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Benchmarking a Portable Low-Cost Spectrometer for Algal Fluorescence: Applications in Remote Sensing and Water Quality Monitoring

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Abstract

Philippine inland waters experience increasing pressures of nutrient enrichment and algal blooms which threaten water quality, biodiversity, and human health. Chlorophyll monitoring, the most critical indicator of algal biomass, plays a key role in eutrophication evaluation and identification of harmful algal blooms (HABs). Satellite and unmanned aerial vehicle (UAV)-based remote sensing technology provides large area chlorophyll-a mapping, with accuracy dependent on precise ground-truth measurements for calibration and validation. This paper presents the design and verification of a low-cost fluorescence spectrometer for potential in-situ chlorophyll-a measurement that supports geospatial benchmarking and the validation of remote sensing. The spectrometer consists of a Hamamatsu C12880MA mini spectrometer contained in a Raspberry Pi microcontroller with an LED-based excitation source to detect chlorophyll a fluorescence emission in *Chlorella vulgaris* samples. Laboratory tests compared the developed spectrometer with a commercial Ocean Optics fluorescence spectrometer, and with a high correlation between excitation spectra ($R^2 = 0.9304$) and moderate correlation between emission spectra ($R^2 = 0.7269$), validating that the system can detect chlorophyll-a fluorescence signals as relevant to the spectral bands used in satellite-based water quality indexes. Though proven under laboratory conditions, the low-cost, compact design provides for prospective field deployment for real-time monitoring. The built fluorescence spectrometer thus provides an emerging, scalable approach to ground-based spectral measurement, bridging laboratory instrumentation and geospatial remote sensing applications to improve the accuracy and temporal resolution of freshwater quality monitoring.

1. Introduction

Algae are crucial to aquatic ecosystems and are extensively applied as biological water quality indicators. Algae are ideally suited for tracking environmental change due to their rapid growth, nutrient sensitivity, and brief life cycles (Gokce, 2021). Chlorella vulgaris stands out due to its cosmopolitan distribution, ecological significance, and well-documented photosynthetic pigments like chlorophyll a, an important proxy for algal biomass and primary productivity estimation (Gupta et al., 2020; González et al., 2021). Philippine freshwater ecosystems such as Laguna de Bay and Lake Taal are being subjected to more and more eutrophication due to agricultural, industrial, and domestic effluent releases, causing harmful algal blooms (HABs) that have detrimental effects on biodiversity, fisheries, and water security (Azanza et al., 2018). Early detection of pigment fluctuations is necessary for water quality determination and HAB management (Hu et al., 2019; Cadondon et al., 2023).Traditional chlorophyll-a analysis relies on laboratory spectrometers and discrete sampling, which are costly and spatially limited (Zhu et al., 2023). Remote sensing technologies such as satellite and UAV-based hyperspectral imaging provide large-scale, near-real-time monitoring but require accurate ground-truthing data for calibration and validation (Dekker et al., 2001; Chang et al., 2021). The absence of reliable, field-level chlorophyll measurements remains a critical bottleneck between remote sensing observations and quantitative water quality estimates. Low-cost optical sensors offer a promising bridge between laboratory precision and field practicality. Recent studies have demonstrated the potential of compact spectrometers, such as the Hamamatsu C12880MA, for water reflectance and absorbance measurements (Laganovska et al., 2020; Jechow et al., 2024). However, most affordable systems lack fluorescence capability, a more sensitive method for detecting chlorophyll-a and related pigments (Hu et al., 2019). This study develops and evaluates a low-cost fluorescence spectrometer using the Hamamatsu C12880MA for in situ algal monitoring with explicit geospatial benchmarking applications. The spectrometer's fluorescence data can serve as ground-reference information for validating chlorophyll-a retrievals from remote sensing platforms such as Sentinel-2, Landsat 8, and MODIS. The device bridges laboratory analysis and geospatial monitoring by establishing spectral correspondence between field-measured chlorophyll fluorescence and satellite-observed reflectance in the red and near-infrared bands. This approach can strengthen geospatial observation networks and support early warning systems for freshwater ecosystems in the Philippines by enabling cost-effective, scalable monitoring.

