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aMixer Mini-Data Acquisition System: An Optimization Approach to Observe of the HCl-Sodium Thiosulfate Reaction

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Abstract: In determining the reaction rate between hydrochloric acid (HCl) and sodium thiosulfate ($Na_2S_2O_3$), conventional experiments commonly rely on visual observation of sulfur turbidity, making endpoint determination highly dependent on lighting conditions and observer judgment. These limitations reduce measurement accuracy, repeatability, and objectivity, highlighting the need for an alternative Data Acquisition System (DAS) capable of providing continuous quantitative measurements. This study focuses on the development and optimization of a Data Acquisition System (DAS) utilizing transducers and photodetectors through the Research Science Design (RSD) approach as an alternative method for reaction kinetics analysis. The experimental setup consisted of a borosilicate reactor enclosed in a black acrylic chamber to minimize ambient light interference, equipped with 3 W high-power LEDs (green, blue, and white) as light sources and a Mini Mixer interface integrated with MGA software for continuous data acquisition. Each LED configuration was evaluated through three experimental repetitions, and the recorded signals were analyzed using Relative Standard Deviation (RSD) to assess measurement stability and determine the optimum light source. Based on the evaluation results, the DAS was capable of (1) continuously recording sulfur colloid formation in real time, (2) demonstrating the highest measurement stability under green light with an RSD of 1.18%, and (3) eliminating observer-dependent visual bias. The proposed system provides a simple, coding-free, objective, and affordable solution for improving the quality and efficiency of reaction kinetics measurements in chemistry education.

Keywords: aMixer Mini; Data acquisition system; Kinetics reaction; Light sensor; Sodium thiosulfate

Introduction

Chemistry education plays a fundamental role in developing students' scientific literacy by enabling them to understand natural phenomena through observation, experimentation, and evidence-based reasoning. Laboratory activities are therefore considered an essential component of chemistry learning because they provide opportunities for students to connect theoretical concepts with experimental observations (Amorim et al., 2025; Xie & Yusuf, 2026). In recent years, advances in educational technology have encouraged the integration of digital tools into laboratory instruction to improve measurement accuracy, objectivity, and data interpretation. Such technological integration supports the development of scientific process skills while promoting more reliable experimental practices in chemistry laboratories (Ahuja et al., 2021; Baach, 2026; Karakuş, 2023). Consequently, many researchers have emphasized the importance of developing laboratory systems that combine authentic experimentation with digital data acquisition to enhance students' understanding of scientific concepts (Ahuja et al., 2021; Karakuş, 2023).

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Reaction kinetics is the study of how concentration, temperature, surface area, and catalysts affect the rate of a reaction. In chemistry class, students often calculate this by changing the concentration of one of the reactants and recording the time it takes for the reaction to reach a certain point (Mather et al., 2025). An example of a reaction kinetic experiment uses hydrochloric acid and sodium thiosulfate, as both produce visible sulfur, which is observed as clouding of the solution. In a traditional lab, students observe the change in cloudiness using the complete reaction method, where the crosshair under the beaker disappears due to the cloudiness or sulfur particles formed. This experiment is simple but has several problems because the results depend on the lab lighting, the student's careful observation, and the time they declare the reaction to be "complete." Furthermore, each student obtains different times for the same reaction and concentration, sometimes even the same student on different days, making it difficult to compare results. These limitations indicate that although the sodium thiosulfate–hydrochloric acid reaction is widely adopted for teaching reaction kinetics, the conventional visual observation method may not provide sufficiently objective and reproducible measurements for educational purposes. Consequently, more reliable analytical approaches are required to support accurate experimental observations while maintaining the simplicity of school laboratory activities.

Previous studies have consistently reported that measurement uncertainty, including uncertainty arising from experimental observations, remains an important challenge in reaction kinetics experiments (Avaro & Santiago, 2022; Seitz et al., 2021; Zhao et al., 2023). Visual observation or methods for measuring reaction endpoints may not always be as reliable as we'd like. Studies have shown that Sakib et al. (2025) and Vignati et al. (2023) this subjectivity means that even when experiments are repeated under slightly different conditions, lighting, background, and even angles, the results will still vary. One study involved two observers observing the same reaction and obtaining different endpoints, typically ranging from 5 to 15 seconds. Another study involved a single observer repeating the experiment three times and obtaining different endpoints each time. This inconsistency means that if teachers want to compare results between classes or across years, these methods can be a source of error.

The reaction between sodium thiosulfate and hydrochloric acid (HCl) is a common example used in $Na_2S_2O_3(aq) + 2HCl(aq) \rightarrow 2NaCl(aq) + H_2O(l) + SO_2(g) + S(s)$. Chemical kinetics lessons. When these two chemicals are mixed, visible sulfur particles are formed, and the solution becomes cloudy over time. This phenomenon can be observed or measured with instruments using the following equation: It is these colloidal sulfur (S) particles that cause the cloudiness. These sulfur particles begin to combine into individual particles, collide with each other, and form a colloidal phase. Teachers often use this reaction because it is harmless, the changes are obvious, and everything happens in just a few minutes, making it ideal for school laboratories (Han et al., 2025; Mather et al., 2025). One reason this reaction is commonly used in high school experiments is that even small changes in concentration can have a huge difference in reaction time. Increasing the concentration of the acid will cause the reaction to occur twice as fast. Students can understand this by simply changing one variable and observing the change in time. This direct relationship makes the abstract concept of response reaction rate appear not only as something mathematical, but also as something that can be concretely verified (Mather et al., 2025; Vignati et al., 2023). These characteristics explain why this reaction has become one of the most frequently used experimental models for investigating reaction kinetics in chemistry education and for evaluating the performance of alternative measurement systems.

Visual observation or reactive methods are easy; however, these practices have limitations. Researchers have developed an optical system to convert light signals into turbidity changes and record these signals in real time (Ahuja et al., 2021). Instead of having students determine when the reticle disappears, the systems not only measure light passing through the solution but also measures multi-point curvature. This process facilitates the transition from human sensory observation (qualitative) to using light emitters and sensors (quantitative measurement), allowing for continuous tracking of results, rather than being limited to a single result. This continuous data provides a detailed and complete picture of reaction kinetics (Karakuş, 2023; Mather et al., 2025; Vignati et al., 2023). Accordingly, data acquisition systems (DAS) have attracted increasing attention because they transform qualitative observations into quantitative measurements that can be continuously recorded and analyzed (Ahuja et al., 2021; Karakuş, 2023; Mather et al., 2025; Vignati et al., 2023).

This system solves this problem by eliminating the need to guess when the reaction is "completed". It continuously collects data from thousands of data points per second, as needed, providing clear statistics such as specific times, variances, and correlations between different tests. Schools using this system report consistent results across student groups. The data can also be used to teach various techniques, such as how to work with continuous measurement data, how to find a signal in noise, how to correct errors in your data, and how to help discover concepts within the material (Mather et al., 2025; Sakib et al., 2025; Vignati et al., 2023).

Despite these advantages, the performance of DAS is still influenced by several optical parameters, indicating that the implementation of sensor-based measurements alone does not automatically guarantee optimal accuracy.

