A photonic sensor system for real-time monitoring of turbidity changes in aquaculture

Mustafa Tolga Tolon[1*], Adnan Tokaç[2], Enis N. Kostak[3], Christoph Strehse[4]

Corresponding author: Mustafa Tolga Tolon, Ege University, Faculty of Fisheries, Aquaculture Department, 35100 Bornova, İzmir, Türkiye; e-mail: tolga.tolon@ege.edu.tr

[1 *]Ege University, Faculty of Fisheries, Aquaculture Department, 35100 Bornova, İzmir, Türkiye; e-mail: tolga.tolon@ege.edu.tr , ORCID ID: 0000-0002-2233-0663

[2] Ege University, Faculty of Fisheries, Fish Capture and Seafood Processing Department, 35100 Bornova, İzmir, Türkiye, ORCID ID: 0000-0002-2968-7315

[3] UiT the Arctic University of Norway, Norwegian College of Fishery and Aquatic Science, Breivika, 9037, Tromsø, Norway

[4] Rostock University, Chair of Ocean Engineering, 18059 Rostock, Germany, ORCID ID: 0009-0007-5479-4722

ABSTRACT

Objective

The objective of this study was to test the compatibility and performance of the developed photonic sensor system, which can serve as a dependable and practical device for continuous monitoring of turbidity changes in aquaculture tanks.

Methods

The fabricated photonic sensor system consisted of an integrated data logger and sensor probe. The sensor probe exhibited a precise emission of infrared (IR) light at a wavelength of 850 nm. Moreover, the sensor evaluates the ambient light across the red-green-blue (RGB) spectrum. To ensure accuracy and reliability, the entire system underwent a thorough calibration process, referencing nephelometric turbidity unit (NTU) values acquired through a specialized handheld turbidimeter. Rigorous trials were systematically conducted in 600 L seawater tanks featuring Sea Cucumber and Gilthead Seabream to ensure the sensitivity and robustness of the photonic sensor system to the aquaculture environment.

Results

A calibration curve revealed a significant correlation between the IR channel values of the sensor (photon counts) and the turbidity values measured by the turbidimeter. The photonic sensor effectively captured turbidity changes in the aquaculture tanks, with significant differences observed between the tanks. The sensor performance was evaluated in trials with Gilthead Seabream, which showed sensitivity to high turbidity changes. The photonic sensor system accurately reflects turbidity changes continuously using its own active light source, independent of ambient light intensity, which is essential for turbid water conditions or for taking measurements in total darkness.

Conclusion

The photonic sensor is a reliable tool for the continuous and accurate monitoring of turbidity changes in aquaculture systems. However, there are specific usage limitations under low-turbidity conditions that can be improved in further studies.

Keywords: Photonic Sensing, Water Quality, Turbidity Monitoring, Aquaculture, Infrared Light

Impact statement

The photonic sensor system, as designed for this study, is capable of accurately measuring turbidity changes using its own active light source independent of ambient light intensity, allowing 24 h monitoring of turbid water conditions or to make measurements in total darkness. Moreover, this system may be useful to detect turbidity changes associated with algal blooms in sea cages, and the poor water treatment performance of filtration systems in recirculating aquaculture.

INTRODUCTION

Turbidity is a measure of cloudiness resulting from the presence of suspended organic and inorganic particles in the water column that are typically invisible to the naked eye (Baniya et al., 2021). Turbidity is an important parameter for assessing overall water quality in aquaculture systems (Lopez-Betancur, 2022). Algal blooms due to nutrient enrichment and soil erosion in extensive and semi-intensive aquaculture systems, uneaten feed, and waste from cultured organisms in intensive aquaculture systems are sources of turbidity. High levels of turbidity can be indicative of various contaminants, including suspended solids, organic matter potentially carrying antibiotics and antibiotic resistance genes, and microplastics, which can transport chemical pollutants and pathogens (Lin et al., 2023; Souza et al., 2016; Xie et al., 2024). These contaminants can negatively affect aquatic organisms by reducing light penetration, leading to reduced oxygen levels, habitat degradation, and disease outbreaks. Moreover, high turbidity results in more intensive water treatment and a higher percentage of makeup water in the RAS. Another reverse effect of turbidity in RAS is the reduced inactivation rate of heterotrophic bacteria by ultraviolet disinfection systems (Gullian et al. 2011). Monitoring turbidity levels and critical changes in turbidity are crucial for maintaining sustainable aquaculture practices (Wang et al. 2018a; Kathyayani et al. 2019).