2. Methods

2.1 Development of the Portable Spectrometer

The spectrometer setup was modeled and developed based on the study of (Tunens et al., 2024). The present study modified and used a spectrometer-based system with fluorescence capabilities. The design was adapted to allow efficient detection of algal pigments. The spectrometer was developed using the Hamamatsu C12880MA mini spectrometer with a spectral response (340 to 850 nm) connected to a Raspberry Pi 4 microcontroller. A light-emitting diode (LED) was the light source, as it has a broad and stable spectral output in the UV-Visible range. The parts, such as Hamamatsu C12880MA, light source, and sample holder, were positioned inside a 3D-printed enclosure to reduce unwanted light scattering and enhance signal stability. The light source illuminated the sample in the cuvette holder. The resulting emission was gathered at a 90° angle with respect to the excitation beam and then detected by the spectrometer, as shown in Figure 1. This configuration avoids complexity and cost with the assurance of stable performance. The Raspberry Pi will read and process the spectral data, utilizing a script (https://osf.io/wy852/metadata/osf) to capture and display the data.

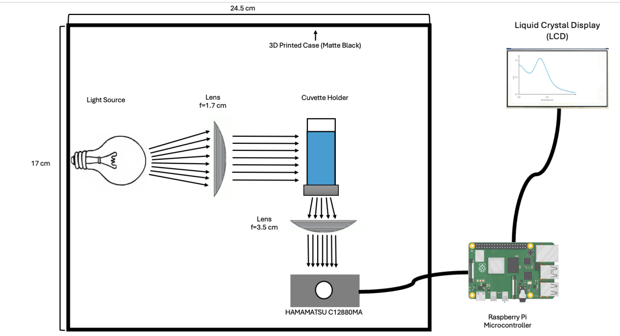


Figure 1. Schematic Diagram of the developed spectrometer for fluorescence analysis.

2.2 Spectrometer Components and Specifications

The developed fluorescence spectrometer was constructed using three main components: the Hamamatsu C12880MA mini-spectrometer, a Raspberry Pi 4 Model B microcontroller, and a 5-inch LCD display. Each component was selected based on its compactness, performance, and suitability for low-cost, field-deployable optical measurements. The Hamamatsu C12880MA module serves as the core detection element, offering a spectral response range of 340–850 nm and a spectral resolution of up to 15 nm. It integrates a diffraction grating, slit, and CMOS sensor in a single compact package, allowing for precise light detection across the visible and near-infrared regions. The Raspberry Pi 4 Model B functions as the central processing unit, equipped with a Broadcom BCM2711 quad-core processor capable of handling spectrometer communication, data acquisition, and signal processing. Python-based software was used to control the spectrometer, visualize real-time spectral data, and perform calibration and normalization routines. The 5-inch LCD touch display provides an intuitive graphical interface developed using PyQt5 and PyQtGraph, enabling the user to view spectral curves, control measurement settings, and save data directly. As shown in Figure 2, these components form a portable and suitable instrument for fluorescence analysis of algal pigments and chlorophyll monitoring.

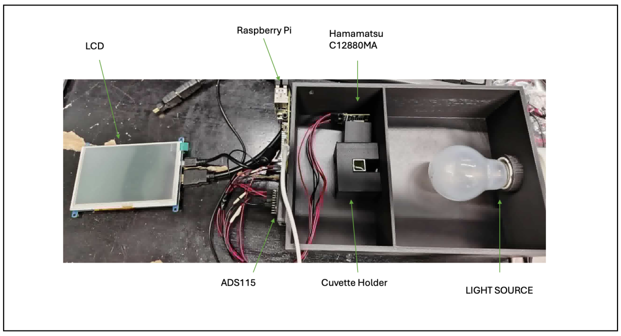


Figure 2. Developed fluorescence spectrometer

Parameter	Specification
Dimensions	20.1 × 12.5 × 10.1 mm
Weight	5 g
Spectral Response Range	340–850 nm
Spectral Resolution	15 nm (max)
Interface	CMOS-compatible video output
Power Supply Voltage	4.5–5.5 V
Operating Temperature	5–50 °C

Table 1. Hamamatsu C12880MA mini spectrometer specifications.