This method is particularly important in the classroom, where different groups of students perform the same experiment; the results must be consistent. The use of sensors helps to ensure consistency, but without sensors, the results are often inconsistent. When the results are consistent, students trust them; they spend their time thinking about the actual reaction, rather than arguing about whether someone mentioned the endpoint or when the reaction stopped (Sakib et al., 2025; Vignati et al., 2023). This limitation underscores the need to optimize system parameters before using a DAS in kinetic studies. Without sufficient optimization, the benefits of DAS may not be fully realized, and measurement errors may still occur (Mather et al., 2025; Vignati et al., 2023).

One crucial factor is the wavelength of light used. In systems where sulfur particles form colloidal suspensions, the light scattering method is highly wavelength-dependent (Ahuja et al., 2021). If the wrong wavelength is chosen, the sensor will be unable to detect anything useful. However, if the correct wavelength is chosen, the sensor can perfectly track the reaction. However, developing a DAS for kinetic reaction analysis is not only about achieving greater neutrality but also requires extensive system parameterization, including appropriate wavelength selection, sensor calibration, and signal processing. This approach aligns with modern trends in chemistry education, which emphasize the integration of advanced technologies and data-driven experiments while keeping pace with the times (Sakib et al., 2025; Vignati et al., 2023). Therefore, determining an appropriate wavelength becomes an essential prerequisite before DAS can be implemented as a reliable analytical tool for monitoring sulfur colloid formation during reaction kinetics experiments.

The wavelength dependence of scattering behavior is closely related to the size of the colloidal particles formed during the reaction. As particle size continuously changes, the light-particle interaction also changes, affecting the detected signal over time (Sakib et al., 2025; Vignati et al., 2023). Optical sensors face fundamental limitations when measuring reaction kinetics using a single-wavelength method. The dynamics of changes in the light scattering pattern occur because sulfur particles form and continue to grow throughout the reaction, with different particle sizes at each stage of the reaction affecting the light scattering characteristics. Previous research in optical sensing has demonstrated that these variations in light scattering related to particle size result in systematic deviations in the measurement data. These changes in the readings recorded by the sensor are not due to chemical transformations, but rather to changes in the optical characteristics of the suspension being measured. For example Malinka et al. (2025), the sensitivity of measurements at a wavelength of 500 nm decreases gradually as particle size exceeds a certain size limit, in contrast to the situation experienced by the same suspension at a wavelength of 700 nm, which exhibits higher light scattering efficiency at later stages of the reaction. These findings demonstrate that wavelength optimization remains a critical issue that should be considered during the development of optical sensing systems for reaction kinetics experiments.

To overcome these challenges, researchers have developed two complementary approaches. The first approach involves conducting simultaneous measurements at multiple wavelengths, enabling the system to calculate particle size increase in real time. The second approach focuses on selecting and optimizing a single, constant wavelength that can be applied across the predicted particle size range during the reaction. It should be emphasized that both methods have limitations. Multi-wavelength measurement systems offer higher reliability but require more sophisticated and complex equipment. For single-wavelength optimization approaches, ease of operation is the primary advantage. However, to ensure that the optimal wavelength is determined in accordance with the characteristics of each chemical system, a thorough initial calibration process remains essential (Malinka et al., 2025).

Previous studies have primarily focused either on developing sophisticated multi-wavelength optical systems with high analytical performance or on investigating the optical behavior of sulfur colloids under controlled laboratory conditions (Ahuja et al., 2021; Karakuş, 2023; Malinka et al., 2025; Sakib et al., 2025; Vignati et al., 2023). Although these studies successfully demonstrated the potential of optical sensing for reaction kinetics measurements, their systems generally require relatively expensive instrumentation, complex calibration procedures, or specialized analytical equipment, limiting their implementation in school laboratories. Consequently, there remains a need for a simpler and more affordable DAS that can maintain reliable performance while using commercially available components suitable for chemistry education.

For the single-wavelength optimization approach, ease of operation is its primary advantage. However, to ensure that the optimal wavelength is determined according to the characteristics of each system, the selection of green, blue, and white LED light sources is based on several important considerations, including

their distinct visible wavelength ranges, affordability, and commercial availability. Unlike previous studies, which mainly employed sophisticated multi-wavelength optical systems or expensive sensing components, this study develops a low-cost photo-transducer-based data acquisition system by optimizing commercially available green, blue, and white LED light sources to identify the most appropriate wavelength for monitoring sulfur colloid formation during the sodium thiosulfate–hydrochloric acid reaction. The proposed system is specifically designed for chemistry education laboratories, providing an objective and continuous measurement approach while remaining simple, affordable, and easy to implement. Therefore, this study aims to develop and optimize the proposed DAS as an alternative analytical method for reaction kinetics. The developed system is expected to improve the objectivity, accuracy, and consistency of reaction kinetics experiments while supporting affordable technology-enhanced chemistry laboratory learning.

Method

Research Design

This study uses the Design Science Research (DSR) methodology, a sequential work step suitable for technology development and continuous improvement in educational contexts. The DSR approach was chosen because it is a structured process for the design, implementation, and evaluation of technological inventions, in this case, DAS, while maintaining scientific objectivity throughout the continuous development cycle. The research design focuses directly on analyzing the effect of light wavelength on the accuracy and reliability of turbidity-based reaction monitoring processes in a sodium hydroxide and sulfuric acid chemical kinetics system (Wang & Costa, 2022).

The independent variables are the wavelengths of light or lamp light, namely: blue (470 nm), green (525 nm), and white (400–700 nm). The dependent variables consist of two additional measurements: (1) the response of the DAS system, measured as the change in light intensity over time throughout the reaction period, and (2) the determination of the reaction endpoint at 0 Lux. To isolate wavelength effects and ensure accuracy in all additional parameters, the reactant concentrations (0.2 M HCl and 0.1 M $Na_2S_2O_3$), total solution volume (40 mL), room temperature (24°C), solution pH, and light intensity were kept constant throughout the experiment, covered with a black acrylic box. This strict regulatory approach is in accordance with the standard procedures that have been determined in research related to turbidity optics, where the light scattering process influenced by wavelength needs to be measured separately from interfering factors to obtain significant quantitative correlations (Yépez et al., 2024).

Data acquisition is carried out continuously throughout the course of each reaction using the DAS device to record the high-frequency spectrophotometer. Data collection was performed by sampling at a frequency of 1 Hz throughout the period of sulfur deposition in solution. This real-time spectral measurement method allows direct characterization of the dynamics of turbidity and opacity increase without relying on manual observation or segmented endpoint estimation. The reaction endpoint for each experiment was determined by an algorithm when the light intensity signal first reached a predetermined intensity threshold of 0 Lux. This approach is an effective method for eliminating observer bias and increasing the repeatability of repeated experiments.

The wavelength settings (blue, green, white) were retested with three replicates. This replication method provided accurate quantitative evaluation capabilities, both for measuring variability within each setting and for assessing consistency across settings. Data analysis was then performed using descriptive statistics as the primary analytical technique, specifically by calculating the arithmetic mean and standard deviation (SD) of reaction times based on three replicates in each experiment for various wavelengths. The resulting summary statistics serve three primary purposes: first, to measure the central tendency and dispersion of reaction times; second, to evaluate the consistency and stability of measurements; and third, to provide a basis for comparing the influence of wavelength on the system's response characteristics. In addition, the coefficient of variation (CV = SD/mean × 100) is calculated to normalize the dispersion on a magnitude scale, thereby allowing a fair comparison between wavelength settings with different absolute ranges.

