Cooking Quantum Dots for Particle Detection

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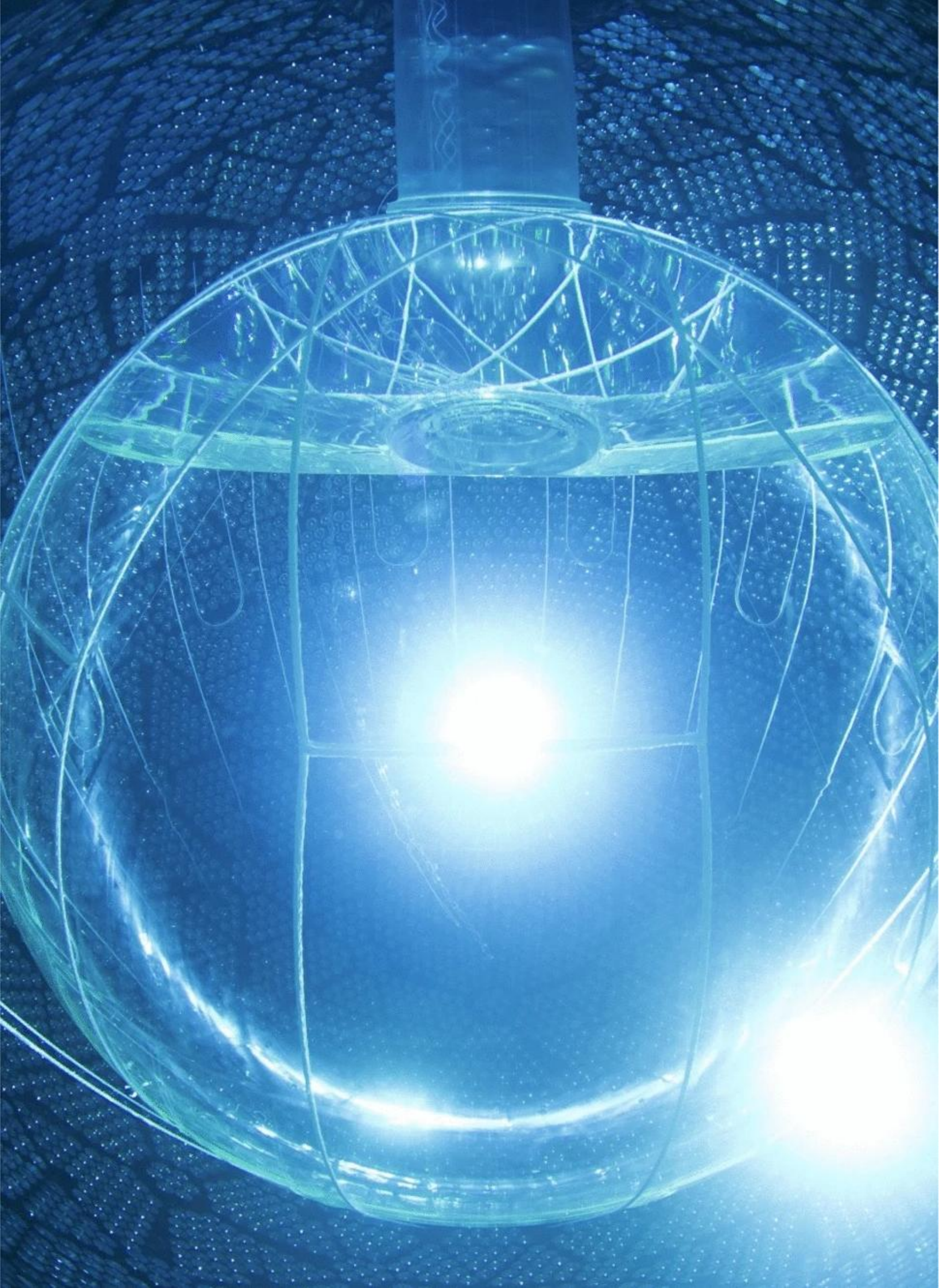
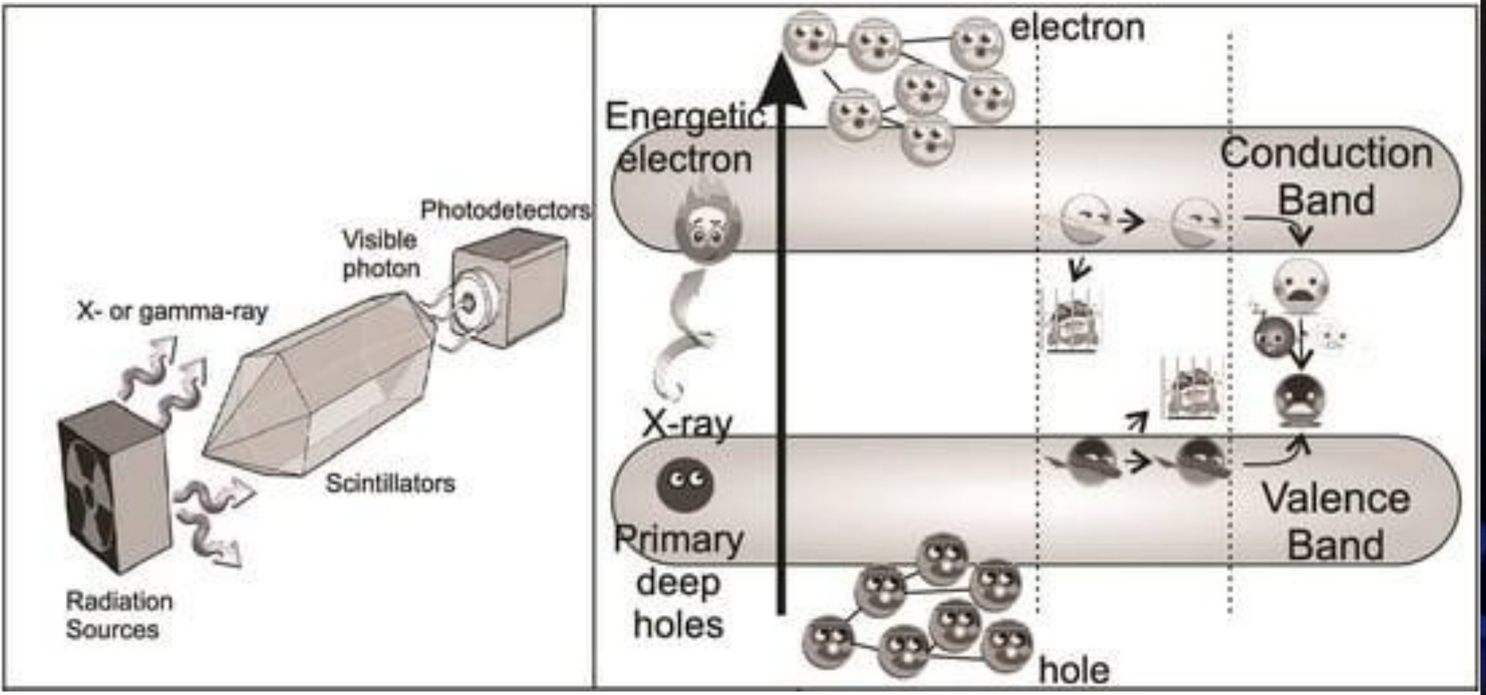
The objective is to develop a transparent, biodegradable, and low-cost liquid scintillator based on carbon quantum dots, while maintaining a measurable optical response under ultraviolet excitation