Parameter	Specification
Processor	Broadcom BCM2711 Quad-core Cortex-A72 (1.5 GHz)
RAM	8 GB LPDDR4-3200 SDRAM
USB Ports	2 × USB 3.0, 2 × USB 2.0
Video Output	2 × micro HDMI (4Kp60 supported)
Networking	Gigabit Ethernet, Wi-Fi 802.11ac, Bluetooth 5.0
Power Supply	5V/3A via USB-C
Operating Temperature	0–50 °C

Table 2. Raspberry Pi 4 Model B specifications.

Parameter	Specification
Display Size	5 inches
Resolution	800 × 480 pixels
Interface	HDMI + GPIO touch interface
Touch Type	Capacitive multi-touch
Operating Voltage	5V
Compatibility	Raspberry Pi 4B, 3B+, and other SBCs
Operating Temperature	-20–70 °C

Table 3. 5-inch LCD display specifications.

Parameter	Specification
Type	LED Light Source
Wavelength	450 nm
Power Rating	10 W
Input Voltage	AC 85–256 V
Application	Excitation source for fluorescence measurements

Table 4. Specifications of the 450 nm LED light source used in the developed spectrometer.

Tables 1–4 summarize the major hardware components and specifications of the developed fluorescence spectrometer and respectively present the detailed specifications of the Hamamatsu C12880MA spectrometer, the Raspberry Pi 4 Model B microcontroller, the 5-inch LCD module and 450 nm LED light source used for data display. Together, these components constitute a fully integrated, low-cost spectroscopic platform capable of performing fluorescence measurements in real time. The compact design, energy efficiency, and modular construction make the system suitable for portable or in-field algal fluorescence analysis.

2.3 Full Width at Half Maximum (FWHM) Calibration

Calibration was carried out using known light sources like mercury lamp to evaluate the resolution of the mini spectrometer. These sources emit light at well-documented, specific wavelengths. By examining the spectral peaks captured by the mini spectrometer, the FWHM values were determined. This is the width of each spectral peak at half of its maximum intensity and is a measure of the spectrometer's capability to resolve closely spaced spectral features.

2.4 Sample Preparation and Measurement

Chlorella vulgaris was obtained from The Phycology Laboratory I, Institute of Biological Sciences (IBS), University of the Philippines Los Ba˜nos (UPLB), Philippines. Each measurement used one (1) mL aliquot of algal suspension. The sample was transferred into a clean cuvette (1 cm) and placed inside the sample holder of the spectrometer setup. All measurements were conducted in a dark room. These measurements are crucial for identifying the pigment signals, which served as a reference for validating the performance of the low-cost spectrometer. Both the developed and commercial spectrometer systems were used to make the measurements for benchmarking.

2.5 Comparative Analysis

Fluorescence spectra of algal pigment samples were sequenced and collected using the two spectrometers while keeping the excitation wavelength and acquisition parameters consistent. The resulting spectral data were normalized for background noise and intensity variation.

Component	Commercial	Developed
Lamp	Xenon PHX-2000 (180–2000 nm)	LED (450 nm)
Monochromator	Monoscan 2000 (250–800 nm, 1 nm)	None
Fiber Optics	P600-2SR (200–1100 nm)	Direct path
Probe	QR600-7-SR-125F, cuvette holder	Integrated holder
Spectrometer	USB2000+XR1-ES (200–1025 nm)	Hamamatsu C12880MA (340–850 nm)
Software	OceanView	Python + RPi GUI
Integration Time	20,000 ms (offset 10000)	10 ms
Power Output	0.0016 mW	0.2405 mW
Max Intensity	1773 a.u	14735 a.u

Table 5. Specifications of commercial and developed spectrometer components.