Aquaculture operations often employ various methods to measure turbidity, including secchi disks, turbidity tubes, nephelometers, turbidimeters, and visual observations, each of which has its own weaknesses. The most economical and energy-efficient option is optical turbidimeters, which use basic optical principles, such as light absorption or reflection, to estimate suspended solid concentrations, that indicate the level of turbidity. However, Kitchener et al. (2017) reported that the relationship between turbidity and suspended solid concentration can be confounded by variations in the particle size, composition, and color of the water. Moreover, the presence of phytoplankton or other turbidity sources can produce density gradients that affect the penetration of irradiance into the water column (Bright et al. 2018). Accuracy of models for turbid waters may be low due to large absorption effect of particulates at short wavelengths (Viegas et al. 2018) and current measurement devices don't allow continuous or frequent measurements. However, monitoring the change in turbidity in an aquaculture setting in the short term is as crucial as accurately measuring the turbidity level to properly manage turbidity, maintain optimal conditions for aquaculture operations, and guarantee the health of aquatic organisms. Although there are some devices that can continuously measure turbidity using two near-infrared (NIR) digital cameras, which provide high accuracy for the determination of standard solutions and real samples (Zhu et al. 2020), such systems are not practical or applicable in aquaculture conditions. The difficult and limited use of conventional turbidimeters due to these disadvantages has questioned the feasibility of using photonic technology for turbidity sensing, where more efficient and miniaturized sensors are available.

The field of photonic technology commonly refers to devices that utilize the principles of photonics, that is, the application of light particles (photons) for various purposes. Photonic sensors frequently employ advanced methods, such as laser light scattering or interferometry, to gauge the number of light photons scattered or absorbed by particles. These sensors are known for their high accuracies and sensitivities. Furthermore, they are adaptable and can be integrated into intelligent wireless mesh networks for continuous monitoring, thereby providing real-time data on environmental conditions (Parra et al, 2018).

The sensor system developed in this study transforms theoretical concepts into dependable, repeatable, and practical configurations that meet the market and user requirements. The biggest technical challenge addressed thus far is the preparation of the system and its optical components to withstand the environmental conditions expected in practical use. The developed sensor system is applicable to a wide range of aquatic environments, including both indoor and outdoor aquaculture tanks, and is structurally capable. Another distinctive feature of the system is its use of an active light source in addition to ambient light, which is essential for turbid water conditions or measurements in total darkness. The sensor system can perform continuous IR light measurements to assess turbidity in the red-green-blue (RGB) range of the light spectrum. Thus, the primary objective of this study was to evaluate the functionality and practicality of the designed photonic sensor system, as it has the potential to serve as a dependable device for regularly monitoring turbidity levels in aquaculture tanks.

METHODS

Photonic Sensor System

The developed photonic sensor system consisted of two major components: an integrated data logger and a sensor probe. For turbidity measurements, the sensor probe emitted IR light at a wavelength of 850 nm, which allowed the detection of the amount of transmitted light. This amount of transmitted IR light correlates with the particle concentration, and thus, the turbidity of the water

(Lambrou et al. 2010). In addition, the sensor can detect light within the RGB range of the spectrum between 350 and 670 nm. The main and auxiliary components of the controller unit include an Arduino Mega 2560 microcontroller that runs the firmware, a MicroSD card module to log the data, and a power bank for the power supply (Figure 1a). To emit IR light with a wavelength of 850 nm for turbidity measurement, the sensor probe included an SFH 4651 IR-LED whose brightness could be adjusted using an LP55231 LED driver. A TSL2572 IR light detector was used to detect the transmitted IR light. The sensor also includes a TCS3472 RGB light detector to assess the influence of light outside the IR range. These light detectors count the number of photons that hit their surfaces during a preadjusted integration time, where each detector is selective for certain wavelengths. The casing for the sensor and optical window were 3D printed using a transparent polyethylene terephthalate glycol filament and waterproofed by casting with polyurethane resin (Figure 1b).

Calibration Process

Sensitivity of the IR channel, reflecting the turbidity changes in the trial tanks was tested by a calibration curve prior to the trials. A calibration chart was prepared by comparing the number of photons detected by the sensor with nephelometric turbidity unit (NTU) values measured using a handheld turbidimeter (WTW Turb 355 IR/T) in samples with different turbidities. To create the turbidity levels in the calibration curve, 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 2, 3, 3.5, 4, 5, 6, 8, 10, 12, 20, 30, and 50 ml of low-fat milk was added to the water to create samples with turbidity values up to 1000 NTU, which is the maximum value that the turbidity meter can measure. NTU values were measured 10 times for each sample (Figure 2).

