CHAPTER 5

ANALYSIS OF MILK FROM DIFFERENT SOURCES BASED ON LIGHT PROPAGATION AND RANDOM LASER PROPERTIES

This chapter analyses the light propagation in various types of milk based on spectrometry and theoretical analysis. The absorbance and fluorescence of light for each milk samples were analysed and compared. Meanwhile, a random laser based on propagation of light in different types of milk was modeled using light propagation theory. The results gained from this research can be used as a reference to develop a random laser based on milk to compare the amount of fat content in various milk in the market.

This chapter is used to achieve the third objective; to model random laser based on light propagation in various types of milk.

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5.1 Introduction

Milk is a valuable contributor to a healthy diet as it contains nutritional components such as fats, proteins, carbohydrates, calcium, phosphorous and vitamins. This chapter aims to differentiate milk from animal, plant and human sources based on light propagation and random laser properties. Experimental, statistical, and theoretical analysis were used. Light propagation in different types of milk such as almond milk, oat milk, soy milk, fresh milk, goat milk and human breast milk was measured using spectrometry method. Near IR and visible light transmission through the diluted milk samples were compared. Soy milk and fresh milk have the highest absorbance and fluorescence of light, respectively due to high content of fat, protein, and carbohydrate. Principal component analysis was used to determine the accuracy of the experimental results. The research method is comprehensive where it covers light propagation from 350nm to 1650nm of wavelength range and non-intrusive where it does not affect the sample. Meanwhile, analysis on milk was also done based on random laser properties such as multiple emission peaks and lasing threshold. Higher fat content in milk produces lower random lasing threshold. Thus, the results show that milk from animal, plant and human can be analysed using light absorption, fluorescence, and random lasers. The research method might be useful for future study on milk contaminants that change the properties of milk.

5.1.1 Theoretical Analysis

The theoretical analysis for this study was done based on light propagation theory. The modeling of random laser was designed to investigate on lasing threshold reduction and linewidth narrowing through various particle densities, dye concentration and pump energies. The modeling was done for almond milk, fresh milk, oat milk and soy milk by calculating milk fat content for each milk. The modeling technique was completed based on light scattering theory using various steps below.

Step 1: Setting up the modeling parameters

The initial pump wavelength was set at 532 nm. The scatterer density, n_s of each milk was calculated through the weight of fat globules in each milk as shown in Equation (5.1) and (5.2).

$$Volume, V = \frac{4}{3}\pi r^3 \tag{5.1}$$

$$Scatterer\ density, n_s = \frac{mass}{volume} \tag{5.2}$$

$$Scattering\ cross\ section = \pi r^2 \tag{5.3}$$

$$Scattering\ mean\ free\ path = \frac{1}{n_s \times Scattering\ cross\ section} \tag{5.4}$$

where diameter, D = 930 nm (Abegaõ et al., 2016).

The scatterer density was varied according to the fat globules presence in each type of milk and the concentration of dye was tested for each milk for 0.1,0.01 and 0.001 M by increasing the pump intensities from 10mJ to 100mJ. The scattering cross section was determined based on (Abegaõ et al., 2016) as in Equation (5.5) and (5.6).

$$Scattering\ Cross\ Section, \sigma_s = \pi r^2 \quad (5.5)$$

$$radius, r = \frac{Diameter\ (D)}{2} \quad (5.6)$$

Step 2: Inserting reference spectra

The reference spectrum (fluorescence of Rhodamine 6G) was inserted into the system.

Step 3: Photon loop

The photon loop starts by determining the direction of travel which is picked randomly from a uniform distribution over 4π steradians. The photons will travel at distance *l* before being scattered. The distance *l* was calculated based on Equation (5.7) (Wood et al., 2001).

$$l = -l_s ln \sum \quad (5.7)$$

where, $\sum$ is a uniform variate $\in (0,1)$.

The scattering mean free path, defined as the average distance the light scatters in the medium between two scattering events was calculated based on Equation (5.8) (Luan et al., 2015).

$$l_s = 1/n_s \sigma_s \quad (5.8)$$

The n_s represents scatterer density whereas σ_s is the scattering cross section of the particles.

Step 4: Designing multiple light scattering technique

The scattering for the simulation is assumed in isotropic condition as in Equation (5.9) with the azimuthal angles ∅ are uniformly distributed over the range of 0 to 2π radians in Equation (5.10).

$$Isotropic\ scattering\ = 1 - 2 \times rand \quad (5.9)$$

$$Azimuthal\ Angle, \emptyset = 2\pi \times rand \quad (5.10)$$

The scattering of light was detected and calculated by Henyey-Greenstein scattering function as in Equation (5.11) (Binzoni et al., 2006)(Hornbeck & Alim, 2019).

$$P(\theta) = \frac{1 - g^2}{(1 + g^2 - 2gcos\theta)^{3/2}} \quad (5.11)$$

where $g =< cos\theta >$, the mean cosine of scattering angle.

Step 5: Light amplification within photon loop

The photon launched was amplified when the dye was excited by the pump source. The gain value was obtained from Equation (5.12) and (5.13), assuming all dye molecules were excited.

$$Stimulated\ emission\ cross\ section, Cemi\ = E(I, 2) \times 57^{-9}\pi \quad (5.12)$$

$$Gain = \exp\ (\mathrm{Cemi} \times \mathrm{Ndye} \times \mathrm{L}) \quad (5.13)$$

where, N_{dye} is the concentration of the dye whereas L is the path length.

Step 6: Intensity detection

The amplified photon from the scattering loop was detected and calculated for each type of milk.

5.1.2 Flow Chart of Theoretical Analysis

The figure 5.1 shows the flow chart of the theoretical analysis.

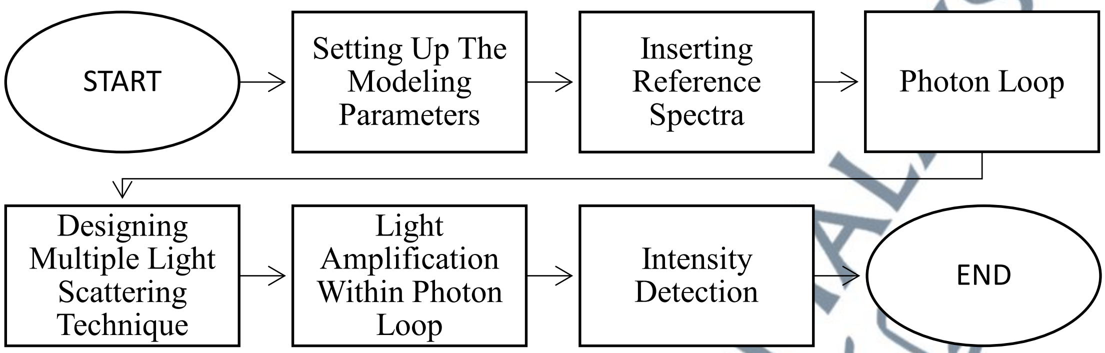

Figure 5.1: The Flow Chart of Theoretical Analysis.

5.2 Methodology

The study was done based on two parts, spectrometry experiments and theoretical analysis. The spectrometry experiments were conducted using VIS-NIR spectrometer and NIR spectrometer where the results of the experiment were shown in Ocean View Software and analysed using multivariate analysis. For the theoretical part, random lasing emission for various milk samples was modeled based on light propagation theory using MATLAB software.

5.2.1 Flow Chart of Experimental Analysis

Figure 5.1 shows the flowchart of experimental analysis in which study on various types of milk was firstly conducted before determining the samples of milk to be used for the experiments. Seven types of milk selected for the spectrometry experiments were then carefully prepared and diluted to prevent spectrometer saturation as discussed in Chapter 4 in Section 4.3.2.3 of sample preparations. Then, the experiment was later performed using Ocean Optic Visible-Near-Infrared (VIS-NIR) and Near-Infrared (NIR) spectrometer.

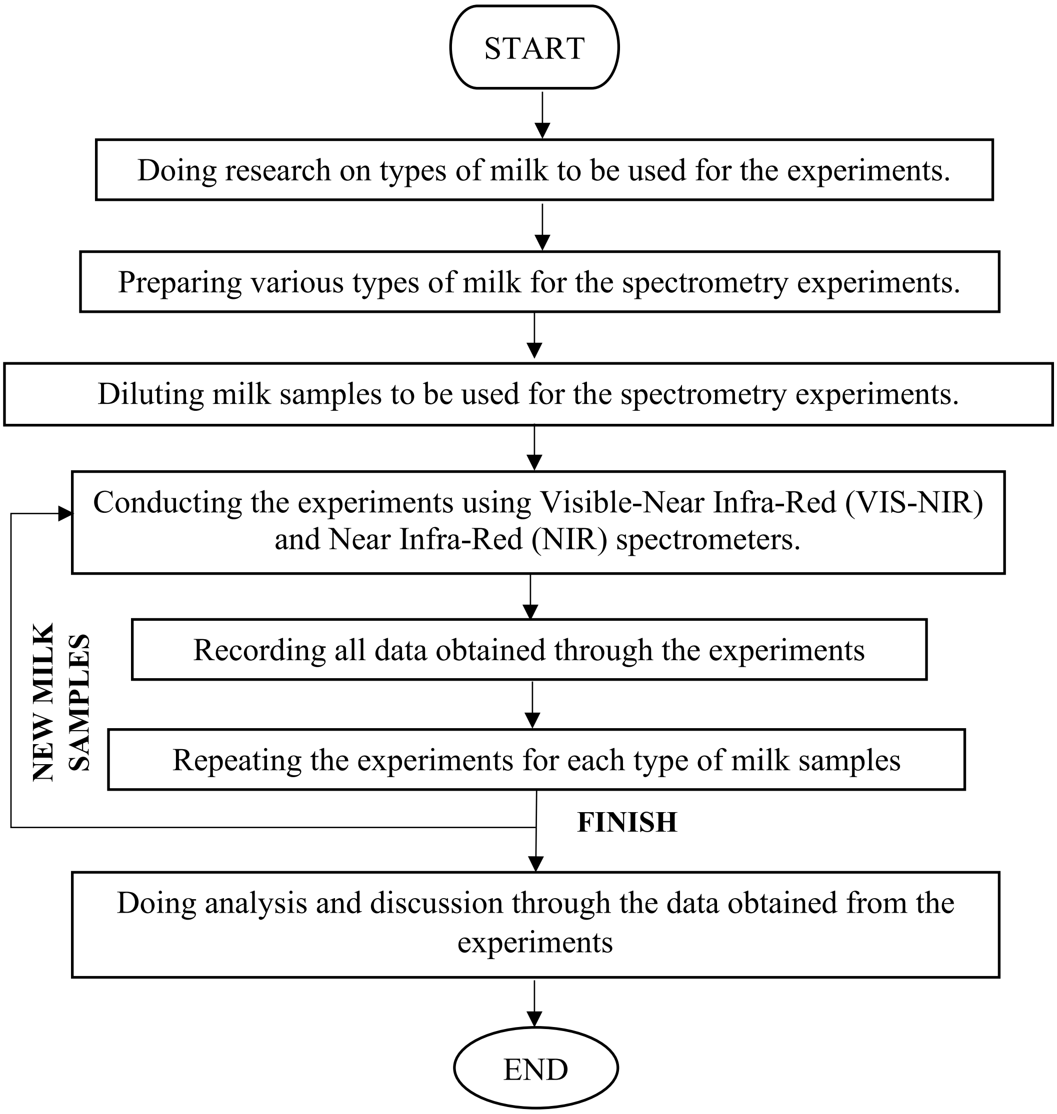

Figure 5.2: The Flowchart Designed For Experimental Analysis.