Data analysis focused on correlating the fluorescence intensity values obtained from the developed spectrometer with those measured using a commercial Ocean Optics spectroscopy system (HPX-2000 Xenon lamp with USB2000+ XR1-ES spectrometer) at the EARTH Laboratory, De La Salle University. As described in the study of (Cadondon et al., 2022), the commercial setup served as the benchmarking reference, ensuring that the custom-built spectrometer produced accurate and reliable results. Table 1 shows the specifications of both spectrometers.

3. Results and Discussions

3.1 Calibration in determining the full-width half max (FWHM)

The Hamamatsu C12880MA mini spectrometer was calibrated using standard spectral light sources, specifically mercury lamp, to ensure wavelength precision and evaluate spectral resolution. The calibration procedure enabled the determination of the spectrometer's full width at half maximum (FWHM). Figure 3 illustrates the recorded emission spectrum of the mercury lamp, showing its characteristic spectral lines.

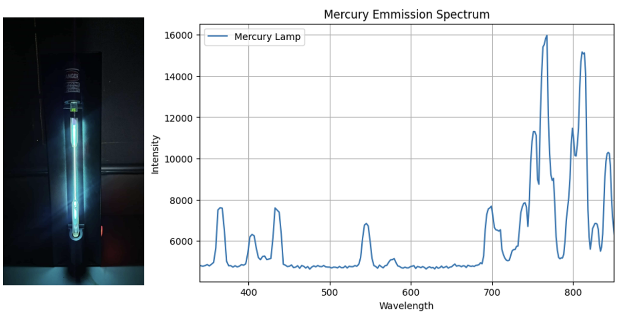


Figure 3. Emission spectrum of mercury lamp captured by Hamamatsu C12880MA

The spectral resolution of the developed spectrometer was evaluated through calibration using emission lines from reference light sources, such as mercury and hydrogen lamps. The full width at half maximum (FWHM) of each distinct emission peak was computed to assess the system's resolving capability. The FWHM represents the width of a spectral line measured at half of its maximum intensity, and it was calculated using the relation:

$$\text{FWHM} = \lambda_2 - \lambda_1 \quad (1)$$

where λ_1 and λ_2 correspond to the wavelengths at which the emission intensity is equal to half of the maximum peak intensity ($I_{\text{max}}/2$). The FWHM values for all identified peaks were averaged to obtain the overall spectral resolution of the spectrometer, as expressed by:

$$\overline{\text{FWHM}} = \frac{1}{n}\sum_{i=1}^{n} \text{FWHM}_i \quad (2)$$

Based on the calibration data obtained from the mercury lamp, the calculated FWHM values ranged between 0.5 nm and 10.3

nm across 19 emission peaks, resulting in an average FWHM of approximately 4.04 nm. This value aligns with the expected spectral resolution of the Hamamatsu C12880MA mini-spectrometer, which is typically within 15 nm under standard conditions.

3.2 Fluorescence Measurement

The performance of the spectrometers was evaluated using the fluorescence analysis of *Chlorella vulgaris*. For every measurement, 1 ml of the algal suspension was transferred into a clean cuvette and measured under the same conditions. Both systems were excited at 450 nm, with the commercial spectrometer measuring emission at 690 nm, while the low-cost developed spectrometer exhibited emission in the vicinity of 690–700 nm. Figure 4 illustrates that both systems show the primary spectral features; however, the low-cost spectrometer has wider peaks with lower relative intensity than the reference spectrometer, whose responses were sharper and included higher spectral resolution. The positions of the spectral peaks determine the system's capability to detect characteristic emission features accurately.