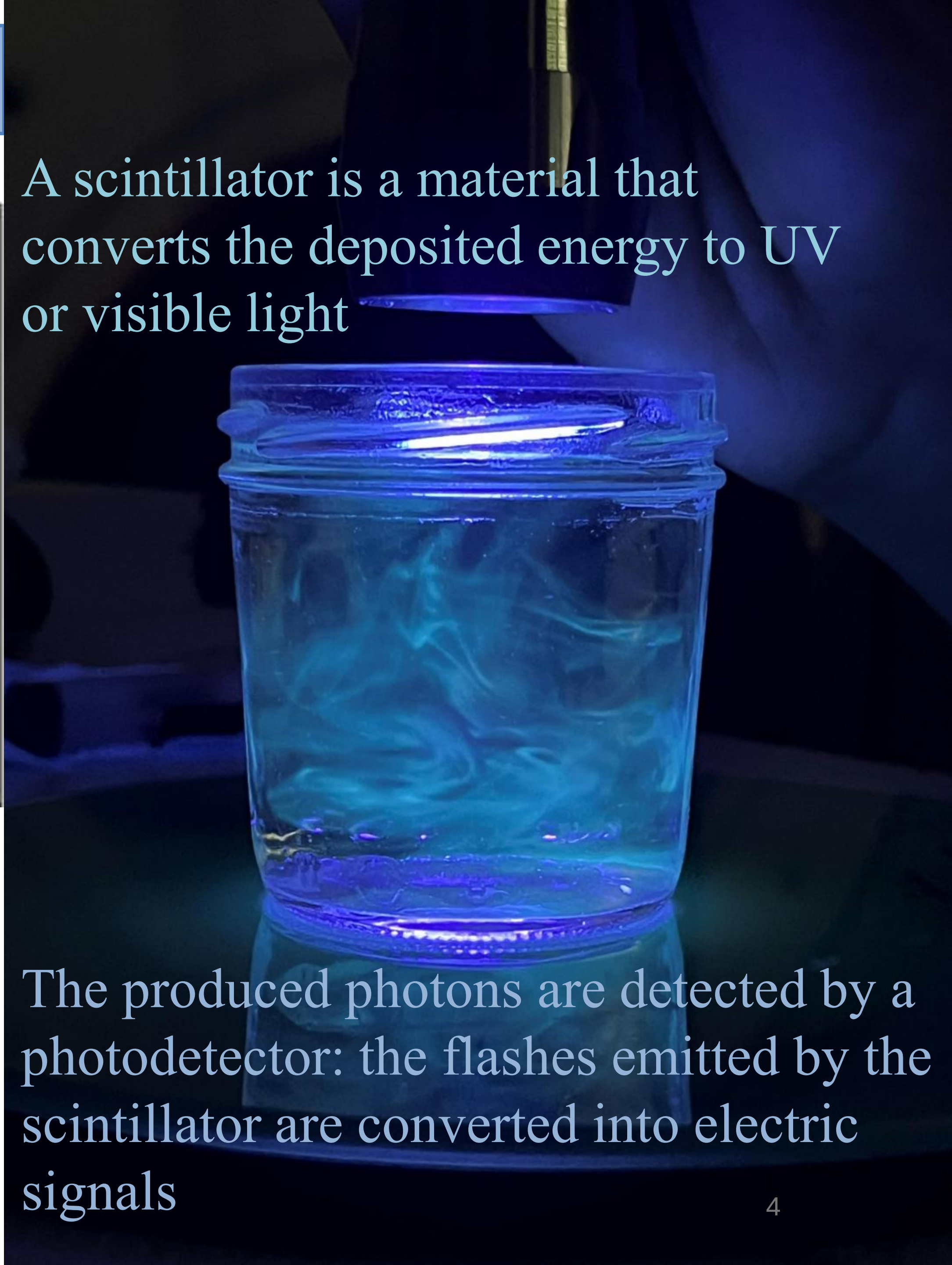
By The SNO+ Collaboration - "Initial measurement of reactor antineutrino oscillation at SNO+" by the SNO+ Collaboration, Eur. Phys. J. C 85, 17 (2025).

Picture of the detector during scintillator fill from an underwater camera mounted next to the PMTs. The horizontal scintillator-water interface is clearly visible, well below the AV neck

Scintillation



Maddalena, F., Tjahjana, L., Xie, A., Arramel, Zeng, S., Wang, H., Coquet, P., Drozdowski, W., Dujardin, C., Dang, C., & Birowosuto, M. D. (2019). Inorganic, Organic, and Perovskite Halides with Nanotechnology for High–Light Yield X- and γ-ray Scintillators. *Crystals*, *9*(2), 88. https://doi.org/10.3390/cryst9020088



A scintillator is a material that converts the deposited energy to UV or visible light

The produced photons are detected by a photodetector: the flashes emitted by the scintillator are converted into electric signals

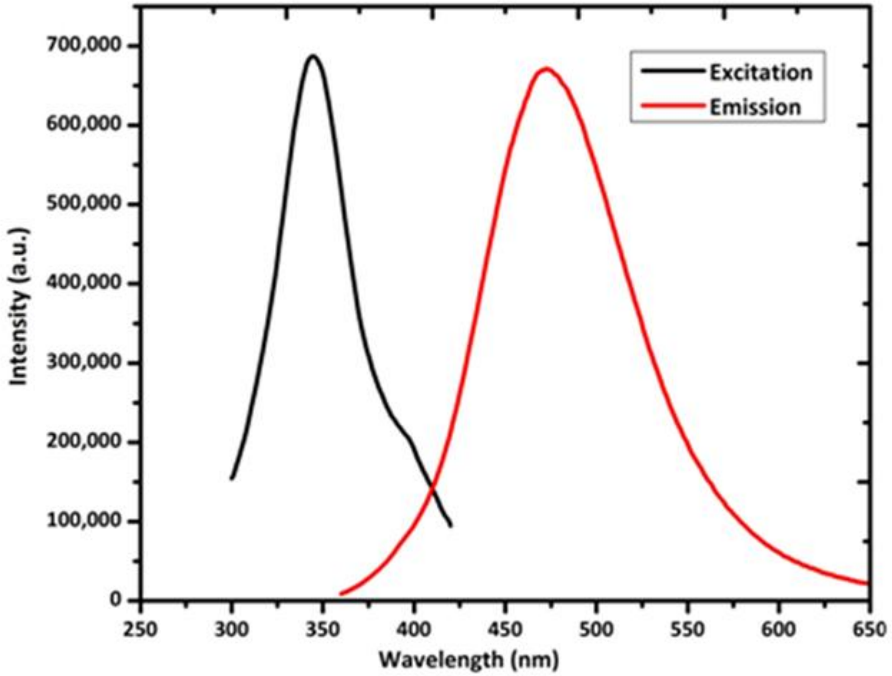
The fluorescence emitted by the quantum dots is recorded using a digital camera and analysed through the red, green, and blue colour channels

The optical response of the resulting solutions is studied for different concentrations to evaluate the **relationship between quantum dots concentration and emitted light intensity**. In particular, the linearity of this relationship is investigated to determine the concentration range in which the detector response can be reliably characterised

Experimental Setup

In order to measure the emitted light intensity, the procedure used was based on retrieving the RGB code from the photographs taken of one of the recipes of different concentrations using two light sources: a UV lantern and a LED

Excitation and emission spectrum of CQDs



Yadav, P. K., Chandra, S., Kumar, V., Kumar, D., & Hasan, S. H. (2023). Carbon Quantum Dots: Synthesis, Structure, Properties, and Catalytic Applications for Organic Synthesis. *Catalysts*, *13*(2), 422. https://doi.org/10.3390/catal13020422

Wavelength peak for the LED: ~ 275 nm

Wavelength peak for the UV lantern: ~ 360 nm

Experimental Setup - Building a black box

- Using a cardboard box with no bottom on top of a piece of black fabric
- Cutting two openings: one for the light source and one for the digital camera

Top-down view of the final setup

Digital Camera

Opening for the camera

Half of this fabric was taped to the workstation table on specific places to mark useful distances: where to align the cardboard box and digital camera

Side view of one iteration of the setup

The other half of the fabric was used to cover the top of the box, minimizing the light that could enter the box from the outside room

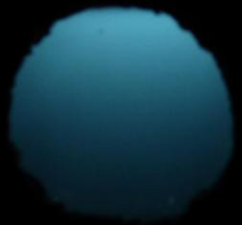
Inside the box, the fabric helped to minimize reflections

Experimental Procedure

Procedure for each concentration

The solutions were transferred to a jar that was small enough to fit inside the box and on top of a little step that we made using cardboard and placed below the fabric. The step was important to make more of the jar visible in the photographs

- Taking three photographs with the UV lantern
- Swapping the light source to the LED
- Taking three photographs with the LED