This experimental setup applies widely recognized principles of optical physics that govern the interaction between light and matter in colloidal suspensions, specifically the Mie scattering theory, which describes how particles interact with electromagnetic energy. The theory states that scattering efficiency and angular scattering patterns are parameters that are significantly dependent on wavelength. In the context of colloidal sulfur particles produced during the reaction between HCl and $Na_2S_2O_3$, particle dimensions undergo continuous changes from the nucleation stage at the nanometer scale to the aggregation process at the micrometer scale. This temporal evolution directly modifies how each wavelength interacts with the growing particle population. Shorter wavelengths (such as blue at 470 nm) exhibit higher scattering sensitivity to sub-micron particles, with Rayleigh scattering efficiency being more dominant in that wavelength range.

But these advantages are offset by increased noise levels and greater sensitivity to fluctuations in particle size irregularity. Conversely, longer wavelengths (such as green at about 525 nm) produce more gradual shifts in turbidity and optimal signal stability, which is particularly advantageous when monitoring particle growth across a broader size distribution range. White light, which covers the entire visible spectrum (400–700 nm), produces a complex mixed signal that mirrors the Mie scattering phenomena simultaneously across various wavelengths. While this potentially provides integrated information on particle size changes, it comes at the cost of reduced wavelength-specific sensitivity.

Based on this, a direct experimental comparison of these three wavelength settings (blue, green, and white) provides an empirical basis for determining optimal operational parameters that maximize sensitivity and measurement reliability in a DAS-based optical turbidity measurement system (Wang & Costa, 2022; Yépez et al., 2024).

Choosing green (525 nm), blue (470 nm), and broad-spectrum white LEDs is based on a combination of optical principles and practical considerations. Green light has proven optimal at detecting submicron-sized sulfur particles, while blue light is more effective on larger particles. The three wavelengths together allow for reaction measurements across a broad wavelength range without the need for expensive optical equipment (Sosa-Díaz et al., 2022). Economic considerations are as important as optical considerations; each LED is sold at an affordable price to support reuse in school settings (Wahyuni et al., 2025). The design of this software also aims to reduce barriers to system implementation. Rather than requiring students and instructors to write code or follow complex calibration procedures, the system uses graphical user interface-based software that is easy to operate for anyone with basic computer skills. This is no mere coincidence; rather, it is central to the philosophy that technology should facilitate experimental learning, not hinder it (Rodrigues dos Anjos et al., 2024). As a result, laboratories in high schools, vocational schools, and universities that were previously unable to perform optical kinetics experiments can now design and deploy this system. With hundreds of educational institutions adopting this approach, thousands of students each year gain hands-on experience with quantitative chemistry integrated with technology. The shift from merely observing reactions to being able to quantify them fundamentally changes how students approach the discipline of chemistry.

Apparatus and Materials

This study used two main chemical compounds prepared specifically for the kinetic experiment: hydrochloric acid (HCl) at a concentration of 0.2 M and sodium thiosulfate ($Na_2S_2O_3$) at a concentration of 0.1 M. These concentrations were selected based on the reaction equation and the principles of stoichiometry.

$Na_2S_2O_3(aq) + 2HCl(aq) \rightarrow 2NaCl(aq) + H_2O(l) + SO_2(g) + S(s)$, This chemical reaction needs 2 moles of HCl for every 1 mole of $Na_2S_2O_3$ to proceed completely. This mixture is then diluted with distilled water to ensure the solution's purity. The sulfur (S) precipitate formed in this reaction acts as an optical target for the light-detection system, producing a characteristic turbidity that enables direct spectroscopic monitoring. The determination of molar concentration was carried out by the research team through an initial optimization study aimed at balancing two interrelated objectives: the reaction must proceed at a rate observable on a timescale relevant to laboratory conditions (typically 15–45 seconds), while maintaining sufficient variation in light intensity so that the sensor can reliably distinguish between clear and turbid surface conditions. To minimize potential experimental errors and ensure reproducibility, all chemicals used were pro-analytical (P.A.) grade chemicals from Labmart, which guarantee high chemical purity and consistent composition across all batches of the experiment.

This setup consists of several integrated subsystems designed to isolate, measure, and document spectroscopic changes as the reaction proceeds. The main part of the setup is a borosilicate glass reactor vessel with an inner diameter of 6 cm and a height of 11 cm, chosen for its superior optical transparency, thermal stability, and chemical resistance to various aqueous solutions. This reactor is enclosed within a custom-made cubic measurement chamber constructed from black acrylic. The primary purpose of this design is to absorb ambient light and prevent scattered photons from reaching the light detector, thereby ensuring stable and uniform optical measurement conditions in every experiment. This controlled measurement environment is crucial, as uncontrolled light interference can introduce systematic measurement errors and reduce the signal-to-noise ratio essential for distinguishing turbidity changes from background fluctuations.

The instrument's lighting component consists of three different high-power light-emitting diode (LED) modules, each rated at 3 watts, powered by two AA batteries, and configured with three wavelength options: broadband white light (400–700 nm, covering the entire visible spectrum), monochromatic green light (525 nm, the peak wavelength), and monochromatic blue light (470 nm, the peak wavelength). The research team positioned each LED module directly above the borosilicate reactor to provide uniform and uniform illumination across the entire horizontal cross-section of the solution during each reaction experiment. This

ensures that changes in light intensity recorded by the sensor reflect true changes in solution turbidity, rather than fluctuations in incident light intensity. By systematically evaluating the optical measurement performance under three wavelength conditions white (broadband), green (mid-wavelength), and blue (short-wavelength), this study allows for a direct empirical assessment of how wavelength selection affects the sensor's sensitivity to particle formation and the stability of the measurement signal over the dynamic dimensional changes of the particles during the reaction.

The photodiode photometer is strategically placed above the reaction vessel, positioned to capture the unscattered light passing through the solution, to measure the transmission of light into the forming sulfur precipitate suspension. This sensor operates continuously, acquiring data, sampling light intensity at a high time frequency, and sending an electrical signal to a laboratory computer equipped with specialized data acquisition software (Addestation version 6.0). The software application processes the signal in real-time, converting the sensor's raw electrical output into units of calibrated light intensity, and simultaneously displays the intensity-versus-time curve on the computer monitor. This enables simultaneous visualization of reaction kinetics throughout the experiment. The user-friendly graphical interface provides researchers with immediate feedback on measurement quality, signal stability, and data integrity features that are invaluable for resolving experimental issues in real time. To complete the quantitative optical measurements and provide independent qualitative monitoring of the observed optical changes, a digital camera system (A4Tech PK-836MJ) is used concurrently to record real-time images of the reaction's progression, documenting the gradual color change of the solution from clear to turbid. This dual-method approach combines objective high-frequency light intensity data with subjective visual observations. This allows for measurement accuracy verification and ensures the reliability of the relationship between sensor reads and actual turbidity changes, thereby supporting the overall accuracy and reliability of the trial results.