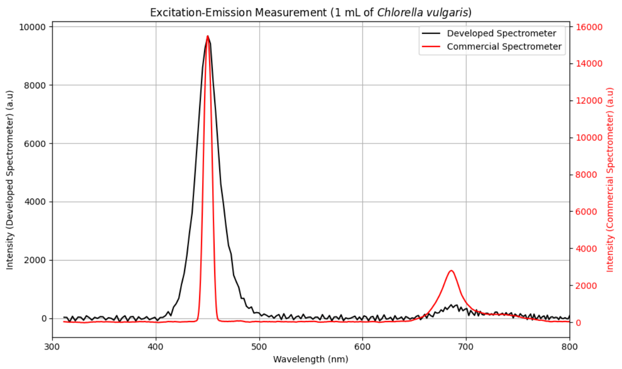


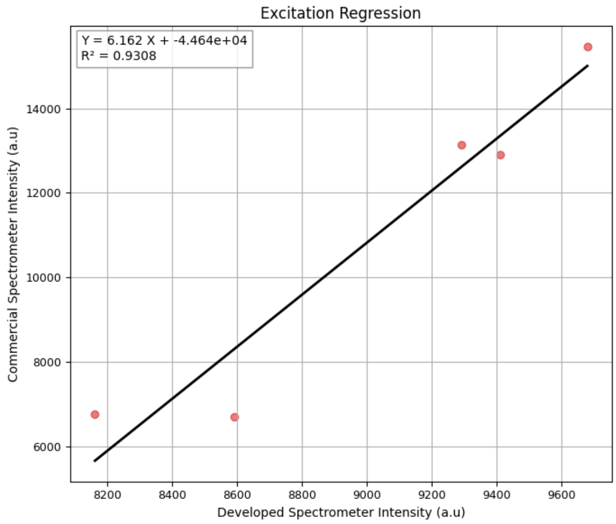
Figure 4. Excitation and Emission spectra of *Chlorella vulgaris* measured using the developed low-cost spectrometer and a commercial spectrometer.

Under blue-light excitation at 450 nm, the fluorescence emission spectrum of the *Chlorella vulgaris* displayed a strong peak centered around 680 nm, which corresponds to the characteristic emission of chlorophyll-a. This red emission band arises from the relaxation of excited chlorophyll-a molecules, confirming the presence and activity of this primary photosynthetic pigment in green algae. The result agrees with previous reports showing that chlorophyll a typically emits in the red region (600–700 nm) under blue excitation. (Cadondon et al., 2022; Marcek Chorvatova et al., 2020) reported that fluorescence emission spectra recorded at various excitation wavelengths (375 nm, 450 nm, and 630 nm) exhibited a maximum emission near 680 nm, consistent with the major fluorescence band of chlorophyll a. Similarly, (Marcek Chorvatova et al., 2020) also showed that blue excitation at 450 nm produced a dominant emission at 680 nm, validating this wavelength as the principal fluorescence signal of chlorophyll a in algae.

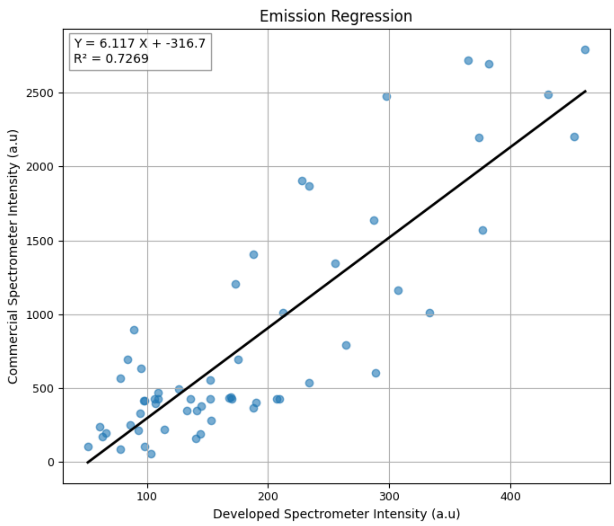
In addition, (Cadondon et al., 2022) observed chlorophyll-a emission peaks in Spirulina using a portable fluorescence system, reinforcing that the 680 nm signal represents the dominant chlorophyll-a emission. In some spectra, weak emissions were also observed near 540 nm, which may be attributed to accessory pigments such as flavins, carotenoids, and other phenolic compounds. These results demonstrate that the developed spectrometer-based system can effectively detect algal pigment and resolve chlorophyll-a emissions under blue excitation.