5.2.2 Flow chart of Modeling Approach

The modeling of random laser was conducted based on light propagation theory and repeated for almond milk, fresh milk, oat milk and soy milk which have different amount of fat contents. Figure 5.2 shows the flowchart designed for the modeling approach.

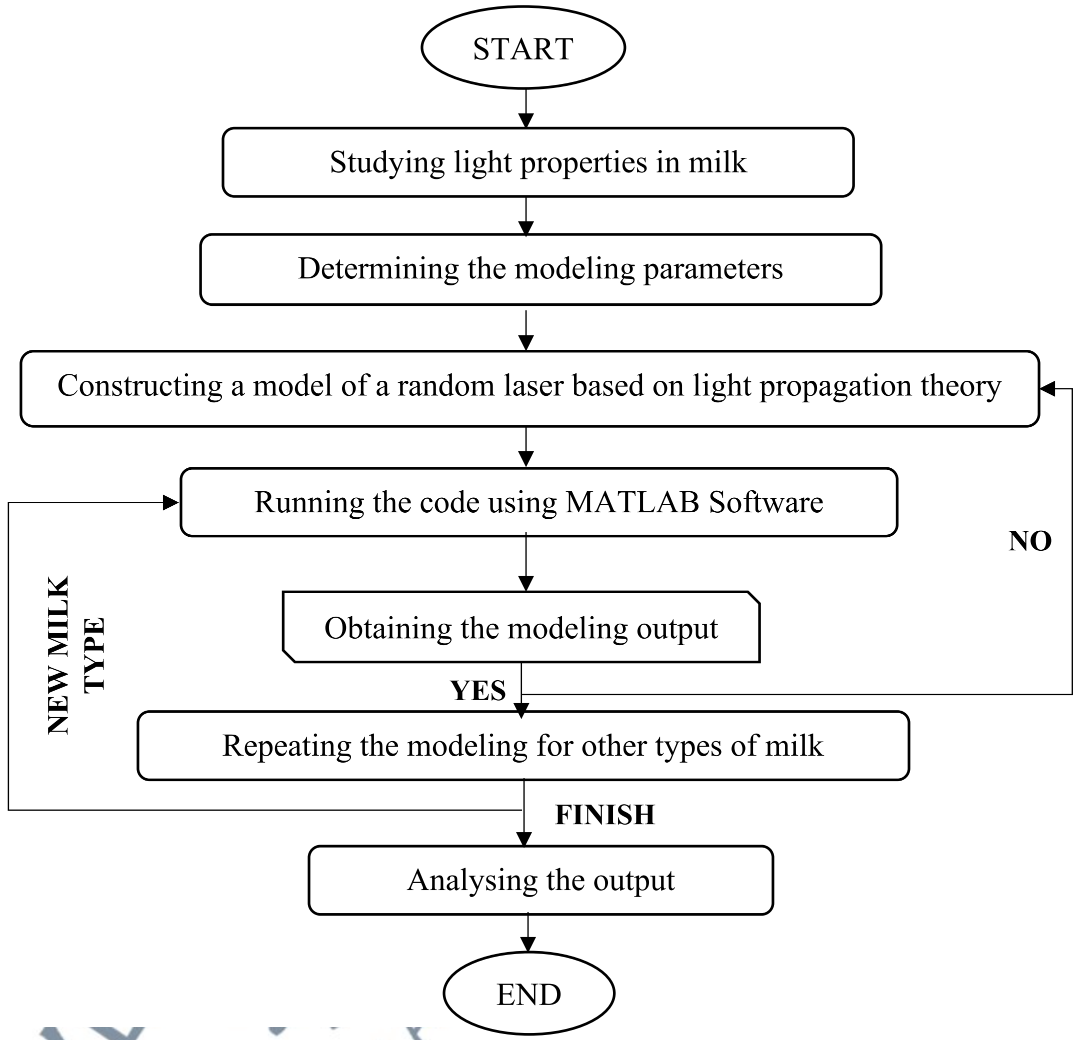

Figure 5.3: The Flowchart Designed For Modeling Approach.

5.2.3 Experimental Approach

The investigation of light propagation in milk was conducted using NIR and VIS-NIR spectrometers to observe the absorbance and fluorescence of light through the respective wavelength. The techniques of spectrometry experiment involve:

A. Preparing the samples for each type of milk accordingly.
B. Assembling the experimental set up.
C. Running the test of absorbance and fluorescence for each type of milk and was repeated for both types of spectrometers.
D. Experiments were done in the lab in normal room temperature.

The spectrometry experiments were done using various types of milk to study the characteristics of light propagation in milk based on their contents. The amount of protein, carbohydrates and fat in milk are factors which influence the absorbance and fluorescence of light in milk.

5.2.3.1. Milk Samples

The study of light propagation in milk was investigated using animal-based and plant-based milk. Seven types of milk were used in the spectrometry experiments such as:

I. Almond Milk
II. Fresh Milk
III. Oat Milk
IV. Soy Milk
V. Goat Milk
VI. Breast Milk (Sample 1)
VII. Breast Milk (Sample 2)

The almond milk, fresh milk, oat milk and soy milk used in the experiments were obtained from the same production brand, Farm Fresh. Meanwhile, the goat milk, breast milk sample 1 and breast milk sample 2 were obtained from the source in which the milk was pure without any alteration and modification. The types of milk which were used in the spectrometry experiments are shown in figure 5.3 and the characteristics of each milk are explained in table 5.1 based on naked eyes.

Figure 5.4: Types Of Milk Samples Used For The Spectrometry Experiments Kept In Capsules.

Table 5.1: The Characteristics Of Milk Samples Used In The Spectrometry Experiments Evaluated By Naked Eyes.

Name of the Milk	Characteristics	Picture
Almond Milk	The milk is dark beige in colour.	
Fresh Milk	The milk is white in colour.	
Oat Milk	The colour of the milk is slightly brownish.	
Soy Milk	The milk is slightly yellowish in colour.	
Breast Milk (Sample 1)	The colour of the milk is light white.	

Breast Milk (Sample 2)	The sample is in light white colour. The milk shows less dense and more transparent compared to other samples.	
Goat Milk	The milk is white in colour.	

The nutrition facts of almond milk, fresh milk, oat milk and soy milk are easily retrieved as they are provided on the packaging. Figure 5.4 shows the milk used for the experiments while the nutrition facts of each milk are tabulated in table 5.2 until table 5.5.

Figure 5.5: From Left: Almond Milk, Fresh Milk, Soy Milk And Oat Milk (Farm Fresh) Are Used In Spectrometry Experiments.

Table 5.2: The Nutrition Facts Of Almond Milk Per 200ml (Price: RM 3.70)

Average Composition	Per Serving 200ml
Energy	106 Kcal
Protein	2.6g
Fat	6.2g
Calcium	261.2mg
Carbohydrate	10g
Sucrose	7.8g
Sodium	33.6mg
Total Sugar	7.8g

Table 5.3: The Nutrition Facts Of Fresh Milk Per 200ml (Price: RM 2.50)

Average Composition	Per Serving 200ml
Energy	130 Kcal
Protein	6.8g
Fat	7.6g
Calcium	244mg
Carbohydrate	8.6g
Total Sugar (Lactose)	8.6g

Table 5.4: The Nutrition Facts Of Oat Milk Per 200ml (Price: RM 3.70)

Average Composition	Per Serving 200ml
Energy	177.5 Kcal
Protein	4.0g
Fat	6.25g
Calcium	17.25mg
Carbohydrate	26.75g
Sucrose	0.0g
Sodium	129.5mg
Total Dietary Fiber	6.25g
Total Sugar (Natural Sugar)	3.75g
Beta Glucan	0.25g

Table 5.5: The Nutrition Facts Of Soy Milk Per 200ml (Price: RM 2.40)

Average Composition	Per Serving 200ml
Energy	116 Kcal
Protein	7.8g
Fat	3.6g
Calcium	193mg
Carbohydrate	13.2g
Sucrose	9.8g
Sodium	30.2mg
Total Sugar	9.8g

5.2.3.2 Sample Preparation

The samples used for the spectrometry were diluted with distilled water. The samples were diluted to allow a significant amount of light to pass through the solution and can be measured by the spectrometer. The opaque and concentrated solutions such as milk prevent the light to pass through the solutions. The milk samples were diluted with ratio of 1:100, milk to water. After that, the diluted samples were placed into the cuvette (diameter ~1 cm) and shaken lightly before being placed in the cuvette holder. Then, the light from the samples was collected by VIS-NIR and NIR spectrometers, accordingly. The important precaution step that should be considered is eliminating the existence of air bubbles inside the cuvette. The air bubbles can affect the propagation of light where the light can be diffracted once it hits the air bubbles (Sabin, 2011). The diluted samples of each milk are shown in figure 5.5.