Experimental procedure

In practice, the data acquisition system developed in this study consists of several main components: a light source, a borosilicate reactor mirror, a light sensor (light detector), and a mini DAS Mixer interface integrated with proprietary data processing software (MGA). As described by Mather et al. (2025), designing a reliable system requires attention to critical aspects such as light source stability, sensor sensitivity, and minimization of external interference to ensure accurately collected data. This view is reinforced by the specific work of Vignati et al. (2023), which emphasizes the importance of controlling environmental conditions such as lighting and room temperature

For this experiment, 20 mL of 0.1 M sodium thiosulfate solution and 20 mL of 0.2 M hydrochloric acid were used as reactants. The DAS system was connected to a laptop with a Mixer mini-interface, and a camera was installed to record the reaction process. Data acquisition was done using Addestation version 6.0 software with the following settings: measurement range 0-5000 lux, recording duration 10 minutes, and sampling rate 1 Hz. The light intensity scale was set to 125 lux/channel and the time scale to 30 seconds/channel.

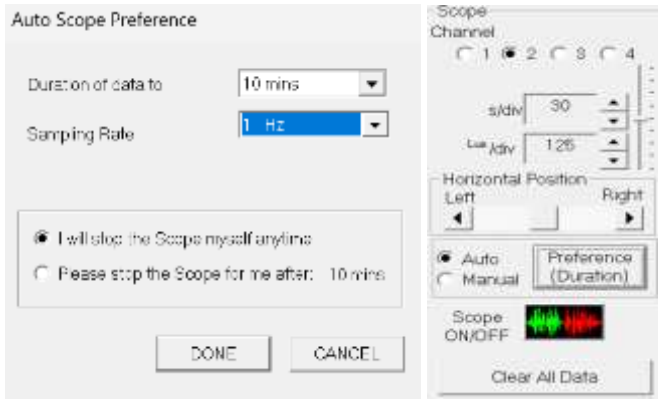

Figure 1. DAS software configuration

The lighting source used was a high-power LED (HPL) with a power of 3 watts in three color variations: white, green, and blue. Before starting the experiment, the selected lighting source was turned on to ensure lighting stability. After the reactants were mixed into the reaction vessel, the system was immediately closed with a light-tight room to reduce the influence of external lighting sources. Data recording began simultaneously with the start of the reaction using the Scope ON/OFF feature available in the data acquisition system software. During the reaction, the system continuously recorded the light brightness level (in lux) versus time (in seconds) until a stable condition was reached. The data was then displayed as a graph in the DAS software interface. Each experiment with green, white, and blue light was repeated three times (three sets) to ensure the reliability and repeatability of the data.

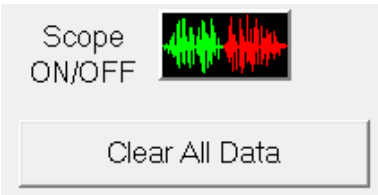

Figure 2. The DAS software's on/off status is marked in red and green

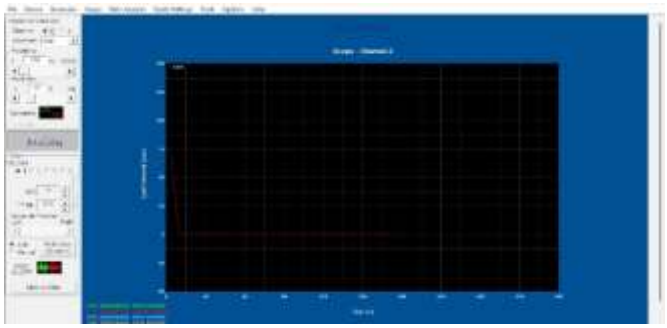

Figure 3. DAS Software Interface

Data Analysis

Quantitative data obtained from the DAS were used to create a graph showing the relationship between time and light intensity (lux). This data was then processed and analyzed using Microsoft Excel. For each light intensity level (blue, green, and white), three experiments were performed to ensure data reliability and repeatability. The reaction endpoint of each experiment was determined by considering the point at which the light intensity dropped to 0 lux. The reaction times from all three experiments were then averaged. The standard deviation (SD) was calculated using a sampling method to assess measurement uniformity; a lower SD indicates higher data reliability. Comparisons between different light intensity levels were made considering the average reaction time and accuracy level of each level. In addition to SD, system stability was evaluated using the relative standard deviation (RSD). The optimal light source was identified based on the lowest RSD, with an error margin of less than 2%, indicating excellent repeatability and signal stability during the measurement process. A detailed diagram of the optical data acquisition system and electrical circuitry of the instrument set is shown in Figure 4.

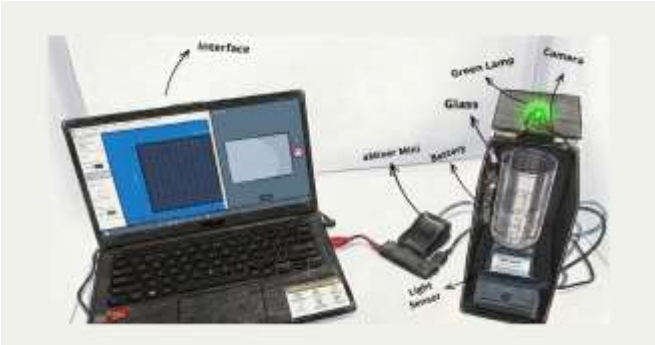

Figure 4. DAS tool kits

Result and Discussion

Result

The measurement results obtained from the DAS system are displayed as a graph of light intensity versus time for each light source.

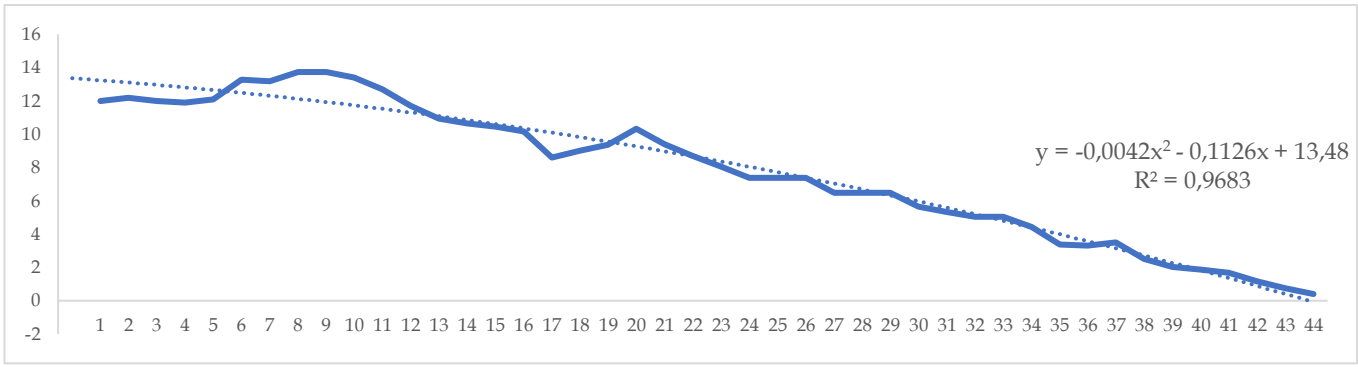

Figure 5. Shows a graph of light intensity (lux) versus time (seconds) on white light