Experimental Design

A 600 L seawater tank (200 × 50 × 60 cm; length × width × depth) containing the Sea Cucumber *Holothuria tubulosa* (SC), Gilthead Seabream *Sparus aurata* (GS), or no organisms (CN) was used to conduct sensor tests at the Aquaculture Laboratories of the Faculty of Fisheries of Ege University in Urla, İzmir, Türkiye. The tank was filled once with

1µm filtered and UV-sterilized seawater at a salinity of 37.9 ppt, with no water change or filtration during each trial to measure turbidity variations. A digital salinity tester and an integrated thermometer (Hanna HI98319) were used to measure the salinity and water temperature. The average temperature was maintained within the optimal range of 22.8±0.63 °C (min. 20.9, max. 23.6) and 13.4±0.6 °C (min. 12.5, max. 14.5). The mean seawater temperature in the control tank was 17.4±0.9 °C (min. 15.4, max. 19.5). Temperature adjustment was not utilized in this study due to the small temperature discrepancy observed during the sampling period. This decision was made following preliminary examination, which indicated that temperature variations of less than 10 °C had no substantial effect on the photonic sensor measurements. A low stocking density was adopted for the species in the trials to prevent the possible mortality caused by unfiltered or exchanged water. Thus, 20 GS (100±13.4 g, ±SD) and 15 HC (120±18.6 g, ±SD) placed at a stocking density of 3 kg/m^3 and 500 g/m^2 in relevant trials, respectively. To minimize the measurement bias, trials were carried out sequentially using the same photonic sensor unit. GS and SC were provided with daily rations of commercial fish feed, with GS receiving 1.3% of its biomass and SC receiving 1% of its biomass in tanks. A 12 h light: 12 h dark ambient light schedule was applied to the trial tanks by daylight fluorescent bulbs, and the ambient light intensity inside the tank was recorded by the RGB channel of the photonic sensor.

The photonic sensor probe was placed approximately 20 cm above the bottom of the tank to take advantage of the water circulation caused by the diffused air from the 120 cm (4 × 30 cm) long air stone placed at the bottom. Photonic sensor measurements were initialized after one hour, when the temperature of the sensor probe was equilibrated with the water. The photon count reliability of the photonic sensor in reflecting the turbidity changes in trial tanks was tested by taking 21 water samples from the vicinity (10-15 cm) of the sensor probe and measuring them with a handheld turbidimeter at random times during the 52-hour trial period.

The time interval between photonic sensor measurements was set to 15 min in all trials. The brightness of the IR LED was adjusted by the current flowing through the LED and the duty cycle (pulse-width modulation, PWM) via the LED driver. These variables can be set in the firmware to values between 0 and 255 (1 byte), with one step corresponding to 0.1mA. The integration time of the light detectors can also be adjusted. An additional ambient light measurement was performed at each time interval with the RGB detector, which enabled the capture of the applied light schedule that did not emit light in the IR spectral range. The photonic sensor's parameters were set to PWM90, Current 9.0 mA, IR detector integration time 609 ms, and RGB detector integration time 609 ms. For each measurement, the sensor readings were converted to Java Script Object Notation (JSON) format and logged on the SD Card located in the top unit.

Statistical Analysis

The raw data collected by the detectors were transferred from the JSON format to SPSS version 25 for statistical analysis. Descriptive statistics used for interpretation of the data within trials. The paired t-test was employed to assess the differences in sensor measurement data collected at 15-minute intervals within a single treatment group. Each measurement was paired with the subsequent measurement, allowing for the comparison of mean differences between consecutive measurements. Assumptions of normality and independence of paired differences were verified prior to conducting the analysis by Shapiro-Wilk and Durbin-Watson tests. In each trial, Pearson’s correlation or Spearman's rho coefficients were used to examine the degree of correlation between photonic sensor values and turbidimeter NTU values. Results were considered statistically significant at $\alpha<0.05$.