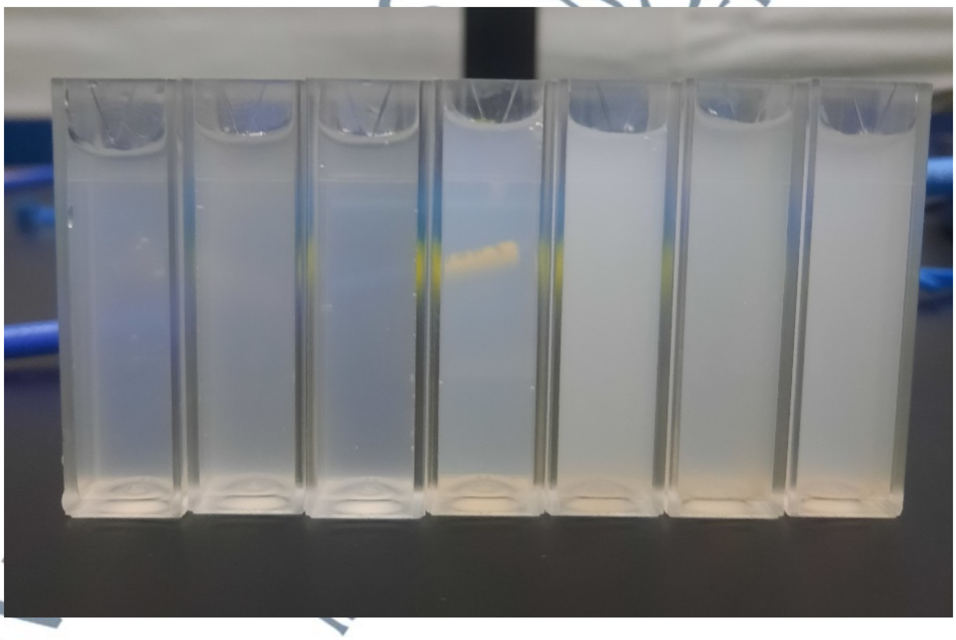

Figure 5.6: The Milk Samples After Being Diluted With Water, From Left: Breast Milk Sample 2, Breast Milk Sample 1, Goat Milk, Oat Milk, Fresh Milk, Soy Milk And Almond Milk.

5.2.3.3 Experimental Set-Up and Analysis Software

The experimental set-up used for this research is similar with **Chapter 4** (section 4.3.2.1 of Experimental Set-Up).

5.3 Results and Discussion

Study on milk contents was done by investigating the characteristics of light propagation in different types of milk such as almond milk, fresh milk, oat milk, soy milk, goat milk and breast milk. The study was performed based on experimental and theoretical analysis. NIR and VIS-NIR spectrometers were used to observe the absorbance and fluorescence of different types of milk to compare the milk contents. The statistical analysis was carried out using principal component analysis (PCA) to analyse and evaluate the validity of the experimental result. Meanwhile, light propagation theory was used to model random lasers for different types of milk. The features such as threshold reduction and linewidth narrowing were analysed based on milk density, dye concentration and pump energy. The output from both experimental and modeling approach were analysed and discussed systematically in this chapter.

5.3.1 Experimental results

NIR and VIS-NIR spectrometers can measure emission spectra of milk samples from 950 nm to 1650 nm and 350 nm to 1000 nm respectively. The absorbance and fluorescence spectra of different types of milk were observed using Ocean View Software. Almond milk, fresh milk, oat milk, goat milk and breast milk were the samples used in the spectrometry experiments. Figure 5.6 and figure 5.7 show the absorbance spectra of various types of milk measured by both NIR and VIS-NIR spectrometers.

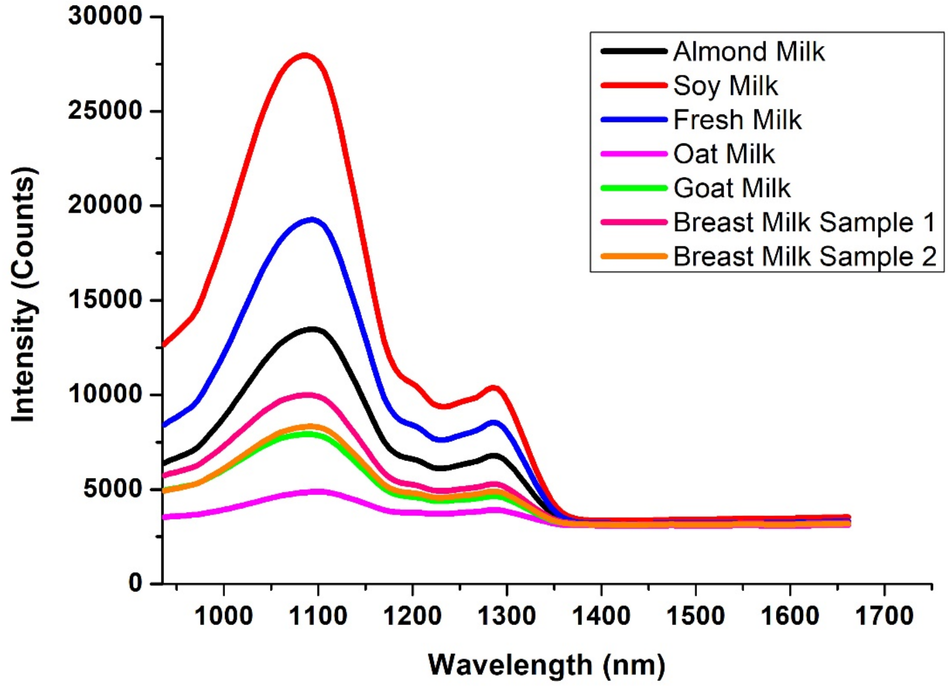

Figure 5.7: The Absorbance Spectra Of Various Types Of Milk Samples Through NIR Spectrometers.

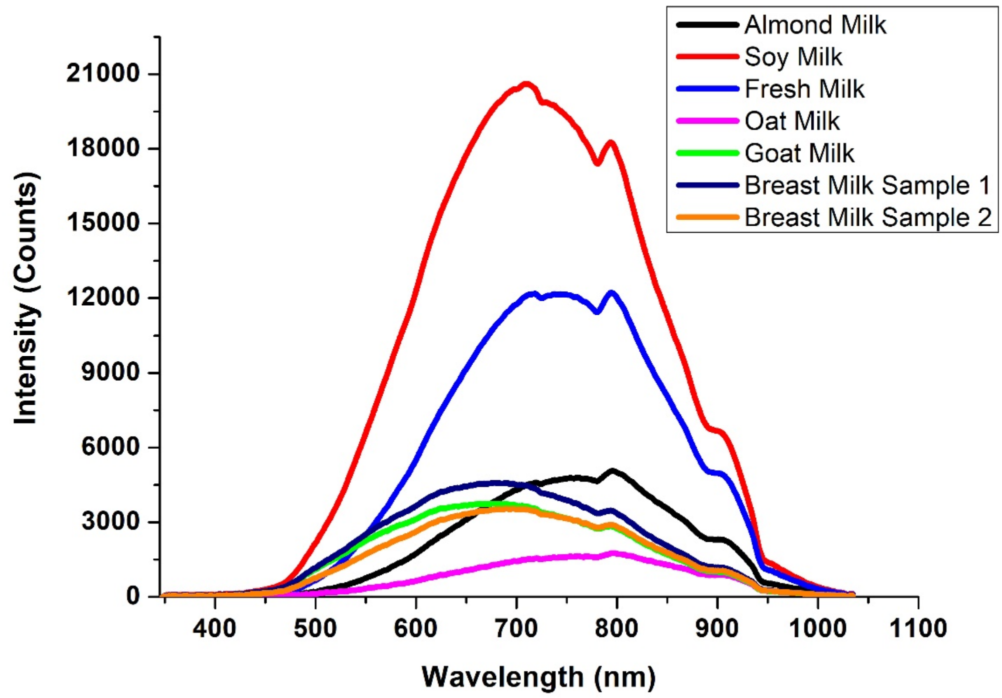

Figure 5.8: The Absorbance Spectra Of Various Types Of Milk Samples Through VIS-NIR Spectrometers.

Figure 5.6 and figure 5.7 show the absorbance spectra of various milk samples used in the experiments captured by NIR and VIS-NIR spectrometers, respectively. It is clearly shown that soy milk has the highest absorbance spectra compared to other samples. It is attributed to the high amount of protein, fat and carbohydrate contained in the soy milk, as shown in table 5.7. The soybean seed itself consists of lots of proteins and carbohydrates compared to raw cow's milk (YİĞİT, 2019). Fresh milk shows the second highest absorbance due to high amount of fat, protein and carbohydrate as well. The thicker consistency of the soy milk than fresh milk is one of the factors that affecting the absorption of light in the soy milk. Figure 5.7 shows that absorption peak of fresh milk (750 nm) is slightly different with the absorption peak of soy milk (700 nm). Meanwhile, breast milk (sample 2) has the lowest absorbance spectra as the sample is quite transparent and less dense compared to others. The intensity of absorbance spectra only reaches 4500 and 2800 through NIR and VIS-NIR spectrometers respectively. The results clearly show that the milk contents can affect the light propagation.

Many recent studies have been developed to study the properties of milk such as developing a hand-held susceptible fiber optic milk fat sensor using U-bent plastic optical fiber (POF) to study milk fat content in milk (Gowri et al., 2019b), developing a fluorescence-based technique to study time-based milk degradation at room temperature and pH of the milk (Choudhary et al., 2019b), and developing ultra-high performance liquid chromatography mass spectrometry to quantify micronutrients (B-vitamins) from milk samples (Shetty et al., 2020). All methods are complicated and consume time, money and energy. Furthermore, the methods are done based on intrusive approach where the samples can be affected result in less reliability of the data.

Figure 5.8 shows the fluorescence spectra of various types of milk using NIR spectrometers. The fluorescence spectra show that the fresh milk has the highest emission intensity compared to other milk samples. This is because the fluorescence emission can be affected by the amount of fat content and fresh milk contains the highest milk fat content compared to other milk (Shaikh & O'Donnell, 2017). The fluorescence peaks for all samples are from 1000 to 1100 nm, depicting that the milk might have ingredient that can emit light within the wavelength ranges. More comprehensive characterization studies should be done to identify the milk contents which can emit light. Besides that, the light source can be changed to lasers instead of tungsten halogen light that is currently used in the experimental set up.