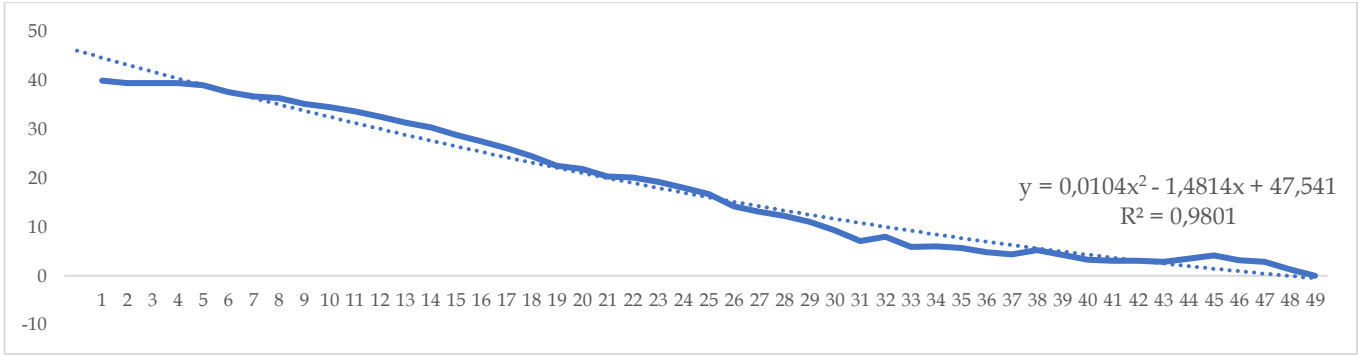

Figure 6. Shows a graph of light intensity (lux) versus time (seconds) on a green light

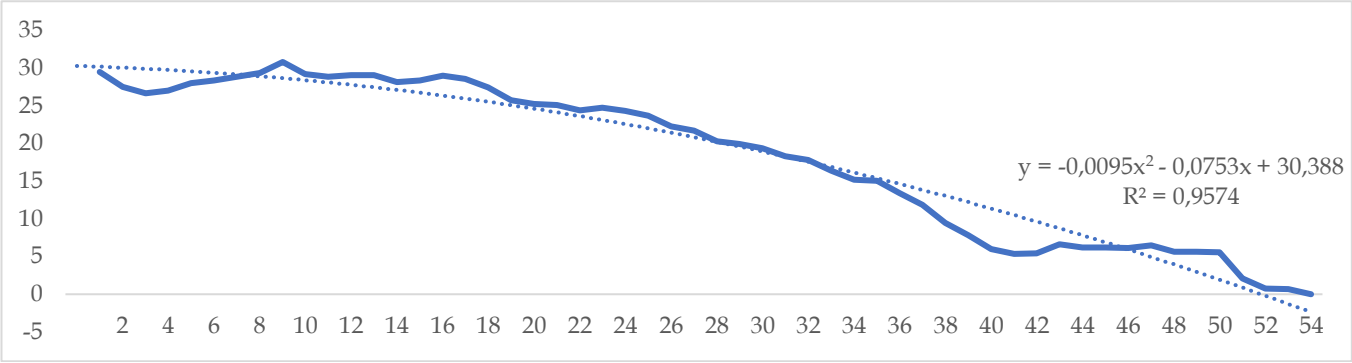

Figure 7. Shows a graph of light intensity (lux) versus time (seconds) on blue light

In Figure 5, the white light response can be observed with a steadily decreasing brightness level from the initial phase to the end of the experiment. Figure 6 depicts the green light response, which exhibits a similar decreasing pattern, while Figure 7 visualizes the trajectory of blue light throughout each reaction. All three visualizations display a similar universal pattern: throughout the formation and precipitation of sulfur particles in solution, the opacity of the solution increases, leading to a reduction in the amount of light reaching the detector, resulting in a gradual decrease in the brightness reading. The reaction completion time for each experiment was objectively determined when the brightness level exceeded a predetermined threshold, eliminating the influence of subjectivity and ensuring the validity of the results in the third experiment. Based on the data collected throughout the entire experiment using simple statistics, both the mean and standard deviation indicate that the light detector system operated consistently and reliably throughout the repetition period.

Table 1. Comparison of Mean Values and Standard Deviations of Response Times between Different Categories of Lighting Sources

Light source	Average response time (seconds)	Standard deviation (SD)	RSD (%)
Green light	48.66	0.577	1.18
White light	43.66	1.527	3.49
Blue light	52.66	11.547	2.19

Table 1 shows a comparison of the mean values and standard deviations of response times across different categories of light sources. The results clearly indicate that the green light source provides superior stability among the three wavelength conditions evaluated. Green light exhibits the lowest relative standard deviation (RSD) of 0.57 seconds, equivalent to a best relative standard deviation (RSD) of 1.18 percent. This RSD falls below the 2 percent threshold commonly used in analytical chemistry, confirming that green light provides the most reproducible and stable data compared to white and blue light sources.

Based on the characteristics of the three light sources analyzed, white light recorded the shortest average response duration, at 43.66 seconds. However, this speed advantage has its limitations: white light exhibited a larger standard deviation, indicating a wider spread of data and inconsistency in measurement results across repeated experiments. In contrast, blue light produced the longest response duration of the three, with a stability level that fell between white and green light. This finding reveals a fundamental principle: determining the optimal light source for monitoring opacity levels cannot be based solely on response speed, but also on the uniformity and reliability of the resulting data. Based on these considerations, green light is the most suitable choice for a DAS system, given its ability to produce the most stable and reliable measurement data across repeated experiments.

Discussion

The optical DAS operates through a neat but accurate setup that records changes in solution turbidity as the reaction proceeds. A 3-watt LED light source illuminates a light sensor placed in the center of a glass reaction vessel. When two chemical solutions (0.2 M hydrochloric acid and 0.1 M sodium thiosulfate) are mixed in the reaction vessel, sulfur particles begin to form and continue to increase in size as the reaction proceeds. The solutions initially appear completely clear, allowing light to pass through unimpeded. However, as time progresses and interactions between the sulfur particles increase, these fine particles scatter the light and block it from reaching the sensor on the other side. Light sensors only detect light that passes through unimpeded, converting this measurement into

a digital value in lux. The computer interface then processes this signal at a rate of about once per second, producing a detailed digital record that accurately captures changes in light intensity as the reaction proceeds.

The system produced corresponding graphs for the three colors of light tested, with each displaying a distinct pattern influenced by the interaction of specific wavelengths with the growing sulfur particles. White light began recording at 13.48 lux and gradually decreased to near zero over 44 seconds, with the equation $y = -0.0042 x^2 - 0.1126 x + 13.48$, with an R^2 value of 0.9683 indicating good agreement with the empirical data. Green light exhibited different characteristics, starting at the higher 42 lux range and decreasing slowly and evenly over 49 seconds without signal spikes or interference, with the equation $y = 0.0104 x^2 - 1.4814 x + 47.541$ and an R^2 value of 0.9801 indicating higher precision with the data. This green light pattern was very stable, effectively avoiding random signal fluctuations throughout the particle growth process. Blue light produced a more complex pattern. Starting at 30.39 lux, the reduction took longer, eventually reaching 54 seconds, with the equation $y = -0.0095 x^2 - 0.0753 x + 30.388$ and an R^2 value of 0.9574. In contrast to the smoother green light response, the blue light signal exhibited a visible waveform and even remained constant for a short period between 39 and 48 seconds. This phenomenon occurs because the shorter blue wavelength is inherently more sensitive to subtle changes in particle dimensions, as sulfur particles form and clump.