RESULTS

In calibration process, average turbidity measurements ranged from 0.88 to 966.83 NTU (n=240). Correspondingly, the standard deviations varied from 0.08 to 14.87 NTU, reflecting the precision and reliability of calibration measurements across a wide range of turbidities. IR photon counts corresponding to NTU values were measured between 19955.67 and 36371.03 (n=530). The third-degree polynomial exactly fits the calibration data, highlighting the robust relationship between photon counts and turbidity levels (P<0.001). The high correlation coefficient (r=0.99) indicates an excellent fit of the third-degree polynomial to the data, demonstrating that the polynomial model can accurately predict turbidity based on IR photon counts across the measured range. Furthermore, the polynomial fit's precision is validated by the low standard deviations of turbidity measurements at various points, ensuring that the calibration curve can be reliably used in practical applications. However, it can be seen that the first two measurement points at 0.88 NTU and 3.35 NTU do not match the rest of the calibration curve obtained. Because this deviation from the calibration curve makes the interpretation of the measured sensor data in the low-turbidity range considerably more difficult, the conversion of the measured IR photon counts into the corresponding NTU value is omitted (Figure 2).

The photonic sensor conducted 210 measurements of the IR channel during the 52-hour period of each trial. The IR signal averaged 38,655.70 ± 562.10, 35,843.87 ± 1,507.01, and 34,486.79 ± 217.41 photon counts, in the SC, GS, and CN tanks, respectively. Turbidity measurements were not affected by the applied ambient light intensity (P = 0.98) when comparing the differences between the average photon counts during the ambient light and dark periods within tanks (Figure 3).

In the GS tank, the number of photons decreased from 37,443 to 30,048 counts during the trial period. The seawater in the tank became noticeably turbid, and the most dramatic change was recorded between the 190th and 210th measurements compared with the previous measurements (P=0.02). The photon counts obtained from the photonic sensor IR channel and the NTU levels measured by the turbidimeter were strongly negatively correlated (r=-0.783, P<0.001). The NTU level in the GS tank exhibited a linearly increasing trend between the 26th and 40th measurements. Similarly, a synchronous decreasing trend in the photon counts of the IR channel was observed (Figure 4).

The low turbidity change reflected by both the IR photons and handheld turbidimeter NTU was negligible in the SC tank. The number of IR photons measured by the IR channel of the photonic sensor exhibited a steady change from 36,844 to 39,969 photons. No significant changes in IR photon counts were observed between measurements (P=0,09). The mean NTU level measured by the turbidimeter was 1.77±0.51 (min 1.25, max 3.74) without any significant change among the measurements. An inverse and significant correlation (Spearman rank) was found between IR photon counts and NTU levels (r=-0.323, P=0.04).

In the control tank, where no aquatic organisms were present in the filtered seawater, the mean photon number for the IR channel was 34,486.79±217.41 (min 33,424, max 35,125) photons. The photon counts followed a steady horizontal course throughout the trial, without any significant change between the light and dark periods (*P*=0.75). The NTU level in tank CN remained constant throughout the trial, as indicated by the mean turbidity measured using the handheld turbidimeter. The mean NTU level was 1.17±0.07 (min 1.02, max 1.28), and there was no significant difference between the measurements (P=0.10). Although the IR photon counts of the photonic sensor were more variable than the NTU levels, the turbidity change reflected by both the IR photon counts and handheld turbidimeter was negligible in the CN tank.

NTU values measured by the handheld turbidimeter (n=21) in each trial tank revealed a turbidity fluctuation pattern similar to that of the IR channel of the photonic sensor. The most extensive range of turbidity fluctuations was in the GS tank with a 3.23 NTU difference between the minimum and maximum turbidity levels (min 3.78, max 7,01 NTU). The SC tank was rated second by a difference of 2.49 NTU (min 1.25, max 3.74 NTU), and the CN tank had the least turbidity fluctuation with 0.26 NTU ranged from 1.02 to 1.28 NTU. The GS tank with the highest range of turbidity fluctuations offered more dependable outcomes for assessing the sensitivity of the IR channel within the photonic sensor to turbidity changes (Figure 5).