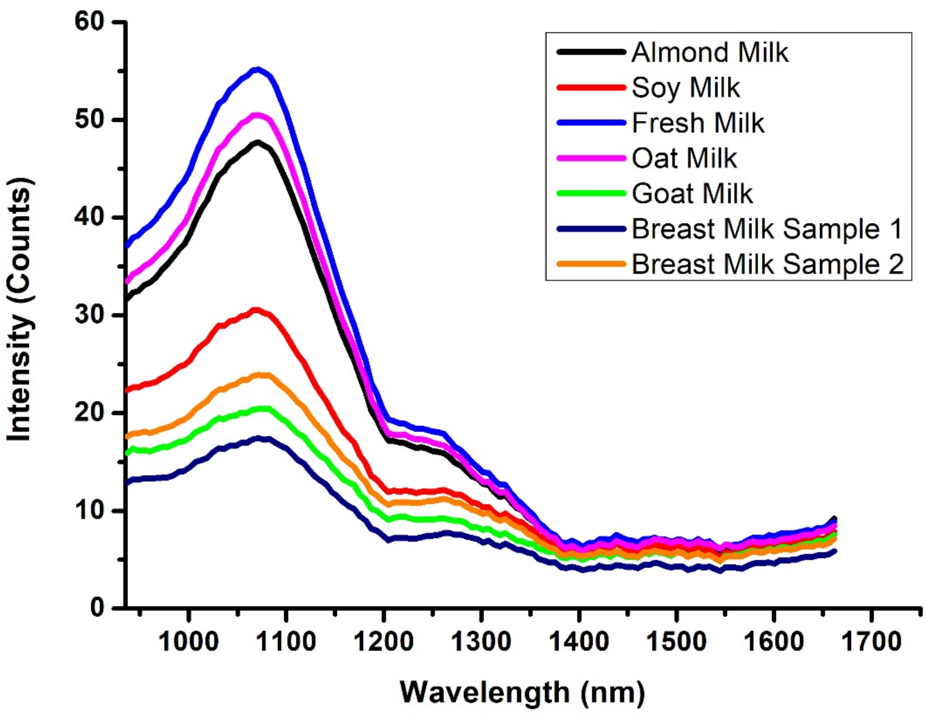

Figure 5.9: The Fluorescence Spectra Of Various Types Of Milk Samples Through NIR Spectrometers.

5.3.2 Multivariate Data Analysis

Principal component analysis (PCA) is a flexible tool used in multivariate data analysis in order to extract the important information from the data and to express the information as a set of summary indices (Groth et al., 2013). The data obtained from the experiments have then been analysed using the principal component analysis to collectively observe the pattern and consistency of the data reading from both NIR and VIS-NIR spectrometers. Figure 5.9 and figure 5.10 show the visualization of the data (10 readings) gained from NIR spectrometer and VIS-NIR spectrometer through the principal component analysis.

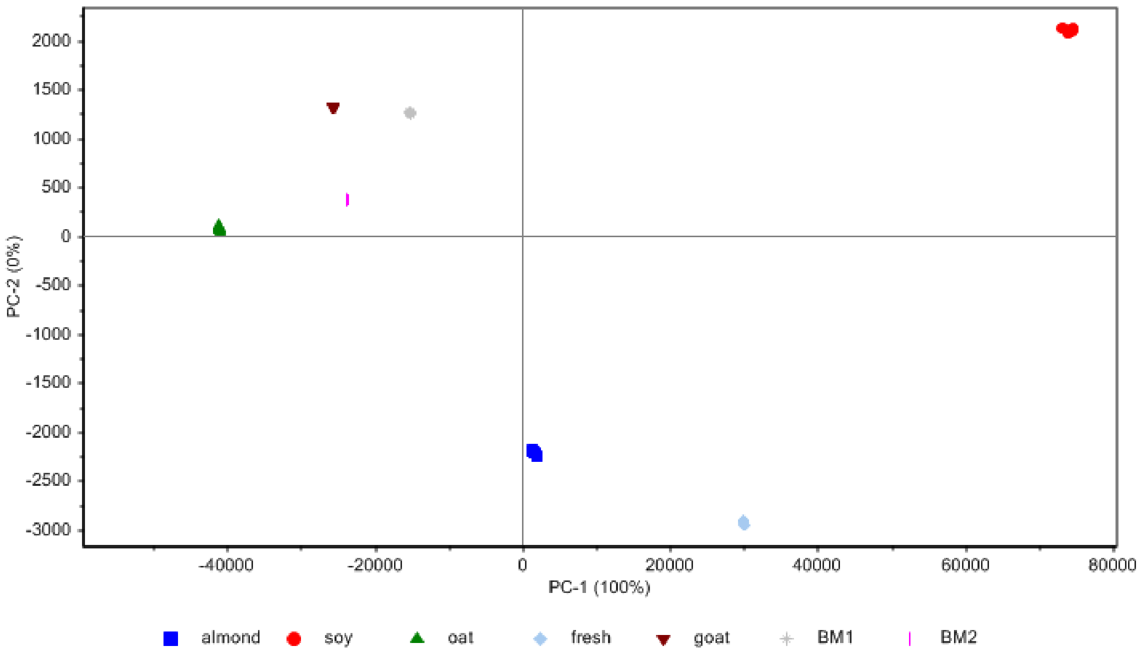

Figure 5.10: The Principal Component Analysis (PCA) For Absorbance Spectra of NIR Spectrometer (BM Is A Short Form For Breast Milk).

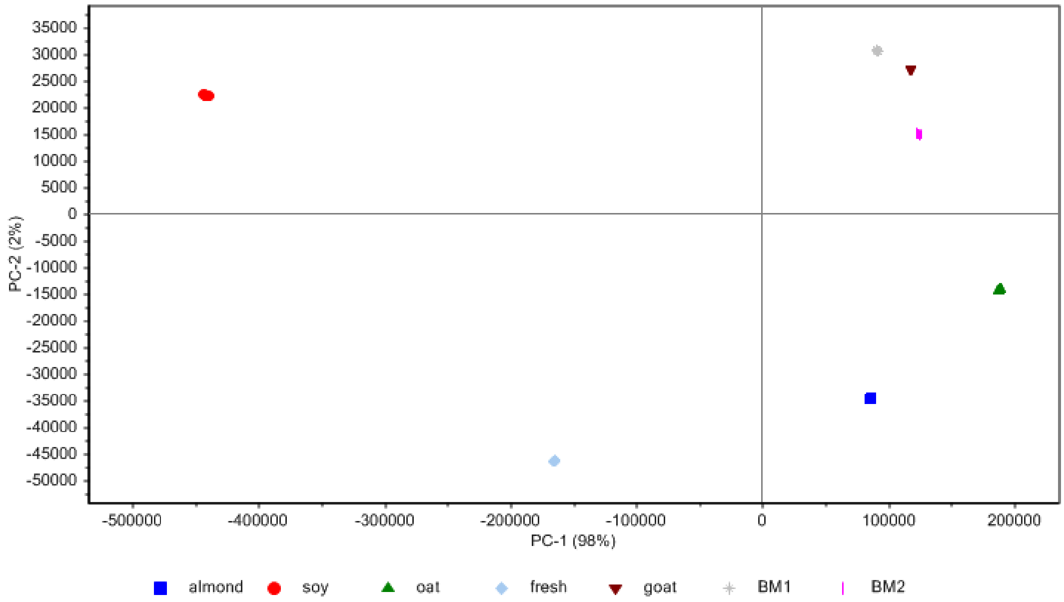

Figure 5.11: The Principal Component Analysis (PCA) For Absorbance Spectra Of VIS-NIR Spectrometer (BM Is A Short Form For Breast Milk).

Figure 5.9 and figure 5.10 show that the absorbance spectra of various types of milk, measured by both NIR and VIS-NIR spectrometers are very consistent and precise. From the analysis, we believe that the experimental data for absorbance are reliable due to the consistency and precise data taken. Meanwhile, the statistical analysis of fluorescence spectra measured using both spectrometers are shown in figure 5.11 and figure 5.12 respectively.

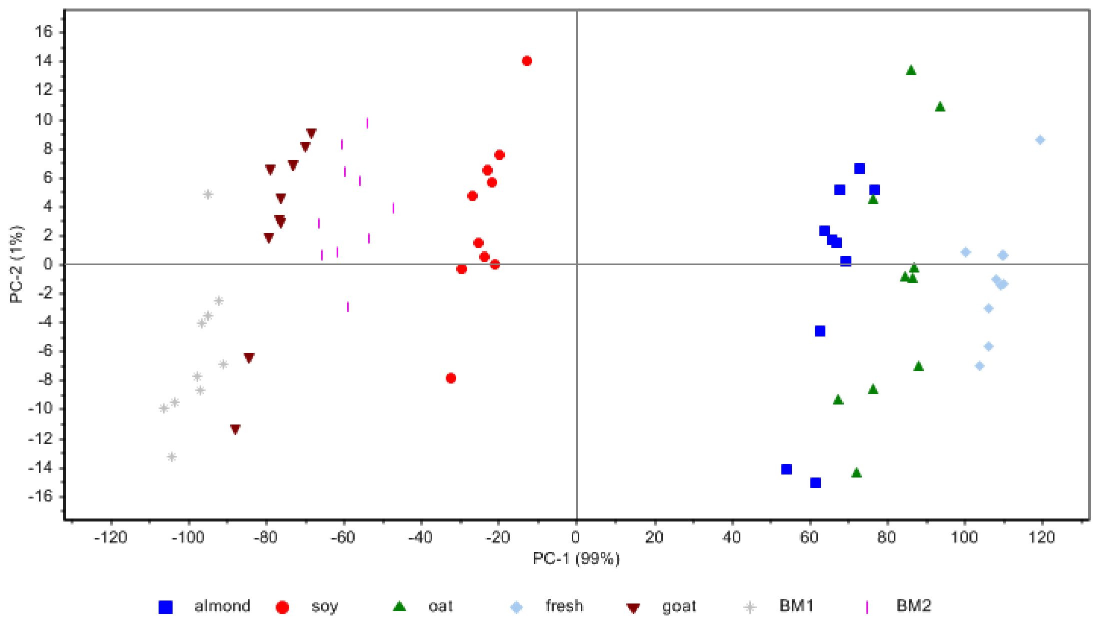

Figure 5.12: The Principal Component Analysis (PCA) For Fluorescence Spectra From NIR Spectrometer (BM Is A Short Form For Breast Milk).