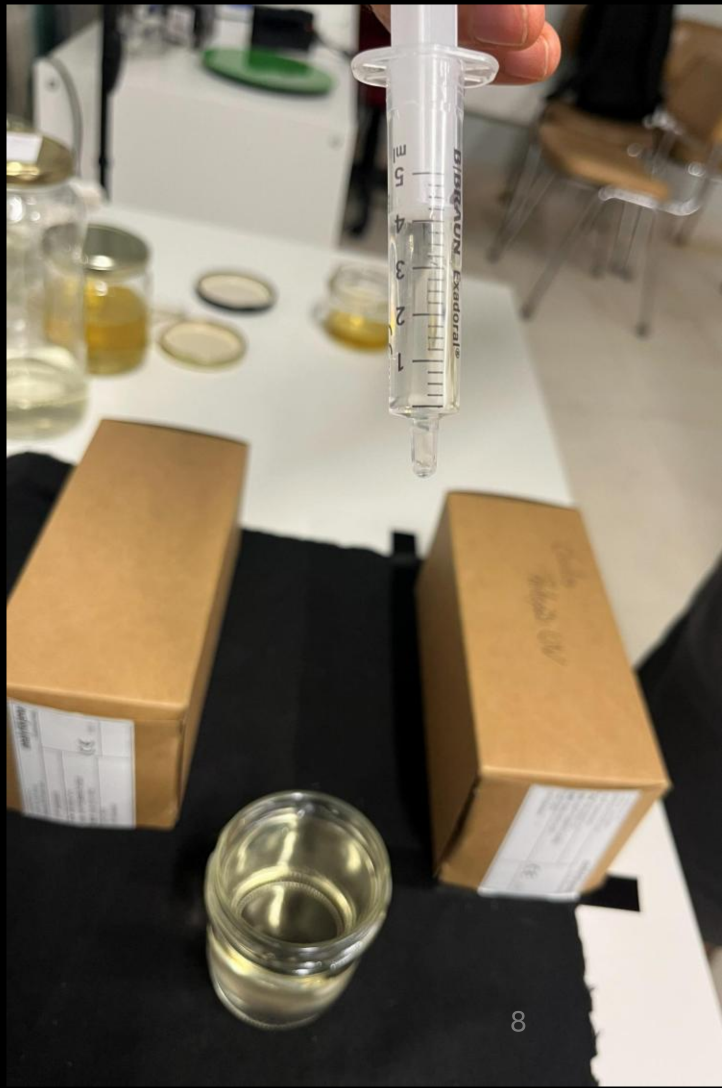


Camera characteristics

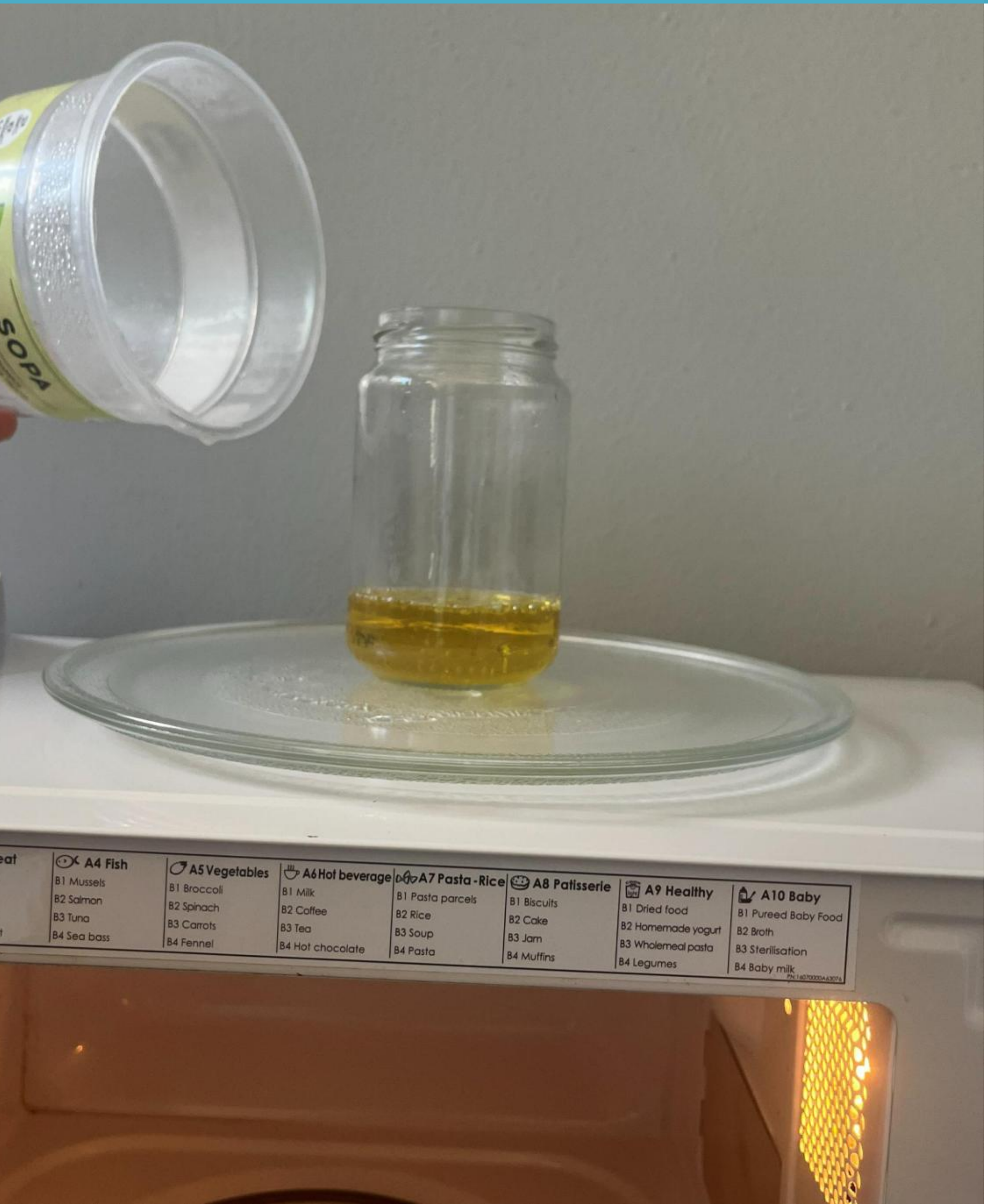
Focal length	Optical aperture (f-number)
~0.3 m	F 3.3

For each light source, the exposure time was selected based on the most luminous sample at the highest concentration (100%). The exposure was chosen to avoid saturation of the camera sensor while maximizing the recorded signal. This exposure time was then kept constant for all concentrations measured with that light source

With this, for the UV lantern it was used a 1/2 s exposure time, and since the signal recorded with the LED was substantially lower in our setup, particularly for the lower concentrations, the maximum exposure time available on the camera, 4 s, was used.

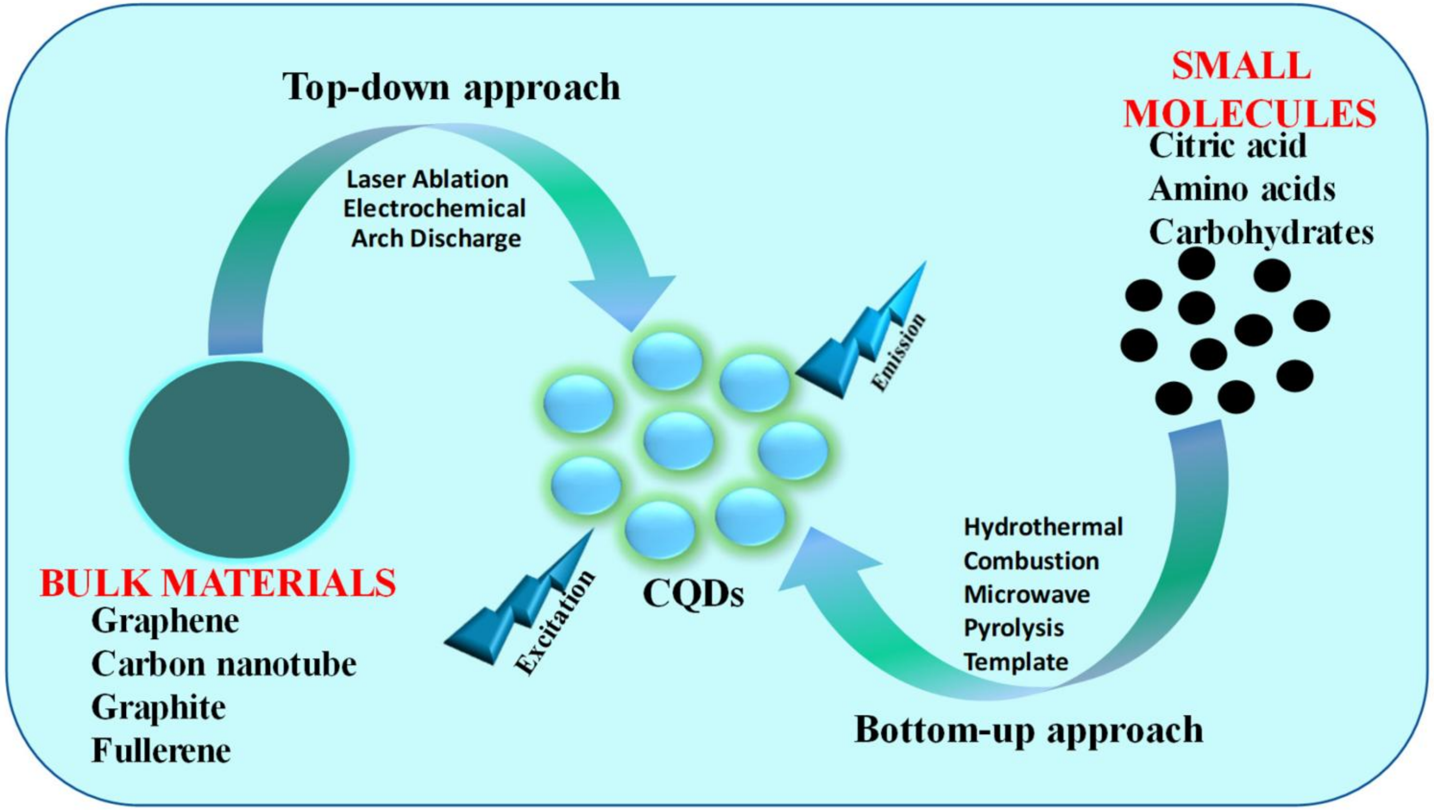


Sample Preparation



Microwave Irradiation Method

- Method for the synthesis of CQDs that requires less time and is more cost-effective compared to other methods, presenting an improved quantum yield
- Drawbacks: non-uniform particle sizes of CDQs, difficult in the separation procedure and purification



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Citric Acid Recipe

- Adding 100 g of citric acid to 100 g of water
- Going to the microwave for 11 minutes