Experimental observations have shown that the entire wavelength range of light (green, white, and blue) exhibits a consistent decrease in intensity over time. This pattern demonstrates that during the chemical interaction between sodium thiosulfate and hydrochloric acid, the formation of colloidal sulfur particles results in a gradual increase in the turbidity of the solution. This increase in turbidity leads to increased light scattering, resulting in a decrease in the intensity of light reaching the sensor. According to Kayeye et al. (2025), the development of colloidal particles in the reaction system increases the intensity of light scattering and decreases the level of light transmission. In line with these findings, Rana et al. (2025) and Sheng et al. (2025) describe that as the concentration and dimensions of colloidal particles increase, the optical characteristics of the solution transform, particularly due to increased scattering, which weakens the light transmission capacity.

Data acquisition systems sensors continuously record changes in light intensity, documenting the entire reaction rather than simply identifying its endpoint. This characteristic makes photoelectric sensors effective monitoring and analysis instruments for assessing reaction progress. Several studies have reported that photoelectric sensors are capable of converting physical phenomena, such as turbidity variations, into measurable electrical signals, and Sekine et al. (2025) have verified that light-based approaches yield highly optimized results for particle-forming systems such as colloidal suspensions. From a pedagogical perspective, this real-time information shifts the learning process from passive, qualitative observation to active, data-driven investigation, where students interact directly with graphical representations, linking macroscopic opacity changes to microscopic concepts such as collision theory and nucleation rates, and developing higher order thinking skills (HOTS) competencies, digital literacy, and scientific modeling through time-series curve analysis, slope interpretation, and evaluation of reaction rate variations, rather than simply documenting a single, static endpoint.

In terms of kinetic chemistry, the decrease in light intensity over time means that the reaction rate changes as the process proceeds. In the early stages of the reaction, the rate of product formation is faster due to the high initial concentration of reactants. As the reaction proceeds, the concentration of reactants decreases while product formation increases, thereby causing a change in the rate of reaction. The discussion on the analysis of light signal variations over time by Chen et al. (2025) can be used as an indirect method to evaluate reaction kinetics. The slope of the light intensity curve against time indicates that the reaction rate is not a constant value, but varies according to the prevailing system conditions. This observation aligns with classical kinetic theory, which states that reactions are primarily influenced by reactant concentration, which fluctuates continuously throughout the reaction.

The analysis results in this study indicate that the choice of wavelength range significantly affects the accuracy of the collected data. Even though white light recorded the shortest average response, at 43.66 seconds, the high RSD value of 3.49% indicates significant data variability and reduced stability. In contrast, green light demonstrated more optimal stability with an RSD value of 1%, indicating that the wavelength range acts as a critical factor in influencing the stability of the optical sensor system. As previously explained, Rinanti et al. (2021) stated that the interaction between light and colloidal particles is very sensitive to wavelength, especially during the light scattering process. Furthermore, it Li et al. (2025) argued that the medium wavelength range tends to produce more stable signals due to its lower sensitivity to small variations in particle dimensions when compared to the shorter wavelength range.

Green light with a wavelength of 525 nm provides optimal performance compared to blue and white light for this measurement system due to two main factors. According to Mie scattering theory, the 525 nm wavelength falls within the range where the scattering intensity gradually decreases as sulfur particles grow. This avoids the anomalous oscillations that often occur with shorter wavelengths of blue light due to the instability of constantly changing particle dimensions, which leads to higher measurement variability (up to 2.19%) for blue light. In addition, silicon photoelectric sensors operate optimally at wavelengths of 500–570 nm, resulting in a greater electrical response and sharper signal graphs when using the green spectrum compared to the blue spectrum. Using white light as a measurement source has certain disadvantages: the full spectrum of white light in the 400–700 nm range is scattered simultaneously with different speed and angle characteristics. Furthermore, the cylindrical glass reaction vessel causes non-uniform refraction of light for each wavelength. As a result, different colors of light are focused at different positions on the detector surface, rather than concentrated at a single point. This situation results in a complex, irregular signal, which does not produce clear and reliable measurement data. Too short a wavelength range or excessive spectral mixing introduces more noise into optical systems that are not adequately shielded from environmental influences (Yu et al., 2024). Relative Standard Deviation (RSD) analysis corroborates these findings, proving that green light sources exhibit the least data variation compared to white and blue light. Based on the results of this study, it can be concluded that the use of green light in the measurement process produces data that has a higher level of consistency and can be easily reproduced. Guo et al. (2025) emphasized that stability is a crucial parameter in optical sensor systems, because this factor greatly influences the level of accuracy of the data obtained. A stable signal display with a low noise level provides researchers with the opportunity to conduct kinetic analysis with a higher level of precision. On the other hand, Sezer et al. (2025) stated that the presence of high-frequency noise in the measurement process has the potential to cause deviations in the interpretation of data results, especially in the stage of forming a kinetic model.

Compared with traditional observation techniques, the use of a data collection system in this study resulted in significantly better performance in terms of objectivity and data quality. The data collection system supports continuous monitoring and is independent of human perception, thus minimizing the influence of subjectivity. Scientific studies have shown that systems utilizing optical sensors improve data consistency because they are not affected by variations in perspective between observers. Furthermore, Guo et al. (2025) stated that continuous data acquisition allows for more comprehensive kinetic analysis. This differs from traditional endpoint measurement methods, which are only capable of producing data at specific points in time.

However, this study also shows that the performance of a digital image capture system is highly dependent on system settings, particularly the determination of the light spectrum range and the stability of the light emitter. If these parameters are not properly set, measurement accuracy can be reduced. Sezer et al. (2025) emphasized that errors in setting optical parameters can lead to systematic deviations. For this reason, the parameter optimization process is a crucial step in the development of a digital image capture system. In this study, the optimization process was carried out by comparing three different light spectrum ranges, and the results showed that green light produced better performance in terms of signal stability and uniformity. This conclusion is reinforced by the findings of Kamal Mohamed et al. (2025) who stated that optical sensor systems require the determination of an optimal spectrum range to achieve the best signal-to-noise ratio. In addition, Sanchez-Salvador et al. (2023) emphasized that in colloidal systems, dynamic changes in particle size during reactions alter optical interactions through complex mechanisms. Therefore, determining the light spectrum range is a crucial factor in producing high quality signals.

Furthermore, three replicate experiments, investigations complemented by statistical analysis, such as calculating the mean, standard deviation (SD), and coefficient of variation (RSD), increase the reliability of the data obtained. Davidson & Niepa (2022) stated that experimental repetition plays a crucial role in reducing the level of random variation or bias in research data. Despite limitations related to the number of repetitions, this study lays a solid foundation for the development of more impartial endpoint determination techniques. Future research could consider multi-wavelength-based approaches to further improve measurement accuracy, as recommended by El-Helou et al. (2025). Overall, green light achieves optimal equilibrium in producing consistent and reliable data, providing a practical alternative to traditional techniques without the need for complex coding steps.

