Q_{ext} \) and scattering, \( Q_{sca} \) can be identified in forward-scattering theorem and in the integration of the power scatters in all directions. The absorption efficiency, \( Q_{abs} \) can be identified through energy conservation [9]. Meanwhile, the backscattering efficiency, \( Q_{b} \) is applicable to monostatic radar [10]. Equations (1 - 4) for absorption, scattering and backscattering efficiency are shown as:

\[
Q_{ext} = \frac{2}{x^2} \sum_{n=1}^{\infty} (2n + 1)Re(a_n^2 + b_n^2) \\
Q_{sca} = \frac{2}{x^2} \sum_{n=1}^{\infty} (2n + 1)(|a_n|^2 + |b_n|^2) \\
Q_{ext} = Q_{sca} + Q_{abs} \\
Q_{b} = \frac{1}{x^2} \sum_{n=1}^{\infty} (2n + 1)(-1)^n(a_n - b_n)^2
\]

Where

\( x \) = parameter size

\( n \) = Spherical Bessel function order \( n \) (\( n = 1, 2, ... \))

3. Milk Quality

Milk can contribute to a healthy diet as it contains nutritional elements such as calcium, phosphorous, and vitamin D. Infants to the elderly people worldwide consume milk as part of their daily diet as milk is the best calcium source. Consuming milk is highly encouraged to build strong bones, teeth, muscles, and joints. The lack of calcium in our diet may lead to diseases such as osteoporosis, muscle cramps, and dental problems. Besides that, human body does not produce calcium. Therefore, a good calcium balance should be maintained based on the recommended daily intake to prevent fragility fractures [11].

Milk can be processed and modified to produce more nutritious and scrumptious products to meet consumers, markets and worldwide demand. Some people cannot consume milk in its original form as they suffer from lactose intolerance. Therefore, milk is processed to meet everyone needs in terms of extending its storage life, enhancing the taste and maximising the nutrition of the milk. The processed milk can be found in various forms and taste such as cheese, yoghurt, flavoured milk, formula milk, and ice cream.

Throughout the years, many research have been done to study on milk. In 2019, Gowri and team [12] had developed a hand-held, susceptible fibre optic milk fat sensor using U-bent plastic optical fibre (POF) probes based on the refractive index (RI) of milk. Then, a fluorescence-based technique that is fast, sensitive, and effortless, in order to study the time-based milk degradation at room temperature was
developed by Choudhary and team [13]. Besides that, there was a research to create a forecast model using (Mid-Infrared) MIR spectroscopy the study on milk. The milk samples were collected individually and examined by inductively coupled plasma optical emanation spectrometry [14].

3.1. Types of Milk
Various types of milk are consumed globally. With the evolution of technology, milk can be classified into animal-based and plant-based milk. Animal-based milk is derived from mammals’ consumable milk glands, while plant-based milk is pasteurised from plant sources such as almond, oat, and soy.

Milk has initially been secreted from mammals such as cows, sheep, and goats to be consumed for the past 10000 years [15]. The luxurious taste and nutritional elements in milk are favoured and cherished by millions of consumers worldwide. This situation led to the inspiration of producing the alternative milk that suits vegan consumers and the people who suffer from allergy from mammals’ milk, such as lactose intolerance [15]. Plant-based milk is vegan-friendly as it does not contain carbohydrates and cholesterol in the mammal’s milk [16]. The milk gains popularity among consumers as it has a creamy texture and luxurious taste, more environmentally friendly and less prone to having allergies.

Besides that, plant-based milk can be altered to match the taste, texture, and the same nutrients as animal-based milk. Despite being the alternative to healthier and eco-friendly milk choice, plant-based milk is still human-made. Milk such as almond milk, oat milk, and soy milk are just almond, oat, and soy processed with water, minerals, and vitamins. The largest downside of plant-based milk is to catch up with cow’s milk flavour, texture, and taste, lots of sugar and additives are added throughout the process [17]. On the other hand, plant-based milk is much more expensive than animal-based milk as producing plant-based milk is made from scratch and requires much more cost. Oat milk price in the market is around twice to thrice times the cow’s milk, causing people to reject plant-based milk as part of their daily diet.

3.2. Milk Fermentation
Milk fermentation occurs when the milk undergoes the conversion of carbohydrates to alcohols (lactose to lactic acid), carbon dioxide or organic acids using yeasts, bacteria, or all of these combinations, which is under anaerobic conditions [18]. Bacteria in milk gains energy from lactose, producing more bacteria, turning lactose into lactic acid [19] making milk become curdle and tastes sour. It indicates that the milk cannot be consumed anymore.

During the fermentation process, the milk turns into a semi-solid medium like yoghurt texture. If the milk state turns into such a yoghurt texture, the milk particles will be aggregated during the coagulation [20]. Lactic acid is produced when the milk thickens, and the bacteria causes the milk to decay, experiencing a decrease in pH level [21]. Salmonella, E. coli, and Listeria are examples of diseases caused by consuming spoiled milk [22]. Our previous research on fermented milk [5] had been done using the spectroscopy method to compare the quality of milk after being kept at the room temperature for several days.