Result: after cooling down, we got a solid compost with a lemon-yellow colour with a small white layer at the surface

- Dissolving the solid compost, adding another 100 g of water, using close to half before going to the microwave for 2 minutes and the rest after, helping to completely dissolve the compost

Sodium Bicarbonate Recipe

Initially, the solution had a colour between green and yellow, very light and transparent. After it cool down, the colour became a darker yellow, but it stayed somewhat transparent

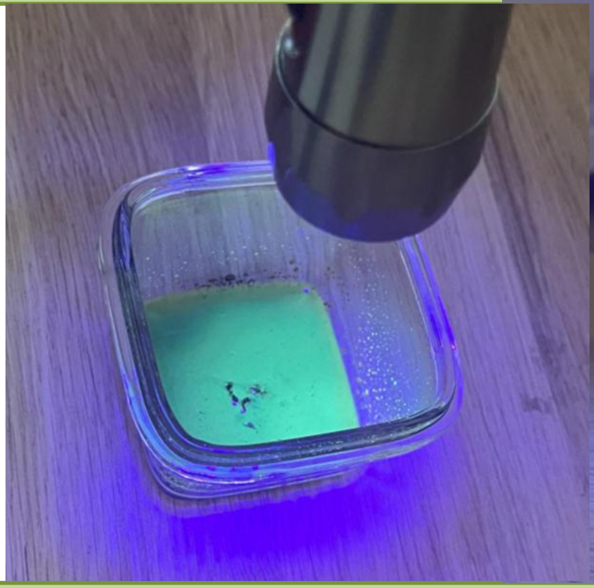
Colour Progression

Water	201 g
Sugar	80 g
Divided in two – the solution is now 139 g	
Vinegar	25 g
Time in the microwave	3 minutes
Let the solution cool down	
Sodium Bicarbonate	10 g
Time in the microwave	3 minutes

Glycine – Recipe 1

- Adding 6 g of citric acid and 6 g of glycine to 150 g of water
- Stirring for several minutes until we have a uniform solution
- Going to the microwave for 3 minutes

- Significant losses by evaporation during the time in the microwave led us to stop and take 10 mL of this solution
- Going to the microwave for 5 minutes



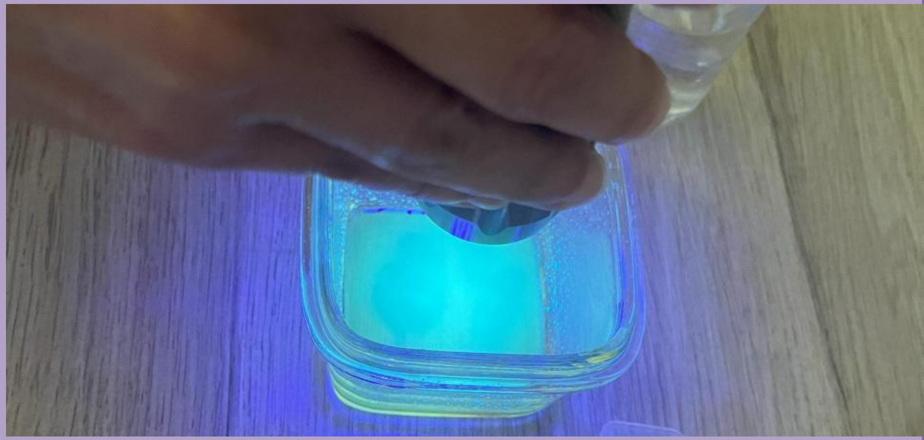
Result: a small brown compost that was first dissolved in 10 mL of water and later used 0.2 g of this solution and mixed it with 100 g of water.

Glycine – Recipe 2

- Adding the citric acid using a citric acid solution that we had made previously: 96 g of a solution with a concentration of 1/34 of the original citric acid solution
- Adding 3 g of glycine to this solution
- Stirring for several minutes until we have a uniform solution
- Getting 10 mL of the solution and going to the microwave for 3 minutes

A failed trial

Result: an even smaller brown compost that was first dissolved in 20 mL of water and later used 0.4 g of this solution and mixed it with 100 g of water



Results and Data Analysis

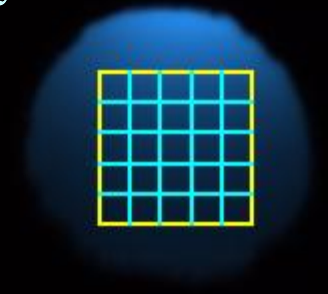
- Combining the photographs obtained using the LED source and calculate their average intensity → **determine the position of the grid**
  - They provide a more homogeneous and clearly defined illumination of the solution, making it easier to identify a suitable region for the analysis.

- Grid of 5 x 5 squares
  - The mean intensity was calculated independently for the red (R), green (G), and blue (B) channels, as well as for the total intensity

- The values ranked 10-14 in ascending order of intensity were used to make a distribution and evaluate their dispersion, providing a measure less affected by the extreme low- and high-intensity regions of the solution.

Total values: 5 values of each RGB channel for every 3 photos of the same concentration

Analysed image of the Glycine 1 solution showing the selected region used for the extraction of RGB intensity data



Colour maps for the citric acid solution at 100% showing the how heterogeneous the region selected can be

5643.97	8490.98	9814.01	9292.58	7407.29
4825.41	7032.89	7912.87	7469.02	6031.97
4159.11	5885.14	6464.69	6180.98	4970.81
3655.18	5022.13	5457.54	5215.61	4278.81
3183.49	4391.14	4716.46	4464.32	3736.19

15934.92	23708.73	27044.22	25751.77	20782.44
13371.46	19572.25	22038.87	20720.51	16701.24
11295.02	16275.53	17978.82	17064.48	13651.03
9653.17	13776.19	14997.58	14288.1	11587.16
8454.52	11855.7	12867.61	12148.88	10006.07

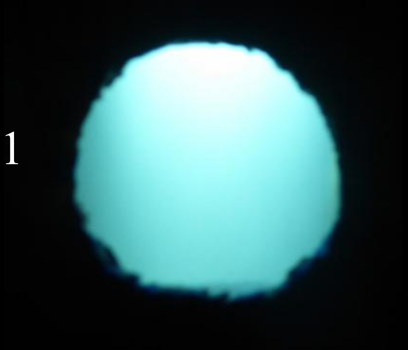
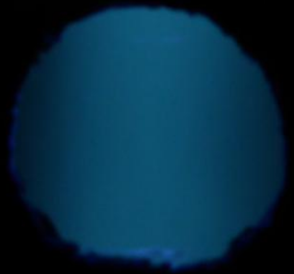
13704.47	20104.34	22815.29	21752.65	17671.41
11468.48	16582.13	18414.89	17325.02	14112.87
9594.62	13622.02	14912.2	14206.57	11437.09
8078.22	11485.95	12459.23	11780.14	9682.43
6959.21	9777.43	10582	9939.36	8272.06

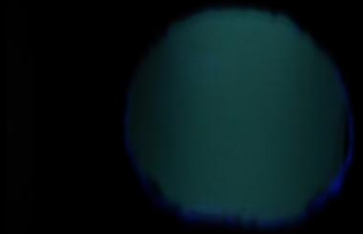
Results and Data Analysis

Linear Regression, Final Colours and RGB meaning

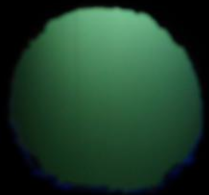
If the solution is transparent, there isn't absorption of light
→ Linear relation between the light intensity emitted and the concentration of the liquid scintillator present

Red – background and total light intensity
Green – dominant in the emission of the citric acid and sodium bicarbonate solutions
Blue   dominant in the emission of the glycines solutions