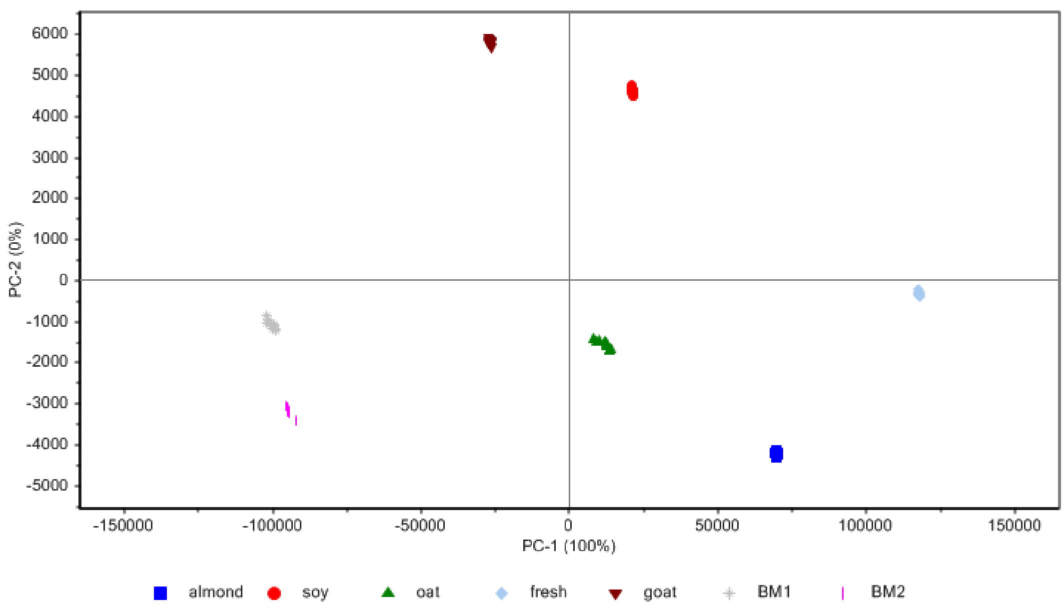

Figure 5.13: The Principal Component Analysis (PCA) For Fluorescence Spectra Of VIS-NIR Spectrometer (BM Is A Short Form for Breast Milk).

Figure 5.11 shows that the fluorescence spectra measured by NIR spectrometer are spread out which justify the inconsistency of the data. Meanwhile, the fluorescence spectra measured by VIS-NIR spectrometer are precise and consistent (figure 5.12). Thus, it shows that the fluorescence spectra from VIS-NIR spectrometer is more reliable compared to the NIR spectrometer. We attribute that to the high variance where a set of number are spread out from the average value (Smith, 2006) (Clark & Ma'ayan, 2011).

5.3.3. Theoretical Analysis Results

Random lasers based on various types of milks were modeled based on light propagation theory. The results are presented in terms of emission spectra and linewidth. The modeling used four types of milk consisted of almond milk, fresh milk, oat milk and soy milk based on the milk fat content provided in table 5.2 until table 5.5. The modeling was designed to investigate the random lasing threshold reduction and linewidth narrowing by varying particles density, dye concentration and pump intensities.

5.3.3.1 Emission Peaks

The modeling results from varying the particles density, dye concentration and pump intensities are shown through graphical representation. The graphs generated from the modeling were further analysed to investigate the random lasing threshold reduction and linewidth narrowing. Figure 5.13 to figure 5.16 depict the emission spectra of random lasers for below, at and above lasing threshold.

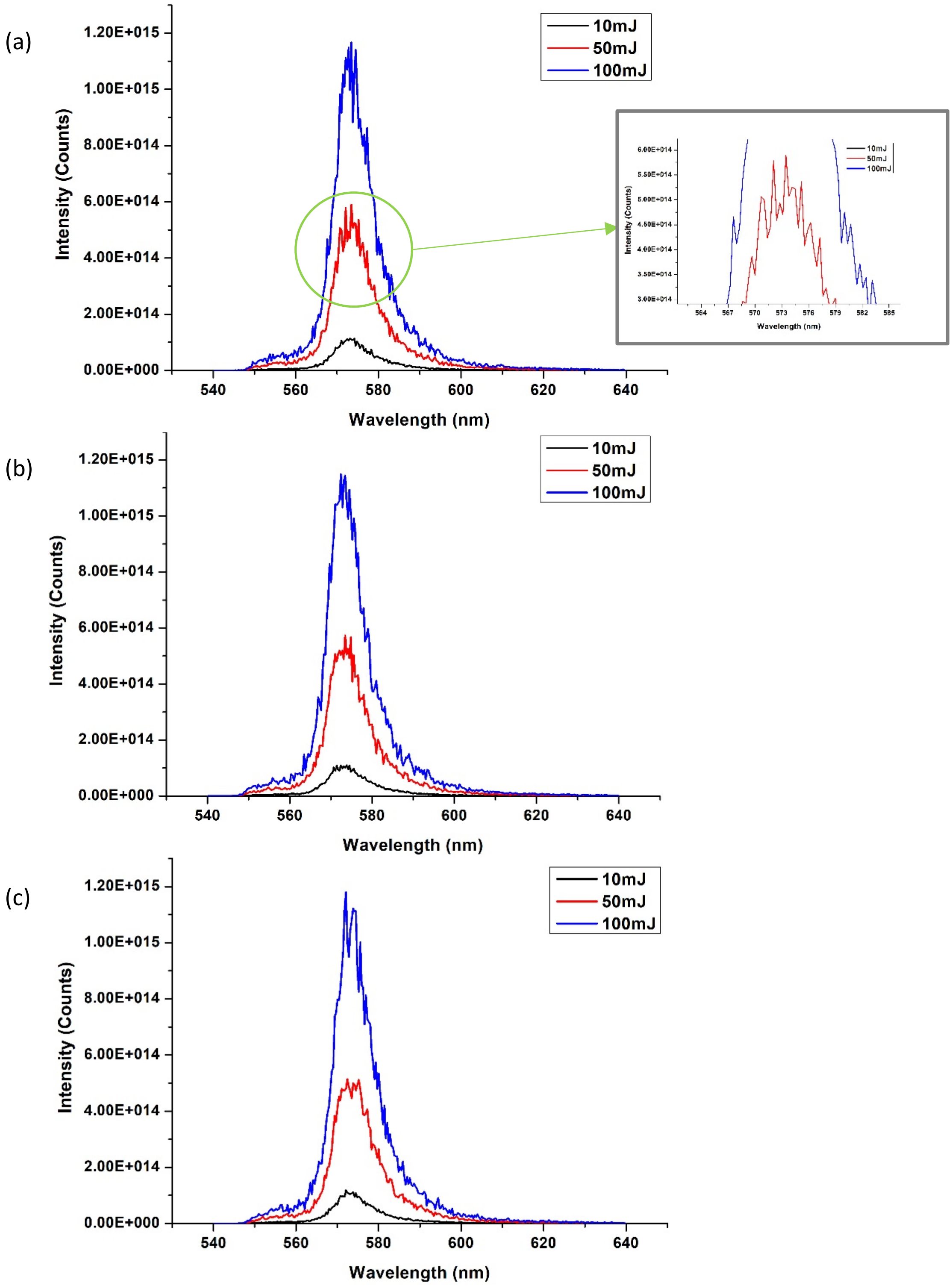

Figure 5.14: The Emission Intensity Of A Random Laser Based On Almond Milk With The Variation Of Dye Concentrations, a) 10^{-2}M, b) 10^{-3}M and c) 10^{-4}M. The Inset Shows The Multiple Emission Peaks In The Closed-Up View.

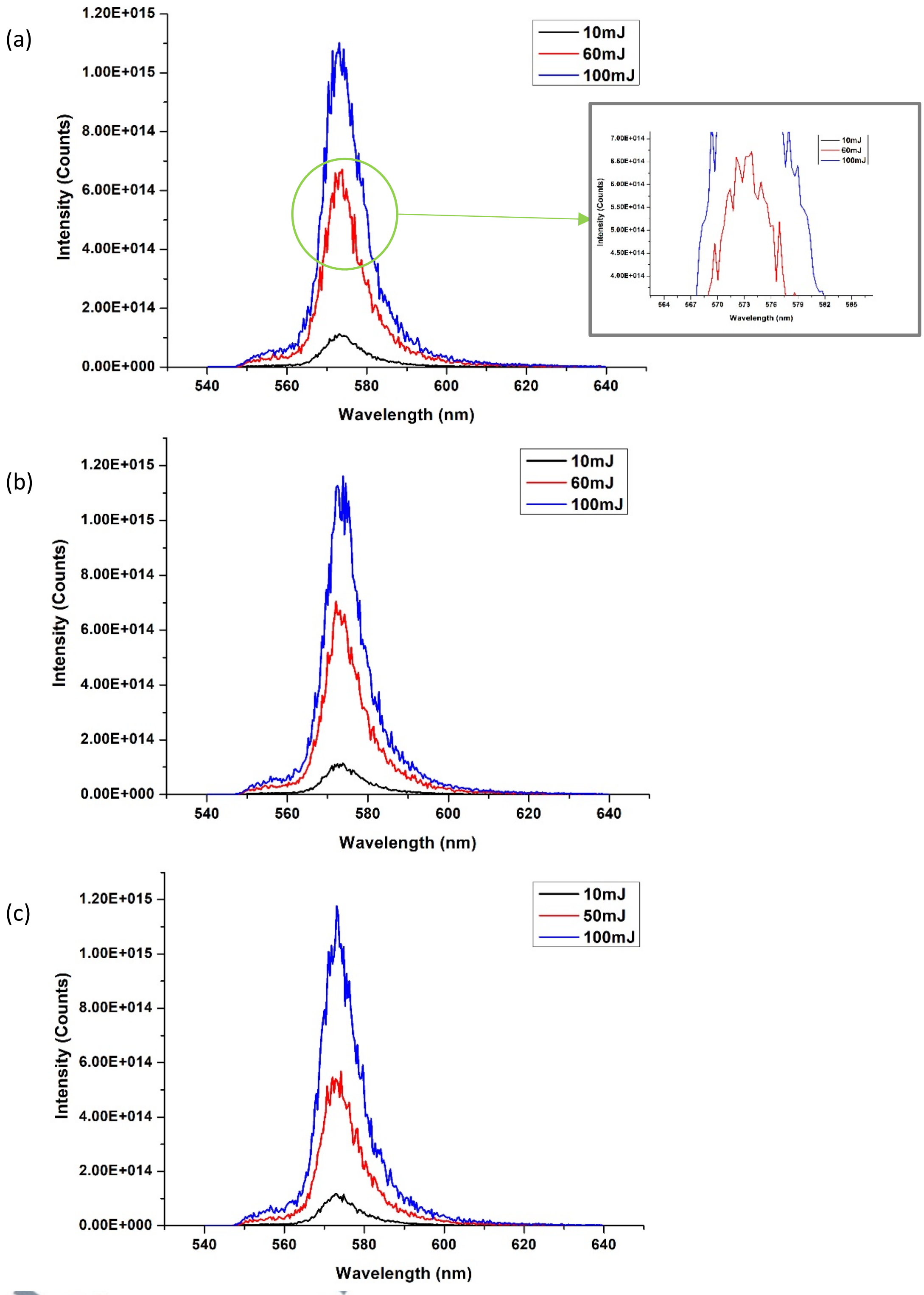

Figure 5.15: The Emission Intensity Of A Random Laser Based On Fresh Milk With The Variation Of Dye Concentrations, a) 10^{-2}M, b) 10^{-3}M and c) 10^{-4}M. The Inset Shows The Multiple Emission Peaks In The Closed-Up View.