However, this study has several limitations. The limitation on the number of iterations may impact the reliability of the results. Furthermore, the determination of the reaction completion moment was based on specific criteria that could potentially lead to data variability. Therefore, further research is recommended to increase the number of iterations and develop a more precise, data-driven endpoint determination technique. Alternatively, a multi-wavelength approach could be an

alternative to gradually improve measurement accuracy and reduce bias. As discussed previously, the implementation of a multi-wavelength strategy by El-Helou et al. (2025) has the potential to improve the reliability of photosensor systems by utilizing a wider range of spectral data. Overall, this study confirms that wavelength selection plays a key role in optimizing the performance of photosensor-based DAS. Green light demonstrated an optimal balance between sensitivity to turbidity changes and signal stability, resulting in more consistent and reliable kinetic data compared to other spectral changes. This study makes significant contributions to the digital transformation of chemistry laboratories in the Industry 4.0 era. The transition from traditional methods relying on subjective visual perception to objective digital data collection systems with an RSD of 1.18% aligns with the information cognition requirements for 21st-century educators.

What truly stands out about this instrument is the systematic tuning of multiple wavelength LED parameters, combined with the acquisition of high-frequency data at 1 Hz, all of which contribute to the creation of a multi-step phase transition map of colloidal sulfur. Traditional chemistry studies have long relied on "vanished point" methods, or subjective perfect reactions, for the reaction between sodium thiosulfate and hydrochloric acid. This research goes a step further by transforming standard educational experiments into a multispectral quantitative analysis instrument without the expense of research-grade spectrophotometers. The precise optical path configuration and wavelength response characteristics demonstrate that high scientific precision can be achieved with a significantly lower investment compared to industrial equipment, creating a practical quantitative alternative for data-driven chemical research. However, two drawbacks must be recognized. The open optical path configuration is susceptible to environmental interference, particularly from broad-spectrum white light sources, which means that external illumination must be maintained at a stable level throughout the experiment. Furthermore, since the data recording process begins when the operator manually mixes the reactants, the highly dynamic nucleation phase in the first few seconds is directly related to the speed and uniformity of the mixing process.

Conclusion

This study successfully developed and optimized a photo-transducer-based DAS for monitoring the reaction kinetics of the hydrochloric acid–sodium thiosulfate reaction. Among the evaluated light sources, the green LED exhibited the highest measurement stability with the lowest Relative Standard Deviation (RSD) of 1.18%, demonstrating its suitability for continuous monitoring of sulfur colloid formation. The developed DAS was capable of continuously recording reaction progress in real time while eliminating observer-dependent visual bias, thereby providing more objective and reproducible measurements than conventional visual observation methods. The main contribution of this study lies in the development of a simple, low-cost, and coding-free photo-transducer-based DAS through the optimization of commercially available green, blue, and white LED light sources for reaction kinetics experiments. Compared with the conventional cross-disappearance method, the proposed system enables continuous quantitative data acquisition, improves measurement consistency, and supports data-driven laboratory learning in chemistry education without requiring sophisticated analytical instruments. Future research should evaluate the applicability of the developed DAS to other chemical reaction systems with different optical characteristics, such as precipitation, colorimetric, or enzyme-catalyzed reactions. In addition, validation against established analytical techniques, such as spectrophotometry, is recommended to further verify the accuracy, reliability, and broader applicability of the proposed system.

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Author Contributions

Conceptualization, I.R.; methodology, I.R.; software, N.S.; validation, G.G.G and A.M.; formal analysis, M.K.N and I.R.; investigation, N.S.; resources, G.G.G. and A.M.; data curation, M.K.N and I.R.; writing original draft preparation, N.S.; writing review and editing, M.K.N. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

References

Ahuja, V., Mehta, S., Rathour, R. K., Sharma, V., Rana, N., Sheetal, S., Bhatt, A. K., & Kieliszek, M. (2021). *Elucidation of new xylose metabolizing pathway in Pseudomonas gessardii VXlt-16 and its correlation with xylitol production from sugarcane bagasse hydrolysate*. https://doi.org/10.21203/rs.3.rs-688929/v2

Amorim, L., Santos, C., & Timmis, K. (2025). Prioritising Microbiology in Secondary Education Addresses

Emerging Scientific-Social-Educational Challenges and Competency Needs. In *Microbial Biotechnology* (Vol. 18, Number 9). John Wiley and Sons Ltd. https://doi.org/10.1111/1751-7915.70224

Avaro, A. S., & Santiago, J. G. (2022). Uncertainty Quantification of Michaelis-Menten Kinetic Rates and Its Application to the Analysis of CRISPR-Based Diagnostics. *Angewandte Chemie, 134*(45), e202209527. https://doi.org/10.26434/chemrxiv-2022-4sg1s

Baach, B. (2026). Digital education and quality assurance: integrating AI and simulations in secondary physics curricula in Morocco. *Physics Education*, *61*(3), 035032. https://doi.org/10.1088/1361-6552/ae6172

Chen, Y., Wen, M., Ding, T., Fan, R., Liu, Q., Liu, Z., & Peng, Z. (2025). Recent progress in electrochemical decomposition of hydrogen sulfide for sulfur recovery and hydrogen production. In *Frontiers in Chemistry* (Vol. 13). Frontiers Media SA. https://doi.org/10.3389/fchem.2025.1698815

Davidson, S. L., & Niepa, T. H. R. (2022). Micro-Technologies for Assessing Microbial Dynamics in Controlled Environments. In *Frontiers in Microbiology* (Vol. 12). Frontiers Media S.A. https://doi.org/10.3389/fmicb.2021.745835

El-Helou, A. J., Liu, Y., Chen, C., Wang, F., Altug, H., Reece, P. J., & Zhu, Y. (2025). Optical Metasurfaces for the Next-Generation Biosensing and Bioimaging. In *Laser and Photonics Reviews* (Vol. 19, Number 10). John Wiley and Sons Inc. https://doi.org/10.1002/lpor.202401715

Guo, Z., Li, J., Zeng, L., Wang, P., Li, M., Su, C., & Wang, S. (2025). Advances in research on novel technologies for the detection of exogenous contaminants in traditional Chinese medicine. In *Frontiers in Pharmacology* (Vol. 16). Frontiers Media SA. https://doi.org/10.3389/fphar.2025.1658241

Han, C., Liu, F.-L., Tao, Q., Liu, Y., Jing, Q.-K., Stock, H.-R., Wang, G.-X., & Ma, N. (2025). Recovery of CdS photocatalyst from spent Ni-Cd batteries using a thiosulfate leaching system and UV photolysis precipitation. *Rare Metals, 44*(6), 4241-4254. https://doi.org/10.1007/s12598-024-03185-8

Kamal Mohamed, S. M., Möllmann, K., Heinrich, C., Schwan, M., & Milow, B. (2025). In-line monitoring of resorcinol-formaldehyde gelation using fiber optic UV-vis spectroscopy in real time: part I. *RSC Advances*, *15*(33), 27084–27095. https://doi.org/10.1039/d5ra03988f

Karakuş, O. (2023). On Advances, Challenges and Potentials of Remote Sensing Image Analysis in Marine Debris and Suspected Plastics Monitoring. *Frontiers in Remote Sensing, 4*, 1302384. https://doi.org/10.3389/frsen.2023.1302384