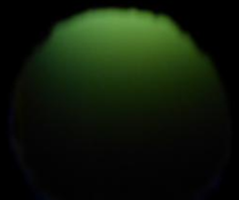
	Lantern	LED
Glycine 1		
Glycine 2		



Citric Acid, Lantern
33%



Sodium Bicarbonate, Lantern
66%

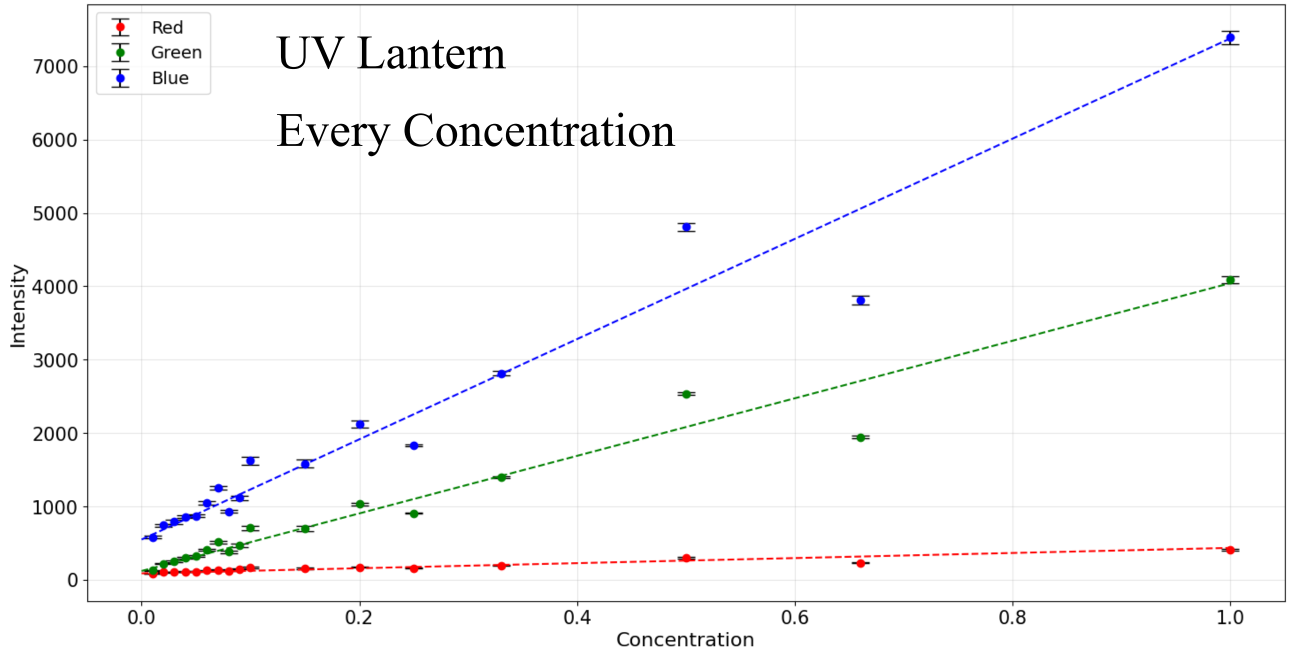


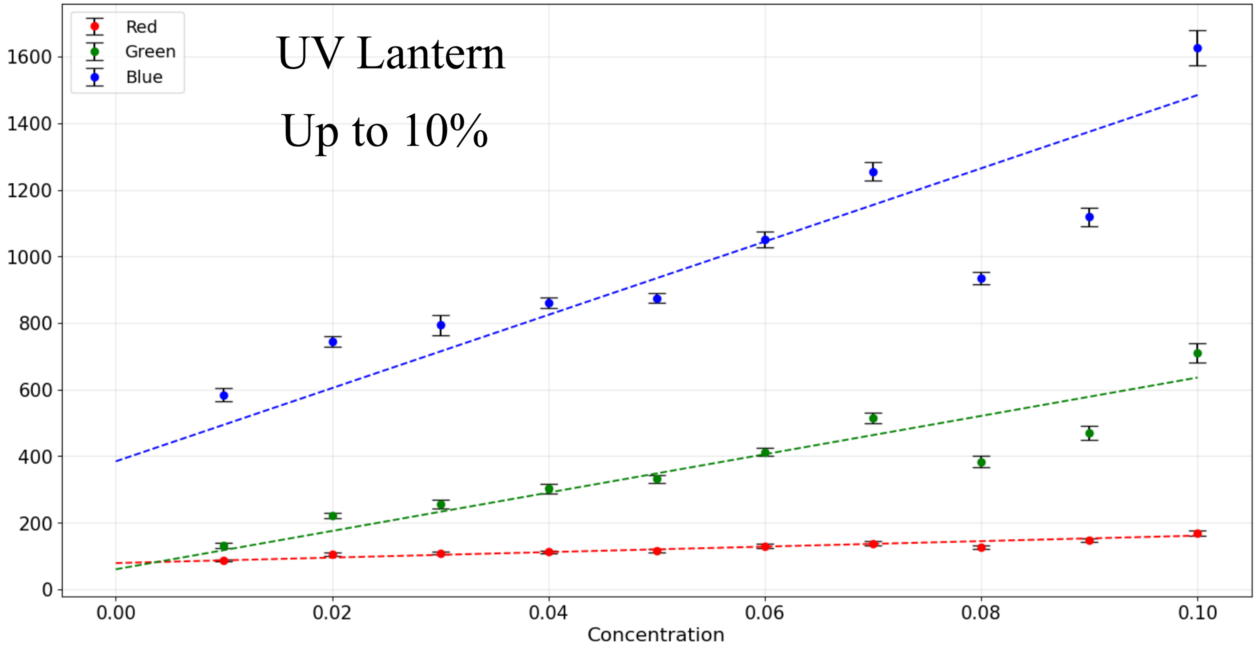
Sodium Bicarbonate, Lantern
100%

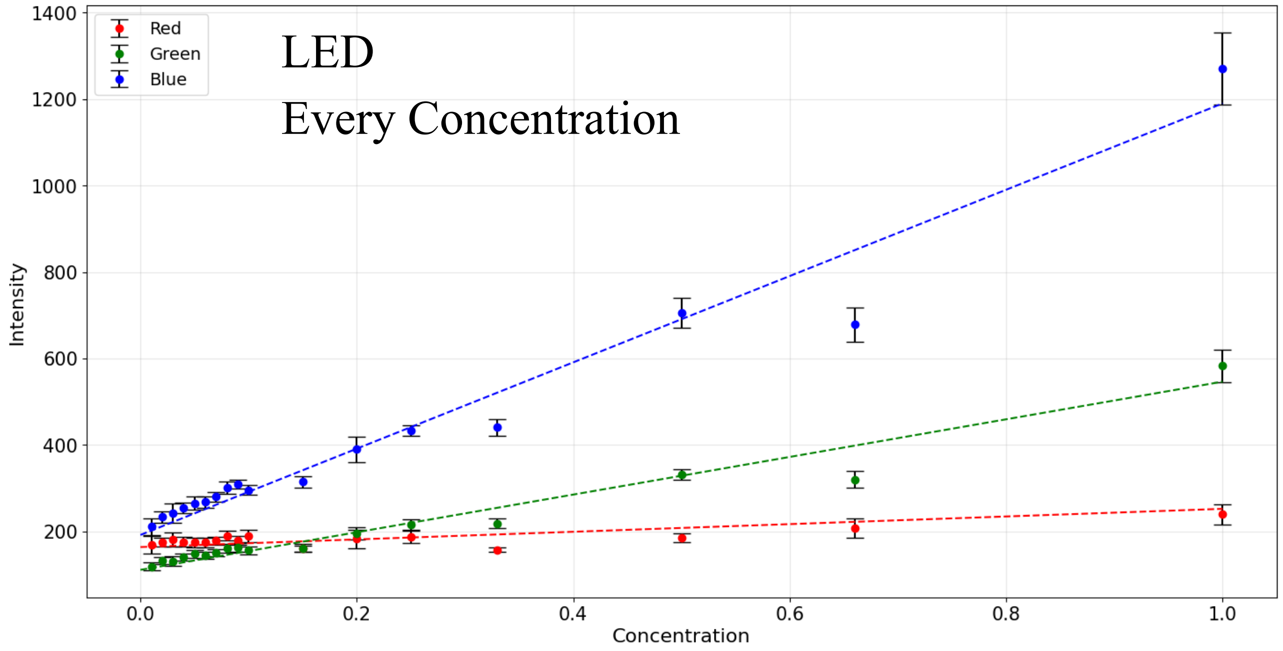
Results – Example, Data Retrieved, Glycine 1, UV Lantern