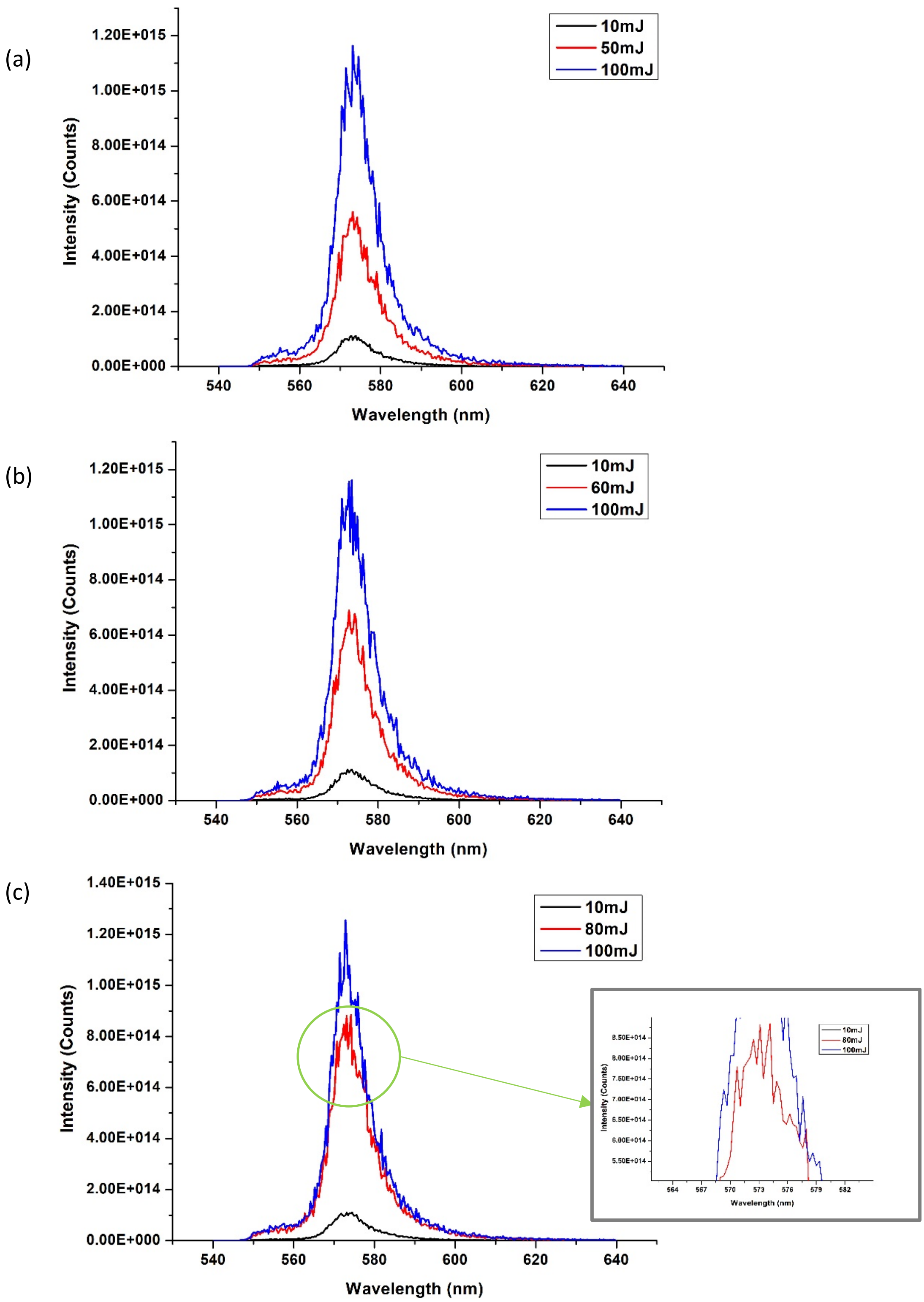

Figure 5.16: The Emission Intensity Of A Random Laser Based On Oat Milk With The Variation Of Dye Concentrations, a) 10^{-2}M, b) 10^{-3}M and c) 10^{-4}M. The Inset Shows The Multiple Emission Peaks In The Closed-Up View.

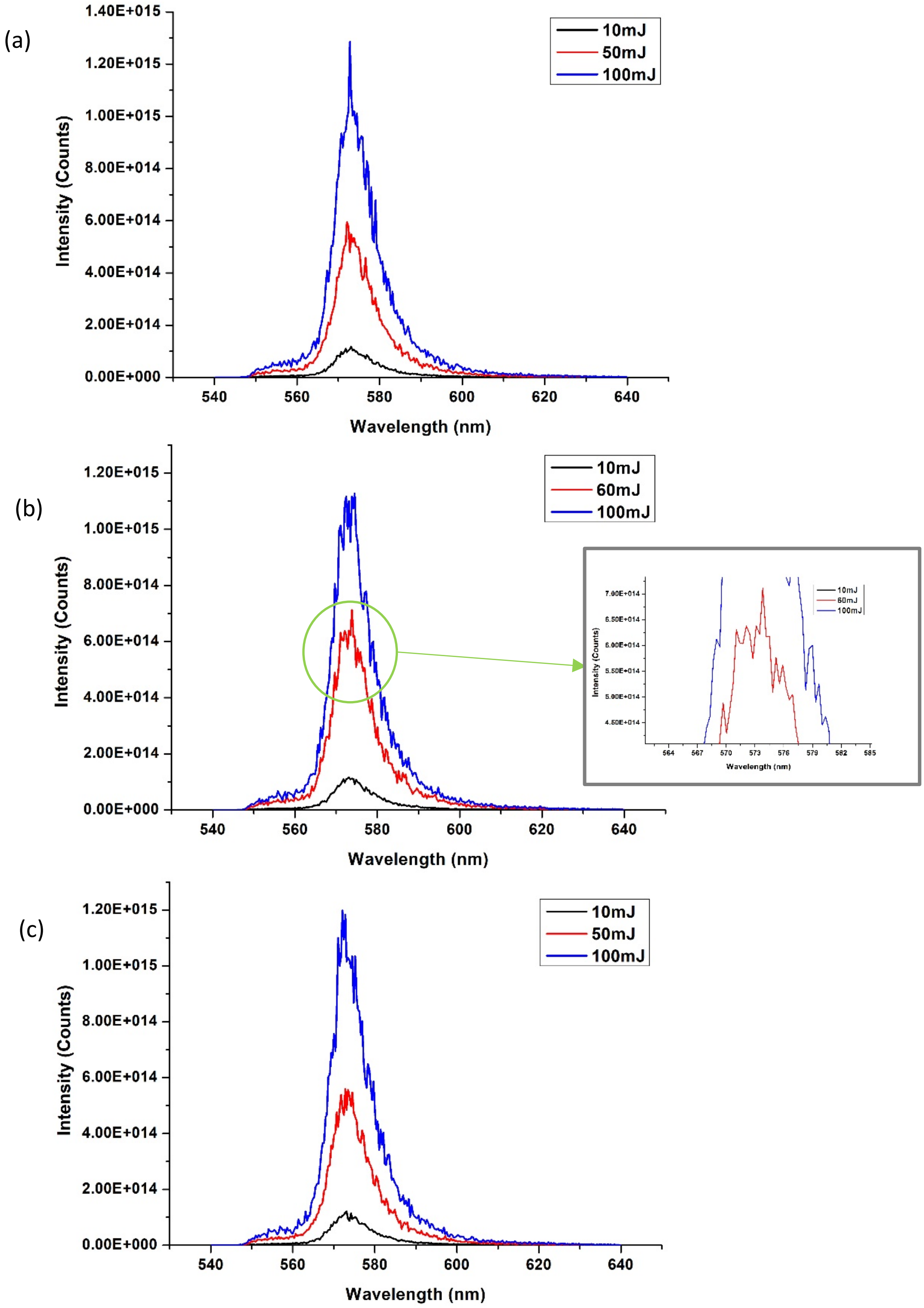

Figure 5.17: The Emission Intensity Of A Random Laser Based On Soy Milk With The Variation Of Dye Concentrations, a) 10^{-2}M, b) 10^{-3}M and c) 10^{-4}M. The Inset Shows The Multiple Emission Peaks In The Closed-Up View.

Figure 5.13 to Figure 5.16 show the emission spectra of modeled random lasers for various types of milk. The emission intensity increases with the increase of pump energy. There are no emission peaks observed for random lasers below lasing threshold. By providing sufficient pump energy, multiple emission peaks appear on top of the fluorescence spectrum that indicates the lasing threshold. The lasing threshold occurs when the optical gain exceeds the losses in the gain medium. The emission peaks become significant above lasing threshold. Figure 5.13 shows the emission spectra of random lasers with almond milk for different dye concentrations. For the lowest dye concentration, 10^{-4}M, no emission peaks appear on top of the fluorescence spectrum when the pump energy was increased to ~50mJ. The emission peaks only appear for the highest pump energy. It is attributed to the least amount of dye molecule in 10^{-4}M to provide light amplification.

Figure 5.14 depicts the emission spectra of random lasers based on fresh milk for different dye concentrations. The emission peaks for the dye concentration of 10^{-2}M is more significant compared to the emission peaks for dye concentration of 10^{-3}M and 10^{-4}M. Meanwhile, the emission spectra of random lasers based on oat milk shows the increment of the lasing threshold (figure 5.15). The emission peaks of the highest pump energy (100mJ) for 10^{-4}M dye concentration is more significant compared to the emission peaks of the highest pump energy (100mJ) of both 10^{-2}M and 10^{-3}M dye concentration. On the other hand, the emission spectra for random lasers based on soy milk (figure 5.16) shows the most significant emission peaks with the dye concentration of 10^{-2}M. As many emission peaks appears at more concentrated dye, it is proven that the amount of dye is a factor that mainly influences the properties of random lasers. The amount of particles is important to provide sufficient multiple light scattering but adequate amount of dye is also needed for light amplification.