3.3 Correlation

Linear regression was performed to evaluate the correlation between the developed and commercial spectrometer measurements for both excitation and emission spectra. First, the raw intensity data from the commercial spectrometer were interpolated to match the wavelength points of the developed spectrometer, ensuring a direct point-by-point comparison. Only data points above a defined intensity threshold were used to minimize noise and non-detectable signals. Subsequently, linear regression was applied to these overlapping data points, yielding the slope, intercept, and coefficient of determination (R^2) for each spectral range. This approach allowed quantification of how well the developed spectrometer reproduces the commercial system's measurements and provides a basis for its calibration.



(a)



(b)

Figure 5. Performance evaluation of commercial and developed spectrometer.

As shown in Figure 5, the regression analysis showed a strong linear relationship between the developed and commercial spectrometers for excitation measurements ($R^2 = 0.9304$), indicating high accuracy in detecting excitation signals. In contrast, emission measurements exhibited a moderate correlation ($R^2 = 0.7269$), showing that the developed spectrometer was still capable of accurately detecting emission signals, though with some variability.

3.4 Geospatial Relevance of the Developed Spectrometer

The developed low-cost spectrometer system has potential applications beyond laboratory characterization, particularly in geospatial and remote sensing studies. By detecting chlorophyll a fluorescence around 680 nm, the device can serve as a ground-truthing instrument for validating satellite-derived chlorophyll indices and fluorescence measurements. In remote sensing, spaceborne sensors such as Sentinel-2 MSI and the upcoming ESA FLEX mission capture red and far-red chlorophyll fluorescence to assess vegetation photosynthetic activity and stress (Alikas et al., 2023; Drusch et al., 2017). Ground-based instruments like the developed spectrometer can provide in situ reference spectra to calibrate or verify these satellite observations under field conditions.

4. Conclusion

A low-cost spectrometer using a Hamamatsu C12880MA and a Raspberry Pi microcontroller was effectively developed and compared with a commercial spectrometer. The regression analysis indicated a good linear correlation for excitation measurements ($R^2 = 0.9304$), validating that the developed system successfully measured excitation signals. Emission measurements also correlated well ($R^2 = 0.7269$), demonstrating that the spectrometer successfully measured emission signals. These observations reinforced the potential of the developed spectrometer to be used as a cost-effective and portable substitute for fluorescence measurements. Moreover, the established correlation will serve as a reference for calibrating the developed spectrometer, ensuring consistency with the performance of the commercial system. The fluorescence-based chlorophyll a measurements obtained from the developed spectrometer can be directly used as ground-truth data for validating remote sensing–derived chlorophyll indices such as NDVI and FAI from satellites like Sentinel-2 or Landsat 8. By establishing point-based fluorescence intensity values, the system enables spectral correspondence between in-situ chlorophyll concentration used in water quality remote sensing.

References

Alikas, K., Kangro, K., Kõks, K.-L., Tamm, M., Freiberg, R., Laas, A., 2023. Consistency of six in situ, in vitro and satellite-based methods to derive chlorophyll a in two optically different lakes. *Frontiers in Environmental Science*, 10. https://www.frontiersin.org/journals/environmental-science/articles/10.3389/fenvs.2022.989671/full. Publisher: Frontiers.

Azanza, R. V. et al., 2018. Freshwater ecosystems in the Philippines, including Laguna de Bay and Lake Taal, face increasing eutrophication. *Environmental Monitoring and Assessment*, 190(5), 1–10.