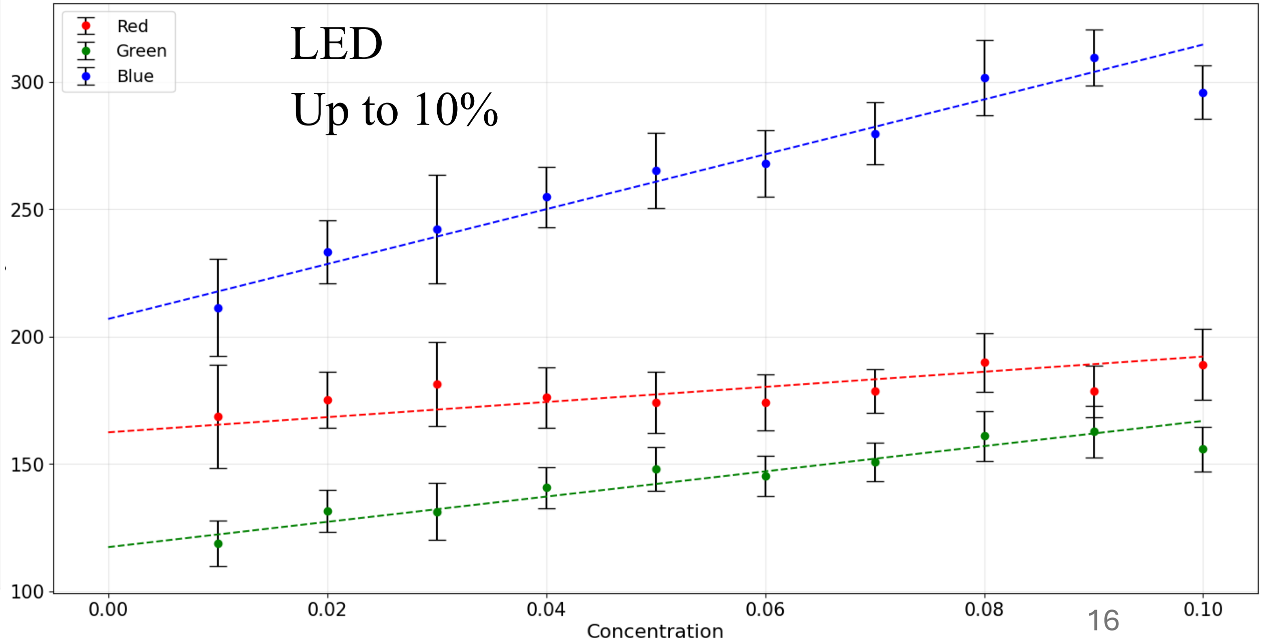
Concentration	Red	σ	Green	σ	Blue	σ
0.01	188.9	7.4	1033.3	15.5	1959.9	30.0
0.02	303.0	9.1	2156.0	46.2	3892.1	77.4
0.03	478.6	4.9	3499.2	30.3	5986.2	79.5
0.04	562.7	18.5	4011.9	128.2	6699.3	220.6
0.05	752.7	30.8	5566.5	198.6	8977.0	331.6
0.06	871.1	21.5	6320.7	172.4	10053.9	282.6
0.07	1145.0	40.8	9028.6	272.1	14343.0	368.1
0.08	1230.4	31.9	9744.3	279.3	15186.8	475.3
0.09	1063.0	18.6	7967.1	177.2	12364.4	275.8
0.1	1288.6	37.7	10010.3	325.4	15455.5	497.7
0.15	1840.5	36.6	15392.4	256.8	23414.9	372.9
0.2	2459.8	50.4	20278.3	377.4	30456.9	587.0
0.25	2363.4	48.0	18844.2	234.6	28133.0	335.8
0.33	3013.0	74.8	22957.2	438.7	33725.2	657.3
0.5	4600.5	179.0	28468.2	889.3	38043.0	1229.4
0.66	5826.6	135.2	38697.3	1113.2	54269.1	1797.3
1	9983.7	673.3	50993.5	3443.9	60300.4	3543.2