5.3.3.2 Emission Linewidth

The emission linewidth is measured by measuring the width of the emission peaks for each pump densities. The pump energy was varied from 10mJ to 100mJ, and the concentration of dye used is varied from 10^{-4} M to 10^{-3} M. Figure 5.17 until figure 5.20 show the emission linewidth for almond milk, fresh milk, oat milk and soy milk for various concentration. The blue line is used to determine the lasing threshold. The lasing threshold can be found when there is a nonlinear decrease of emission linewidth with the increase of pump energy. The lasing threshold is marked using blue circle.

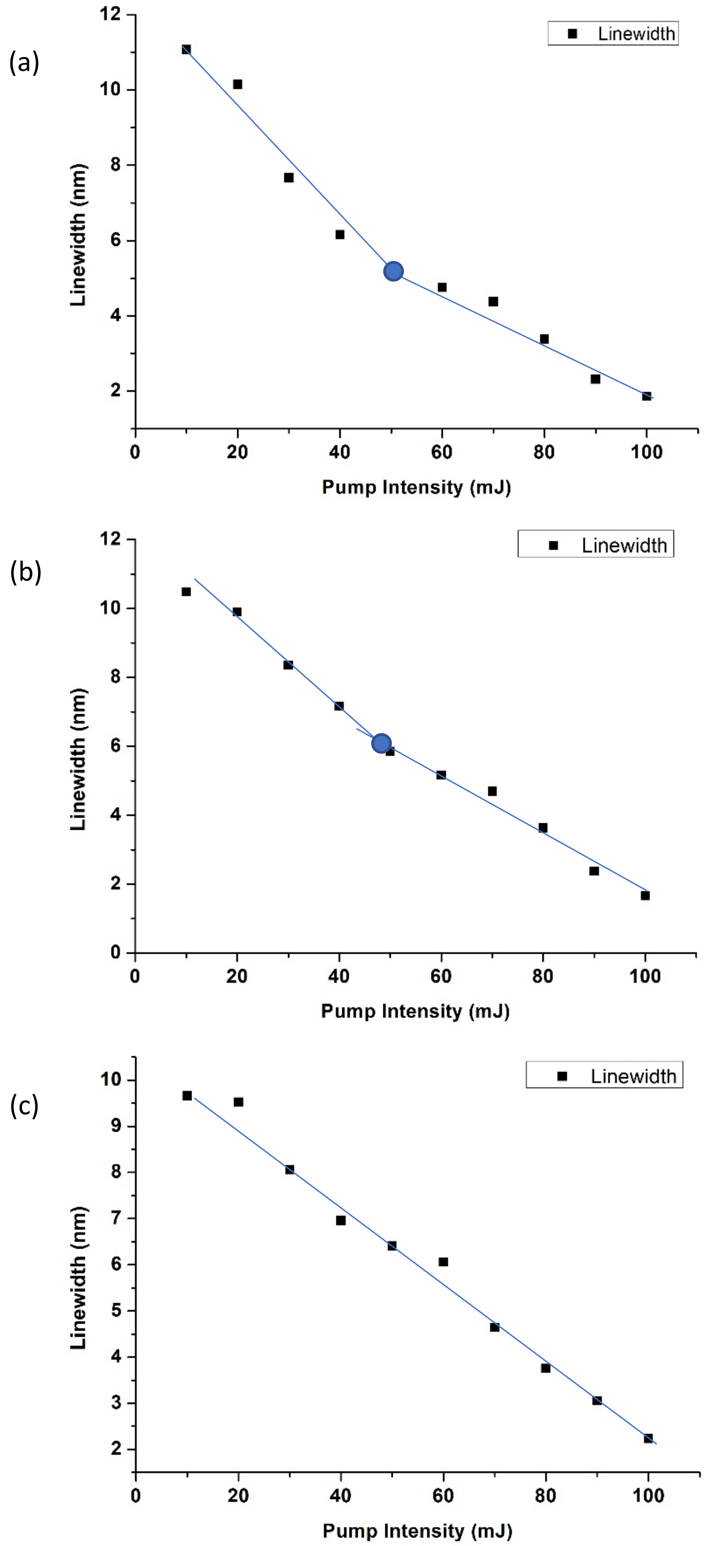

Figure 5.18: The Emission Linewidth Of Almond Milk With Various Dye Concentrations, a) 10^{-2}M, b) 10^{-3}M and c) 10^{-4}M. The Lasing Threshold Is ~50 mJ For (a) And ~48 mJ For (b). No lasing Threshold For (c).

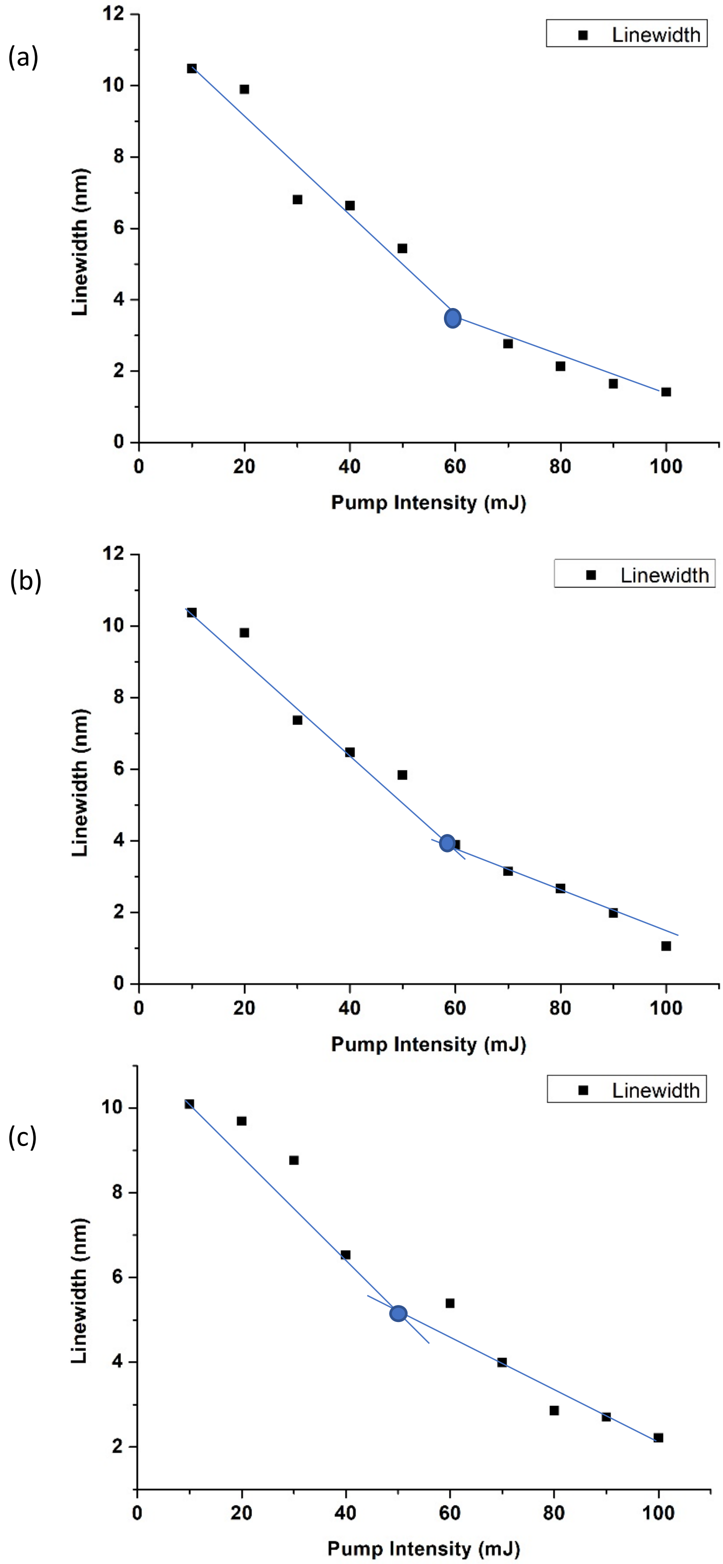

Figure 5.19: The Emission Linewidth Of Fresh Milk With Various Dye Concentrations, a) 10^{-2}M, b) 10^{-3}M and c) 10^{-4}M. The Lasing Threshold Is ~60 mJ For (a), ~58 mJ For (b) And ~50 mJ For (c).

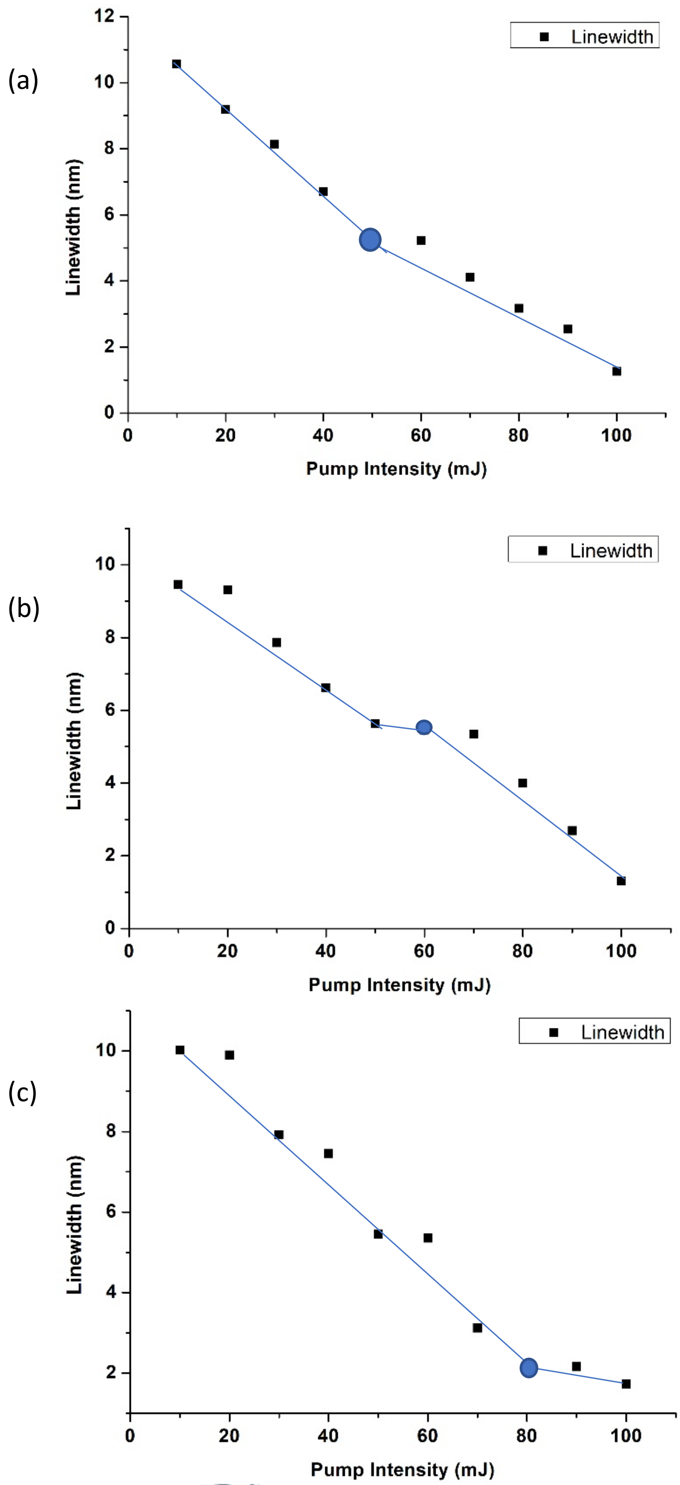

Figure 5.20: The Emission Linewidth Of Oat Milk With Various Dye Concentrations, a) 10^{-2}M, b) 10^{-3}M and c) 10^{-4}M. The Lasing Threshold Is ~50 mJ For (a), ~60 mJ For (b) And ~80 mJ For (c).