Kayeye, T. N., Penton, A., Ashton, J., Noyes, S., Sunna, A., Wang, Y., & Rodger, A. (2025). Intermolecular Interactions in Plant Based vs. Animal Milks: A Comparative Review. *Sustainable Food Proteins*, *3*(3). https://doi.org/10.1002/sfp2.70028

Li, X., Lv, H., Luo, W., Yang, W. J., Kong, L., Zhu, Q., & Zeng, L. (2025). Recent advances in detection techniques for vitamin analysis: A comprehensive review. In *Food Chemistry: X* (Vol. 26). Elsevier Ltd. https://doi.org/10.1016/j.fochx.2025.102226

Malinka, F., Vachek, O., Krizan, D., Stipal, J., Marques, C., Siska, P., & Nedoma, J. (2025). Advanced intensity-modulated fiber sensors for scalable sensing. In *iScience* (Vol. 28, Number 11). Elsevier Inc. https://doi.org/10.1016/j.isci.2025.113670

Mather, J. D., Sculthorpe, N. F., Sanal-Hayes, N. E. M., Berry, E., Mair, J. L., & Hayes, L. D. (2025). Validity of resting heart rate derived from contact-based smartphone photoplethysmography (PPG) compared with electrocardiography (ECG): Protocol for a Systematic Review and Meta-Analysis. *medRxiv,* 2025-06. https://doi.org/10.1101/2025.06.13.25329618

Rana, R., Ahmad, W., Mishra, A., Kumar, S., & Ahmad, A. (2025). Nanocellulose/nanocellulose-based membranes in wastewater treatment: a sustainable path forward for environmental protection. In *Food Chemistry: X* (Vol. 29). Elsevier Ltd. https://doi.org/10.1016/j.fochx.2025.102654

Rinanti, A., Fachrul, M. F., Hadisoebroto, R., Desty, S., Rahmadhania, Widyaningrum, D. A., & Saad, N. A. (2021). Heavy Metal Pollutant Sorption In Aquatic Environment By Microalgae Consortium. *Indonesian Journal of Urban and Environmental Technology*, *5*(1), 51–71. https://doi.org/10.25105/urbanenvirotech.v5i1.10747

Rodrigues dos Anjos, J., & Serrano de Andrade Neto, A. (2024). Uncovering the Origins of Mental Images about the Concept of Light: The Difference Between Novice And Expert Mediation Levels Profile. *Investigacoes Em Ensino de Ciencias*, *29*(1), 92–116. https://doi.org/10.22600/1518-8795.ienci2024v29n1p92

Sakib, S., Hasan, Z., & Roy, N. (2025). A State-Of-The-Art Survey of Remote Photoplethysmography for Contactless Health Parameters Sensing. In *Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery* (Vol. 15, Number 3). John Wiley and Sons Inc. https://doi.org/10.1002/widm.70039

Sanchez-Salvador, J. L., Xu, H., Balea, A., Negro, C., & Blanco, A. (2023). Nanocellulose from a colloidal material perspective. In *Frontiers in Materials* (Vol.

10). Frontiers Media SA. https://doi.org/10.3389/fmats.2023.1231404

Seitz, G., Mohammadi, F., & Class, H. (2021). Thermochemical heat storage in a lab-scale indirectly operated $CaO/Ca(OH)_2$ reactor—numerical modeling and model validation through inverse parameter estimation. *Applied Sciences (Switzerland)*, *11*(2), 1–28. https://doi.org/10.3390/app11020682

Sekine, H., Akaike, T., & Motohashi, H. (2025). Oxygen needs sulfur, sulfur needs oxygen: a relationship of interdependence. *The EMBO Journal, 44*(12), 3307-3326. https://doi.org/10.1038/s44318-025-00464-7

Sezer, E., Ulucan Karnak, F., & Akgöl, S. (2025). Green carbon dots in the era of AI: sustainable synthesis, intelligent drug delivery, advanced diagnostics, and bioimaging. *Turkish Journal of Biology, 49*(5), 498–533. https://doi.org/10.55730/1300-0152.2762

Sheng, J., Yao, L., Dong, Q., Zhou, B., Li, B., Zhang, G., & Liang, H. (2025). Household non-thermal processing for the dissolution of sea buckthorn flavonoids and the effects on its bioactive characteristics. *Food Chemistry: X*, *30*. https://doi.org/10.1016/j.fochx.2025.102941

Sosa-Díaz, M. J., Sierra-Daza, M. C., Arriazu-Muñoz, R., Llamas-Salguero, F., & Durán-Rodríguez, N. (2022). "EdTech Integration Framework in Schools": Systematic Review of the Literature. *Frontiers in Education*, *7*. https://doi.org/10.3389/feduc.2022.895042

Vignati, S., Tugnolo, A., Giovenzana, V., Pampuri, A., Casson, A., Guidetti, R., & Beghi, R. (2023). *Hyperspectral Imaging for Fresh-Cut Fruit and Vegetable Quality Assessment: Basic Concepts and Applications*. *Applied Sciences, 13*(17), 9740. https://doi.org/10.3390/app13179740

Wahyuni, S., Putro, N. H. P. S., Efendi, A., & Andriyani, N. (2025). Revisiting the ethical boundaries and disclosure practices of AI-infused academic writing: a Scopus-based bibliometric analysis. *Journal of Academic Ethics, 24*(3), 79. https://doi.org/10.21203/rs.3.rs-8389622/v1

Wang, Z., & Costa, M. (2022). Autonomous Shipborne In Situ Reflectance Data in Optically Complex Coastal Waters: A Case Study of the Salish Sea, Canada. *Frontiers in Remote Sensing*, *3*. https://doi.org/10.3389/frsen.2022.867570

Xie, Y., & Yusuf, A. (2026). Advancing scientific literacy: A systematic review of trends, pedagogies and challenges in the 21st century. *Review of Education*, *14*(1). https://doi.org/10.1002/rev3.70140

Yépez, S., Velásquez, G., Torres, D., Saavedra-Passache, R., Pincheira, M., Cid, H., Rodríguez-López, L., Contreras, A., Frappart, F., Cristóbal, J., Pons, X., Flores, N., & Bourrel, L. (2024). Spatiotemporal Variations in Biophysical Water Quality Parameters: An Integrated In Situ and Remote Sensing Analysis of an Urban Lake in Chile. *Remote Sensing*, *16*(2). https://doi.org/10.3390/rs16020427

Yu, J., Yu, L., He, Z., Yang, G. P., Lai, J. G., & Liu, Q. (2024). Spatial and seasonal variability in volatile organic sulfur compounds in seawater and the overlying atmosphere of the Bohai and Yellow seas. *Biogeosciences*, *21*(1), 161–176. https://doi.org/10.5194/bg-21-161-2024

Zhao, H., Deng, H. D., Cohen, A. E., Lim, J., Li, Y., Fraggedakis, D., Jiang, B., Storey, B. D., Chueh, W. C., Braatz, R. D., & Bazant, M. Z. (2023). Learning heterogeneous reaction kinetics from X-ray videos pixel by pixel. *Nature*, *621*(7978), 289–294. https://doi.org/10.1038/s41586-023-06393-x