Results - Glycine 2, Linear Regression

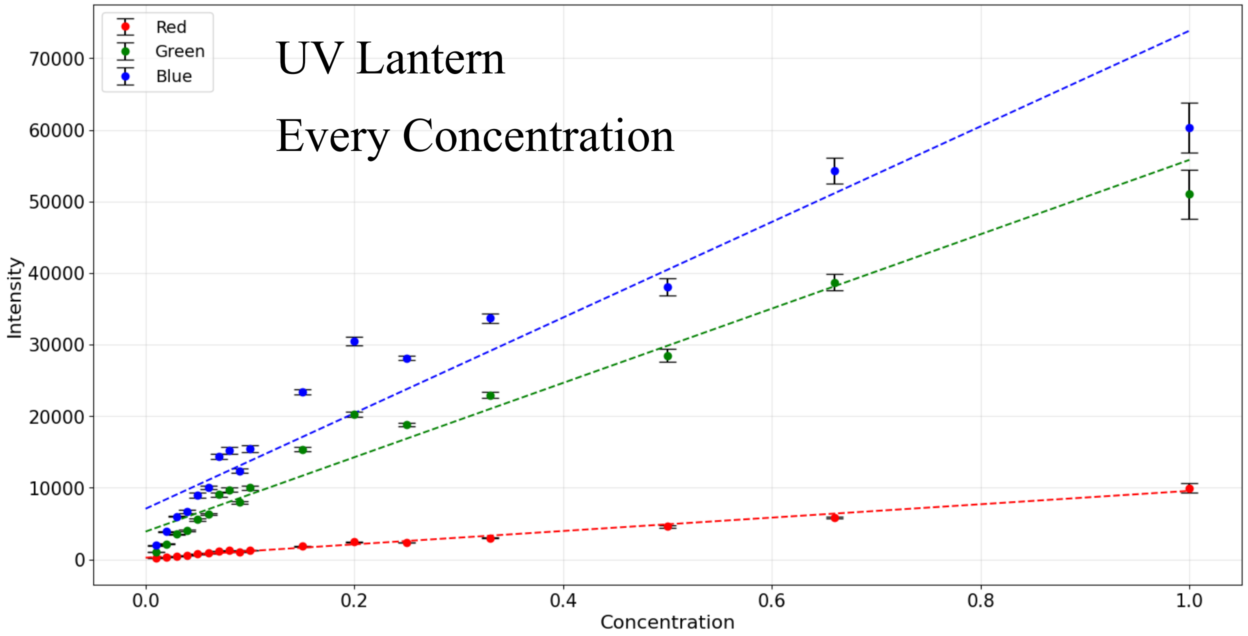


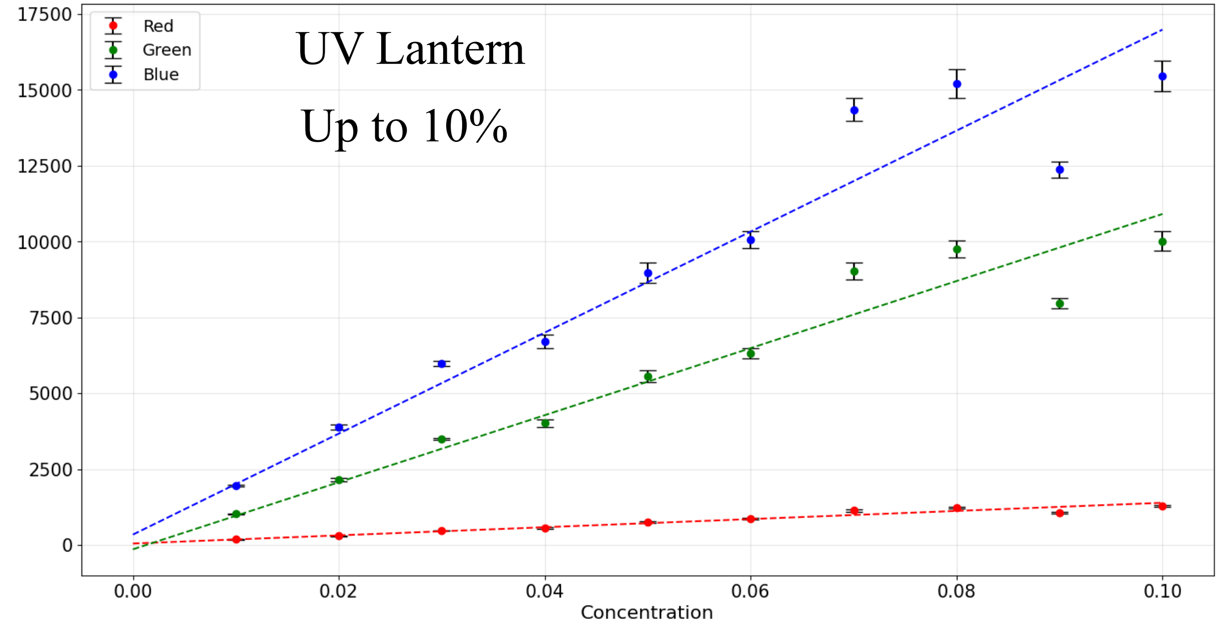


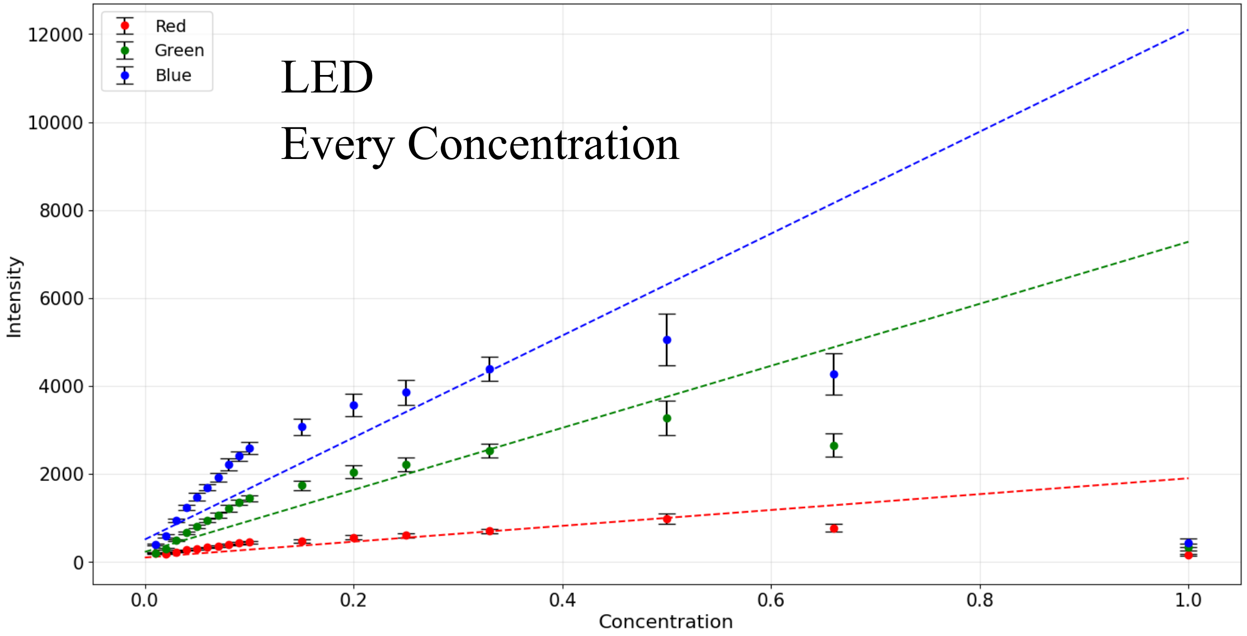


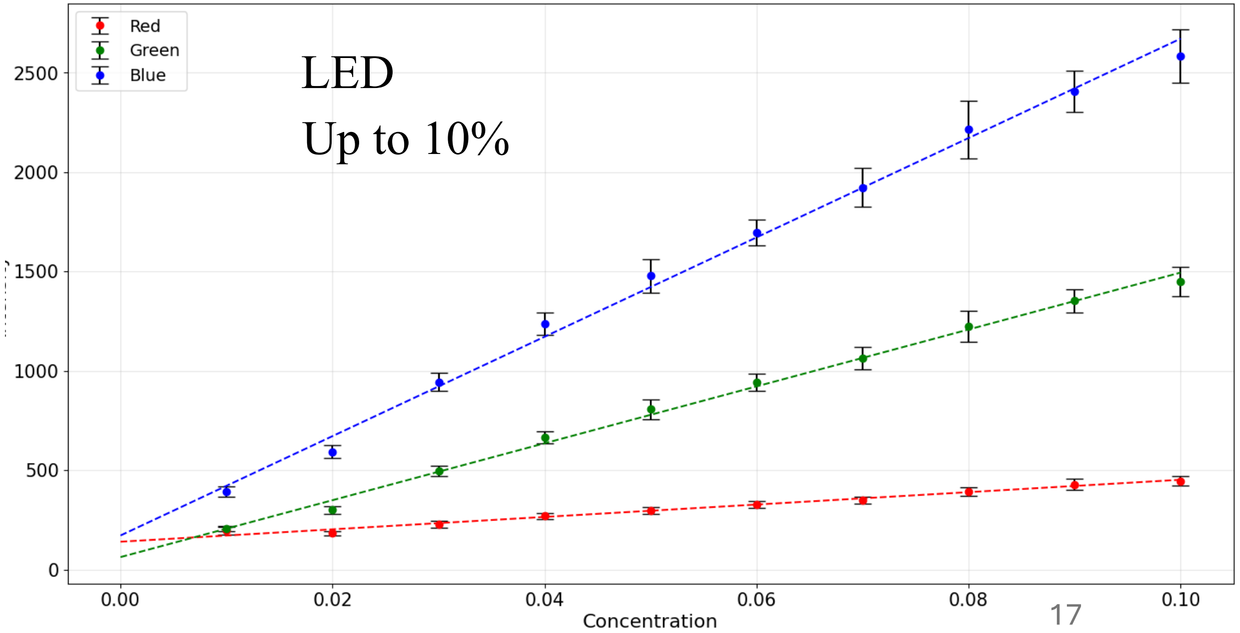


Results – Glycine 1, Linear Regression









Results – Glycine 1 and Glycine 2

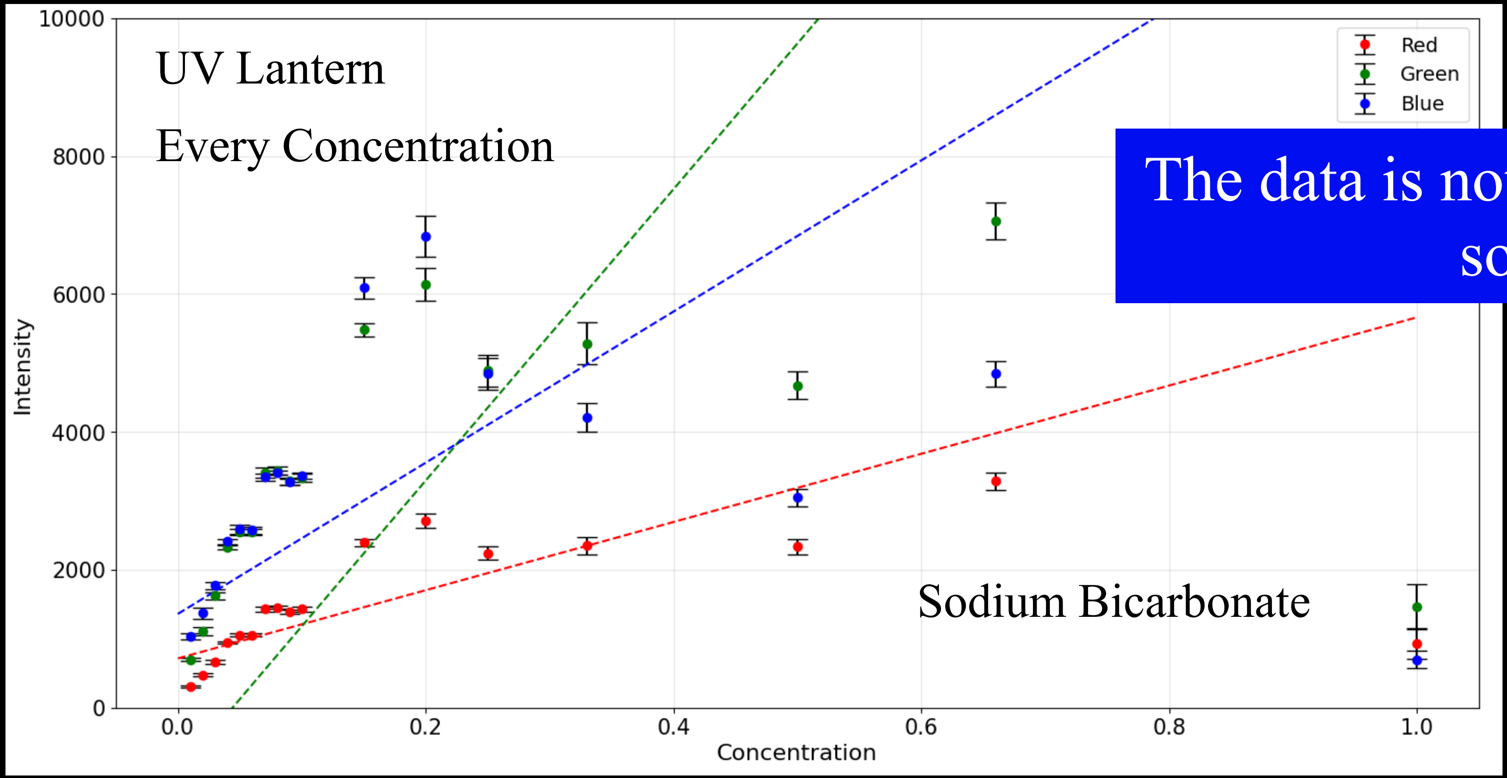
		Red					
		Every concentration			Up to 10%		
		χ^2 reduced	slope	intercept	χ^2 reduced	slope	intercept
Glycine 1	UV Lantern	56.34	9336.27	234.45	22.14	13417.16	50.46
	LED	950.88	2222.67	-30.51	0.71	3117.24	139.77
Glycine 2	UV Lantern	12.30	312.22	101.80	2.49	824.28	78.81
	LED	4.18	88.57	163.74	0.36	309.98	161.48

		Green					
		Every concentration			Up to 10%		
		χ^2 reduced	slope	intercept	χ^2 reduced	slope	intercept
Glycine 1	UV Lantern	3717.44	51928.52	3880.57	29.67	108274.09	10.07
	LED	585.06	6325.27	261.61	0.99	14312.66	62.44
Glycine 2	UV Lantern	158.45	3921.60	122.30	22.41	5941.99	46.61
	LED	2.97	435.16	111.06	0.37	495.63	117.29

		Blue					
		Every concentration			Up to 10%		
		χ^2 reduced	slope	Intercept	χ^2 reduced	slope	intercept
Glycine 1	UV Lantern	2878.09	66779.50	7071.65	32.19	164704.89	457.10
	LED	1007.17	11291.10	376.09	1.24	24992.35	171.26
Glycine 2	UV Lantern	121.15	6828.18	550.54	72.46	11252.22	365.65
	LED	4.46	997.84	191.84	0.56	1077.35	206.88

Results – Sodium Bicarbonate and Citric Acid, UV Lantern

	Red			Green			Blue		
	χ^2 reduced	slope	intercept	χ^2 reduced	slope	intercept	χ^2 reduced	slope	intercept
Sodium Bicarbonate	186.07	5224.09	624.03	330.53	11158.83	1737.87	2313.03	15476.82	-37.23
Citric Acid	44.40	5711.00	35.39	88.22	15607.17	169.16	95.53	12317.99	1080.39