4. Spectrometry
Spectrometry is used to measure spectral power distribution of electromagnetic radiation and the interaction between light and matter [23]. Many types of spectrometers vary in terms of the specialisation and physical characteristics. Mass spectrometers, optical spectrometers, electron spectrometers, and magnetic spectrometers are among spectrometers that are invented to measure the wavelength and frequency of light going through samples. Many types of spectrometers, with many possible variations and modifications are specialized in different applications. Spectrometry techniques were used in previous experiments to detect light properties such as absorption, transmission, reflectance, and fluorescence at any desired wavelength, frequency, and energy. The spectrometers are differentiated based on the ability to capture the light by respective wavelength. During the interaction
between light and a sample, the incident light can be absorbed by, reflected off, or transmitted through the sample. Thus, characteristics of the sample can be then investigated through light intensity obtained from the spectroscopy experiments. Besides, a spectrometer can be used to measure particle composition and distribution size for a sample [24].

Previous work [25] has analysed fat and protein concentrations of milk through backscattering and spectroscopy. Studying of milk characteristics using MicroNIR1700 and MicroNIR2200 spectrometers and measuring composition of raw milk using online milk sensor had been performed by Russell [26]. Meanwhile, Aljaafreh [27] had conducted the experiments of milk properties using (Near-Infrared) NIR spectroscopy to investigate the end of the milk fermentation via the transformation of sugar to lactic acid. On the other hand, Malacarne and team [28] had used mid-infrared spectroscopy (MIRS) to predict detailed mineral composition of bovine milk. Meanwhile, we studied the quality of milk which were fermented in the room temperature using VIS and NIR spectrometers [4] [5]. Figure 1 shows the experimental results from our previous spectrometry experiments conducted through various types and condition of milk.

![Figure 1](image-url)

**Figure 1:** (a) Results of spectrometry experiments conducted in [4] for skimmed milk and full milk and (b) Results of spectrometry experiments conducted in [5] for newly opened milk and fermented milk.
Based on our previous spectrometry experiments, the VIS and NIR spectrometers can be used to observe and investigate the properties of milk.

5. Theoretical Analysis
In the theoretical analysis, the modelling techniques are used to analyse the light propagation in milk. Many modelling techniques can be used to investigate the light propagation, such as Monte Carlo (MC) Simulation, Whittle–Matérn (WM) Correlation Function, Finite Element Modeling (FEM), and Finite Difference Transport (FDT).

5.1. Monte Carlo
Monte Carlo can be defined as randomness, like gambling randomness. Thus, monte carlo simulations are defined as the simulations that occur randomly and used to estimate a random or uncertain possible outcomes for an event. [29]. Monte carlo simulation can be used in many different situations to estimate the outcome with a high uncertainty level in the results. The examples of monte carlo application are electron transport, risk and uncertainties in managing projects, and sensitivity analysis.

Thus, monte carlo simulation was chosen to model light propagation in milk because it can estimate the outcome for the random media. In monte carlo technique, four main steps were used: photon launching, photon absorption, photon scattering and finally, photon detection with continuous propagation. Besides, monte carlo can track the movement of photons inside the turbid medium which experience absorption, scattering and power loss [4]. In our previous study [4] we had conducted a numerical modeling based on monte carlo. The modeling results are shown in Figure 2 which show that full milk has a larger photon count compared to skimmed milk.

![Figure 2](image-url)

**Figure 2:** (a) Forward photon count of skimmed milk (b) Photon loss with various internal coefficients measured in skimmed milk (c) Photon count for skimmed milk and full milk (d) Photon loss for skimmed milk and full milk [4]
Figure 2 shows that the forward photon count in full milk is higher than skimmed milk whereas the photon loss in skimmed milk is lower than in full milk. It is because skimmed milk has less fat globules than full milk. The large fat molecules in full milk absorb and scatter more light over skimmed milk.

5.2. Mie Scattering
Scattering can be divided into elastic and inelastic scattering [30]. Elastic scattering occurs when the direction of light propagation is modified, and the photon energy is conserved. In contrast, inelastic scattering changes the direction of light and the photon energy [30]. Elastic scattering can be described using rayleigh, mie, and geometrics optics modelling. These three types of modelling depend on the size of nanoparticles. Rayleigh scattering model is used for elastic light scattering when the particle diameter is much smaller than the wavelength of the scattered light. Mie scattering model is used to analyse the particles for spherical nanoparticles with the size being almost the same as the light wavelength whereas geometrics optics study the particles with a much larger radius than the light wavelength. Mie Scattering theory is used to investigate the absorption coefficient, scattering coefficient, and scattering angle of the milk samples [31] as it is solely dependent upon the particle size and the wavelength of light. In our previous study [5], we modeled light propagation in milk, water and air based on mie scattering theory. The modeling results in Figure 3 compute the efficiency of scattering, absorption, extinction and backscattering.

![Figure 3](image_url)

**Figure 3:** Modeling results for efficiencies based on Mie Theory for (a) milk, (b) water and (c) air [5]

6. Summary
In conclusion, we have reviewed previous studies on optical properties of milk based on light propagation. Quality of milk can be investigated through light propagation in milk by using experimental and theoretical approach. The experimental approach consists of spectroscopy and laser experiments whereas the theoretical studies involve monte carlo and scattering probability theory. The difference
mineral contents in milk samples can contribute to the difference absorbance, transmission, and reflectance spectra. Thus, the quality of milk can be properly studied to prevent milk adulteration.

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