Cadondon, J. G., Ong, P. M. B., Vallar, E. A., Shiina, T., Galvez, M. C. D., 2022. Chlorophyll-a Pigment Measurement of Spirulina in Algal Growth Monitoring Using Portable Pulsed LED Fluorescence Lidar System. *Sensors*, 22(8), 2940. https://www.mdpi.com/1424-8220/22/8/2940.

Cadondon, J., Lesidan, J. R., Bulan, J., Vallar, E., Shiina, T., Galvez, M. C., 2023. Algal Organic Matter Fluorescence Analysis of Chlorella sp. for Biomass Estimation. *Engineering Proceedings*, 58(1). https://www.mdpi.com/2673-4591/58/1/80.

Chang, Y. et al., 2021. UAV-based hyperspectral imaging for water quality monitoring. *Sensors*, 21(10), 3345.

Dekker, A. G. et al., 2001. Remote sensing technologies—such as satellite and UAV-based hyperspectral imaging—provide large-scale, near-real-time monitoring but require accurate ground-truthing data for calibration and validation. *International Journal of Remote Sensing*, 22(15), 2907–2922.

Drusch, M., Moreno, J., Del Bello, U., Franco, R., Goulas, Y., Huth, A., Kraft, S., Middleton, E. M., Miglietta, F., Mohammed, G., Nedbal, L., Rascher, U., Schüttemeyer, D., Verhoef, W., 2017. The FLuorescence EXplorer Mission Concept—ESA's Earth Explorer 8. *IEEE Transactions on Geoscience and Remote Sensing*, 55(3), 1273–1284. https://ieeexplore.ieee.org/document/7795187.

Gokce, A., 2021. Algae play a vital role in aquatic ecosystems and are widely used as biological indicators of water quality. *Environmental Science and Pollution Research*, 28(17), 21801–21810.

González, M. et al., 2021. Chlorella vulgaris: ecological importance and photosynthetic pigments. *Journal of Applied Phycology*, 33(2), 123–135.

Gupta, R. et al., 2020. Chlorella vulgaris: a notable microalga for its global presence, ecological importance, and well-characterized photosynthetic pigments. *Algal Research*, 50, 101987.

Hu, C. et al., 2019. Early detection of chlorophyll a and algal pigment variations is crucial for water quality assessment and HAB management. *Remote Sensing of Environment*, 221, 1–13.

Jechow, A. et al., 2024. Characterizing and Implementing the Hamamatsu C12880MA Mini-Spectrometer for Near-Surface Reflectance Measurements of Inland Waters. *Sensors*, 24(19), 6445.

Laganovska, K., Zolotarjovs, A., Vázquez, M., Donnell, K. M., Liepins, J., Ben-Yoav, H., Karitans, V., Smits, K., 2020. Portable low-cost open-source wireless spectrophotometer for fast and reliable measurements. *HardwareX*, 7. https://www.hardware-x.com/article/S2468-0672

Marcek Chorvatova, A., Uherek, M., Mateasik, A., Chorvat, D., 2020. Time-resolved endogenous chlorophyll fluorescence sensitivity to pH: study on Chlorella sp. algae. *Methods and Applications in Fluorescence*, 8(2), 024007. https://doi.org/10.1088/2050-6120/ab77f4. Publisher: IOP Publishing.

Tunens, G., Einbergs, E., Laganovska, K., Zolotarjovs, A., Vilks, K., Skuja, L., Smits, K., 2024. Optical fiber-based open source low cost portable spectrometer system. *HardwareX*, 18. https://www.hardware-x.com/article/S2468-0672(24)00024-5/fulltext. Publisher: Elsevier.

Zhu, X. T. et al., 2023. Traditional chlorophyll a analysis relies on laboratory spectrometers and discrete sampling, which are costly and spatially limited. *Environmental Science and Technology*, 57(10), 4567–4575.