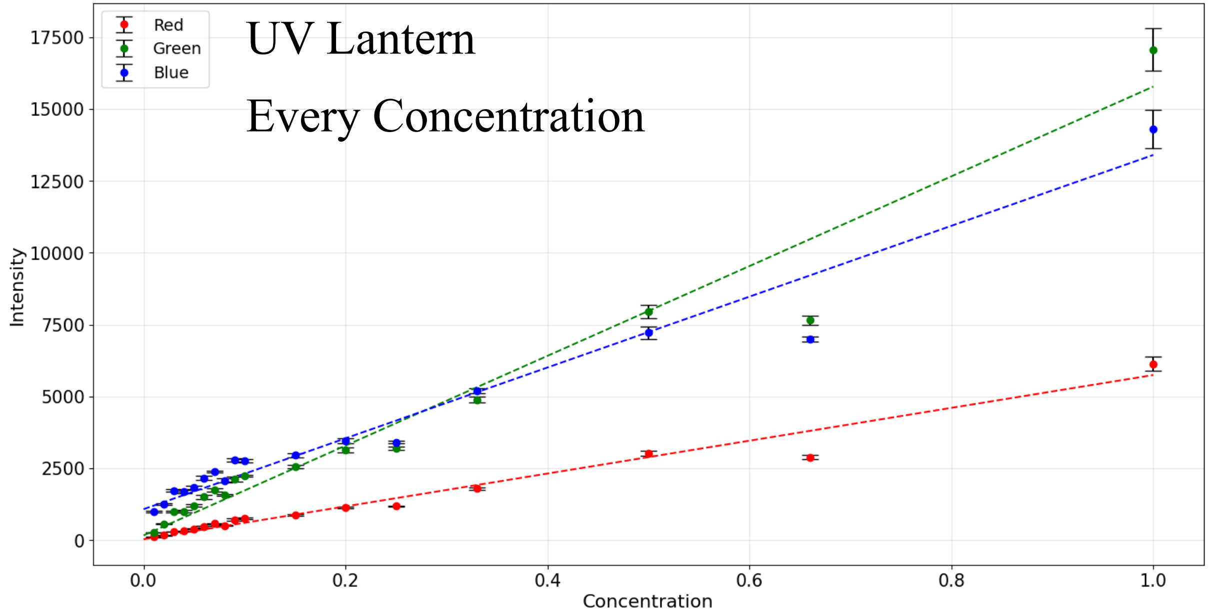


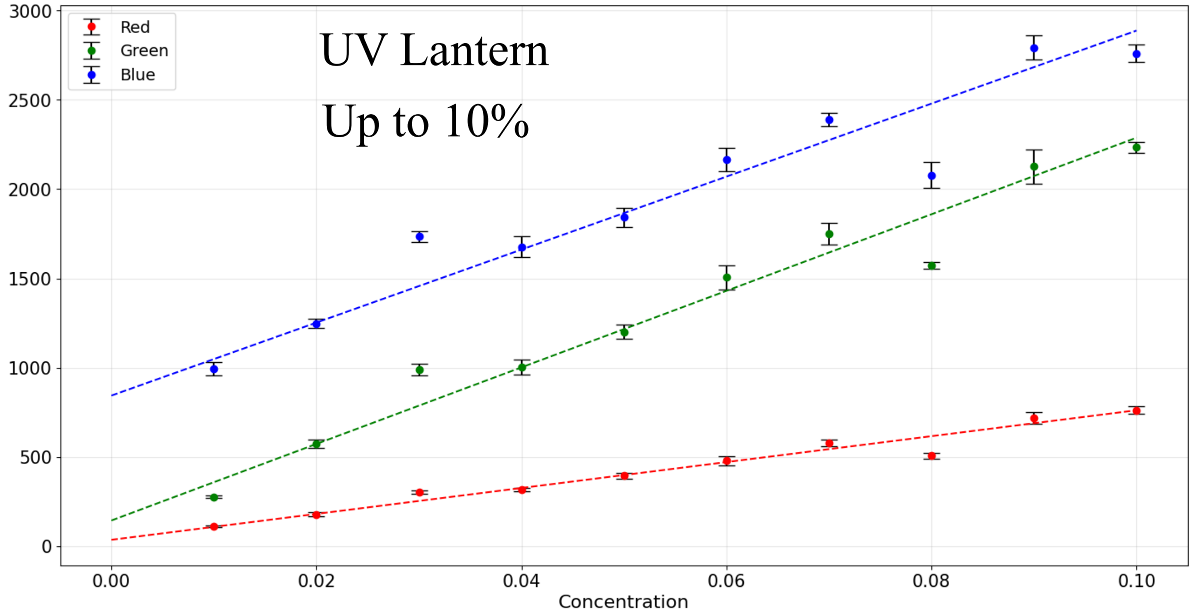
The data is not linear and that was expected, since the solutions are not transparent!

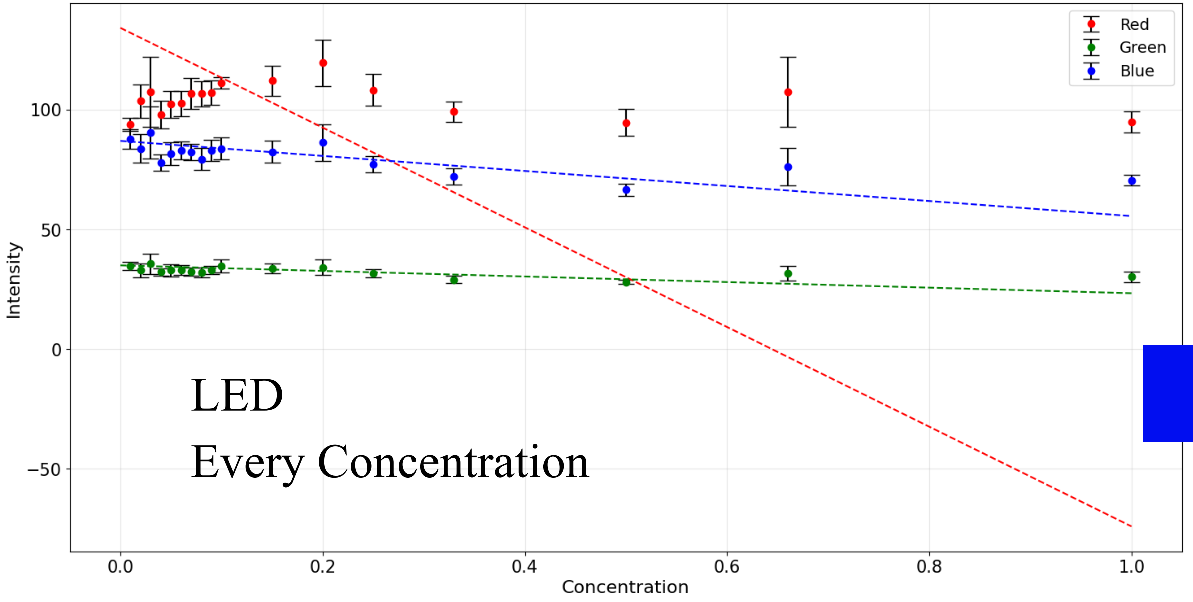
Results – Citric Acid

Every Concentration		Up to 10%	
Green χ^2 reduced	Blue χ^2 reduced	Green χ^2 reduced	Blue χ^2 reduced
330.53	2313.03	453.23	58.57

Not Linear







Linear, but…

Conclusions and Future Work

Conclusions

- Production of 4 different recipes of liquid scintillators based on carbon quantum dots
- Linear behaviour present?
  - Sodium Bicarbonate and Citric Acid – No, because the solutions were not transparent

	Every Concentration		Up to 10%	
	Green χ^2 reduced	Blue χ^2 reduced	Green χ^2 reduced	Blue χ^2 reduced
Citric Acid, UV Lantern	330.53	2313.03	453.23	58.57

  - Glycine 1 and Glycine 2:

	Every Concentration		Up to 10%	
	Green χ^2 reduced	Blue χ^2 reduced	Green χ^2 reduced	Blue χ^2 reduced
Glycine 1, UV Lantern	3717.44	2878.09	29.67	32.19
Glycine 1, LED	585.06	1007.17	0.99	1.24
Glycine 2, UV Lantern	158.45	121.15	22.41	72.46
Glycine 2, LED	2.97	4.46	0.37	0.56

Future Work

- Repeating the experiment:
  - Diluting more the Sodium Carbonate and Citric Acid solutions, so they become transparent
  - Verifying if the behaviour of the Glycine 1 and Glycine 2 solutions is maintained
  - Using spectroscopy to see the emission spectrum of the different recipes with the two light sources
  - Diluting less the Glycine 1 and Glycine 2 solutions so they are not transparent and repeating the emission spectroscopy
    - Repeating the emission spectroscopy for the Sodium Carbonate and Citric Acid solutions when they are not transparent (original solutions)

What happens at higher concentrations?

How can the two different light sources explain the differences in χ^2 reduced?