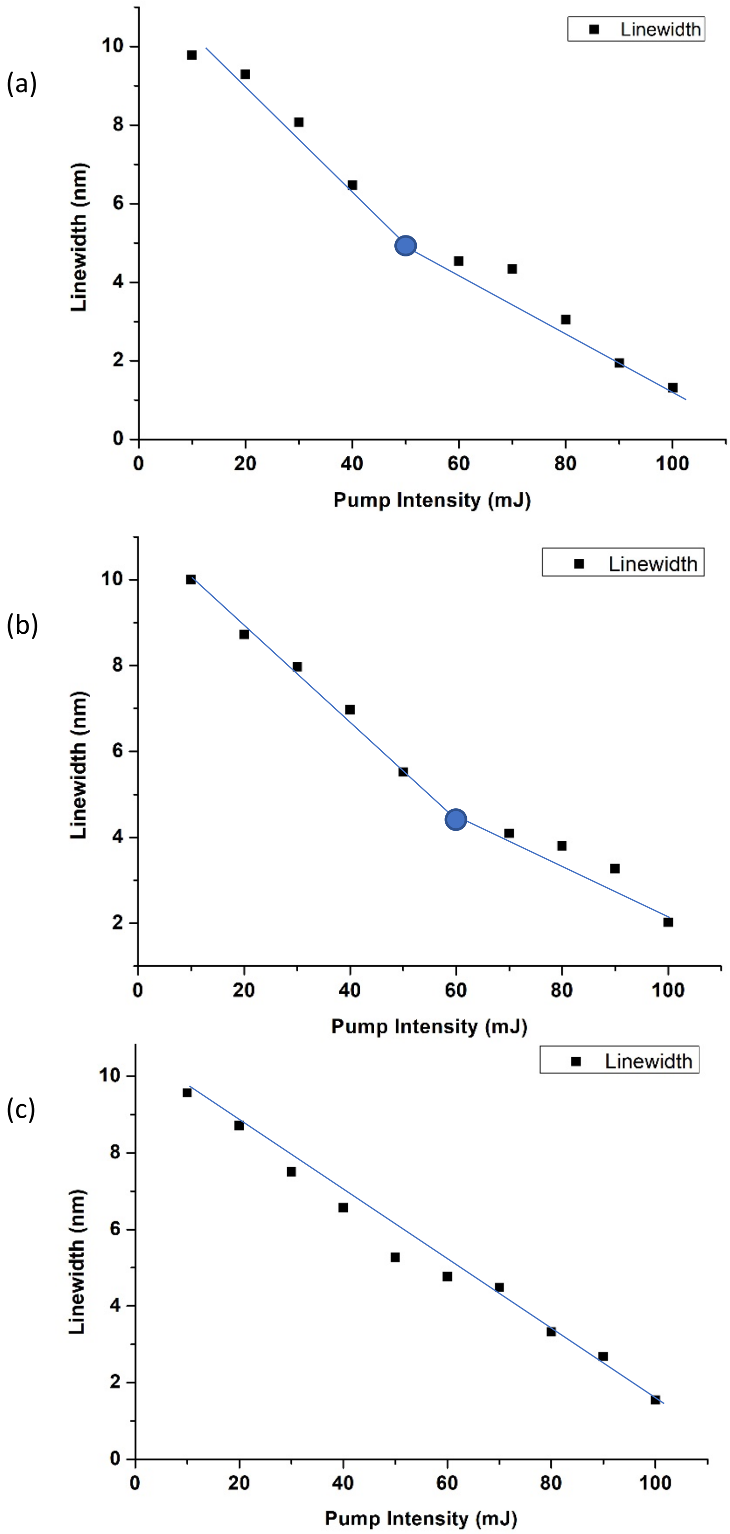

Figure 5.21: The Emission Linewidth Of Soy Milk With Various Dye Concentrations, a) 10^{-2}M, b) 10^{-3}M And c) 10^{-4}M. The Lasing Threshold is ~50 mJ For (a), ~60 mJ For (b) And no lasing threshold For (c).

Figure 5.17 shows that random lasers with almond milk has lasing threshold at ~50mJ for the highest dye concentration, 10^{-2}M. The lasing threshold reduces to ~48mJ when the dye concentration is reduced to 10^{-3}M. When the dye concentration is further reduced to 10^{-4}M, no lasing threshold is observed. Figure 5.18 shows that fresh milk with 10^{-2}M dye concentration has the lasing threshold of ~60mJ, and it further reduces to ~58mJ for 10^{-3}M and ~50mJ for 10^{-4}M. However, the oat milk in figure 5.19 shows the lasing threshold at ~60mJ for 10^{-2}M of dye concentration, ~50mJ for 10^{-3}M of dye concentration and ~80mJ for 10^{-4}M of dye concentration. Furthermore, random lasers with soy milk (figure 5.20) shows the lasing threshold at ~60mJ for the highest dye concentration of 10^{-2}M, while it reduces to ~50mJ at 10^{-3}M of dye concentration. The lasing threshold occurs at ~60mJ at the dye concentration of 10^{-4}M. Table 5.6 shows the lasing threshold of random lasers based on almond milk, fresh milk, oat milk and soy milk which are obtained from various dye concentrations.

Table 5.6: Lasing Threshold of Random Lasers Based on Different Types of Milk with Various Dye Concentrations.

Dye Concentration	**10^{-2}M**	**10^{-3}M**	**10^{-4}M**
	Lasing Threshold		
Fresh Milk (fat content~7.6g)	~60mJ	~58mJ	~50mJ
Oat Milk (fat content~6.25g)	~50mJ	~60mJ	~80mJ
Almond Milk (fat content~6.2g)	~50mJ	~50mJ	No lasing threshold
Soy Milk (fat content~3.6g)	~50mJ	~60mJ	No lasing threshold

Random laser based on almond milk has lasing threshold at ~50mJ for the highest dye concentration, 10^{-2}M. The lasing threshold reduces to ~48mJ when the dye concentration is reduced to 10^{-3}M. When the dye concentration is further reduced to 10^{-4}M, no lasing threshold is observed. Meanwhile, random laser based on fresh milk in

10^{-2}M of dye concentration has the lasing threshold of ~60mJ, and it further reduces to ~58mJ and ~50mJ for 10^{-3}M and 10^{-4}M of dye concentration. Random laser based on oat milk shows the lasing threshold at ~60mJ, ~50mJ and ~80mJ for 10^{-2}M, 10^{-3}M and 10^{-4}M of dye concentration respectively. Furthermore, random laser based on soy milk shows the lasing threshold at ~50mJ for the highest dye concentration (10^{-2}M), while it increases to ~60mJ at 10^{-3}M of dye concentration. We did not observe any lasing threshold in random lasers based on soy milk in 10^{-4}M of dye concentration (Table 5.6).

From the modeling results, we found that milk fat from animal and plant sources can be compared based on lasing threshold. Random lasers need excitation sources (pump energy), optical gain (gain medium) and multiple light scattering (scattering mean free path) to work. The characteristics or properties of random lasers can be affected when the pump energy, gain medium and scattering mean free path are varied. Scattering mean free path can be estimated using equation (5.4) where it depends on scatterer density and scattering cross section. In this research, we varied scatterer density based on mass of fat of each milk and the scattering cross section of the fat particles were estimated according to Abegaõ *et al.* (Abegaõ et al., 2016). We suppose that fat content in milk can contribute to the light scattering where higher amount of fat gives higher light scattering. Indirectly, light scattering can affect the properties of random lasers. Fresh milk has the highest fat content (7.6g) whereas soy milk has the least fat content (3.6g) among all samples. Thus, random laser based on fresh milk shows the lowest lasing threshold in 10^{-4}M of dye concentration because the fat particles can provide adequate light scattering to complement the less concentration of dyes (Table 5.6).

The modeling results also show that the concentration of dye affects the properties of random lasers. The highest concentration of dye (10^{-2}M) gives more light amplification, results in lower lasing threshold. Meanwhile, random laser based on soy milk shows no lasing threshold in the lowest dye concentration because sufficient dye concentration is needed to compensate less amount of fat particles inside the gain medium (Table 5.6).

5.4 Conclusion

In conclusion, this chapter discusses the light propagation in various types of milk based on theoretical, experimental and statistical analysis. The study was conducted on several types of milk such as almond milk, fresh milk, oat milk and soy milk through spectrometry experiments and theoretical simulation. The spectrometry experiments were performed using VIS-NIR and NIR spectrometers to observe the absorbance and fluorescence spectra in the milk samples within visible and near infra-red wavelength. The study clearly shows that the samples which consist higher milk fat content such as fresh milk and soy milk produce higher emission peak. Besides that, the concentration of milk also affects the propagation of light, as the less concentrated milk such as breast milk and goat milk give less absorbance and fluorescence spectra. The experimental result was validated using PCA analysis and referred to model random lasers based on milk. The particles density, dye concentration and pump intensities had been varied in the simulation and the results obtained clearly shows that the particle density and concentration of dye are the main factors affecting the light propagation in a medium. The modeling can be further upgraded to be used in real random laser experiment. Here, the proposed study uses non-intrusive and non-invasive methods, and the results can be used as a reference to study the main ingredient of milk such as fat, protein, and carbohydrates.