DISCUSSION

This study demonstrated that IR counts measured using a photonic sensor can be used to assess turbidity changes in seawater. This finding is consistent with previous studies that reported a negative correlation between transmitted IR light and turbidity using IR turbidity sensors (Postolache et al. 2002; Omar and MatJafri 2009; Wang et al. 2018b). However, measurement accuracy depends on the measurement method used. The sensitivity of the sensor decreased with decreasing turbidity, as shown by the flattened curve for low turbidity values. Moreover, the data points measured for a turbidity of 3.35 NTU and below do not match the rest of the calibration curve, indicating that the transmission method is not as accurate for low turbidity values as for higher ones. To overcome this issue, the developed sensor could include an additional IR detector mounted at a 90° angle to the IR emitter to enable additional scattered light measurements. This approach improves the sensitivity of measurements at low turbidity and compensates for the current deficit of the sensor. However, turbidity changes in the SC tank were also detected by the sensor, which were probably caused by the high metabolic waste that sea cucumbers excreted during their movement and feeding cycles in dark periods. Hence, the developed photonic sensor possesses the ability to detect and measure hazardous and lethal conditions specifically for aquaculture species, particularly those with elevated metabolic waste levels, such as GS. The photonic sensor performed better in the GS trials with high turbidity levels. Considering that high turbidity or sudden changes in turbidity are important indicators of a problem in aquaculture, the developed sensor can fully and precisely detect turbidity fluctuations after 3.35 NTU and reduce the turbidity measurement frequency to 3 seconds and operate under the most challenging conditions. This emerges as a significant advantage of this system over its commercial counterparts in the market.

Many studies on the effects of ambient light cycle and intensity on cultured organisms have revealed that light has significant effects on stress, growth, nutrition, and reproduction (Tandler and Helps 1985; Karakatsouli et al. 2007; Dong et al. 2010; Bögner et al. 2018; Sun et al. 2020;). The interaction of ambient light with the photonic sensor used, as well as the potential deviations in the measured values, are critical for the reliability of photonic sensors. Putra et al. (2022) proposed integrating IR-based turbidity sensors with an RGB sensor, a light sensor, a charged coupled device sensor, or a combination of these to improve the performance of IR light sensors and the accuracy of the obtained data. In the current study, the applied ambient light schedule did not emit light in the IR spectral region, and therefore, had no effect on the IR-based turbidity measurements of the sensor; however, it was detected and measured by the RGB detector. Constant IR channel photon measurements in the dark and light periods in CN confirmed the ineffectiveness of ambient light on IR-based photonic sensors. The inclusion of RGB sensors in a system integrated with IR sensors would be efficient in determining and measuring the ambient light level scattered in the tanks where it is needed, however we did not determine any change in the accuracy of obtained IR channel data.

Biofouling is a major problem in sensor probes used for seawater monitoring. This limits long-term monitoring studies and affects the reliability of data obtained from sensors (Matos et al. 2023). Since the 52-hour period of our study was quite less time for mass biofilm development in filtered seawater, no biofilm formation was observed on the probe surfaces of the photonic sensor, and no bias due to biofilm was expected. However, the time required for biofilm development may vary depending on the specific surface and environmental conditions.

The developed sensor has a 3D rough-surface optical window that requires periodic manual cleaning. Long-term monitoring can cause the accumulation of biofilm on the optical window; however, ongoing developments include replacement of the 3d printed optical window with glass and integration of ultraviolet light to prevent biofilm organism growth on the optical window.

High turbidity changes caused by the growth of phytoplankton or pathogenic microorganisms in water (Zhang et al. 2021), can harm aquatic ecosystems. The early detection of increasing turbidity is essential to prevent minor issues from escalating and causing fish mortality. Current commercial turbidimeters require significant time and effort for the continuous or regular monitoring of turbidity in aquatic environments. However, the photonic sensor developed in this study performed well in aquaculture tanks with different turbidity levels, and with minimal time and labor for system setup and usage. Moreover, the developed system offers the possibility of easy customization for the intended application by adjusting emitter brightness, detector integration time, and firmware sampling rate. The integration of the system is simplified by the compact design of the sensor and the possibility of wireless data transmission from the top unit to a personal computer (PC) or smartphone. In addition to the customizability of the developed open-source-based system, one of the greatest advantages over commercial systems is the cost. Considering that the average price of a reliable turbidimeter is approximately 2000 euros, the hardware and material assembly costs of the developed sensor are less than 150 euros, making it affordable even for small businesses, research institutions, and private users.

CONCLUSION

Overall, the continuous monitoring of turbidity levels is essential for effective water quality management, disease prevention, feed management, and environmental protection in aquaculture. Through early detection of major changes in turbidity levels, aquaculturists can take proactive measures to maintain a healthy and sustainable aquatic environment for cultured organisms. Although this sensor has not yet reached the commercial level, this study demonstrates the potential of the developed photonic sensor to accurately assess turbidity levels above 3.5 NTU or even slightly lower and can successfully capture turbidity changes in its current form. However, owing to its robust structure, practical usage, ease of integration, extensibility, and low cost, the sensor is suitable for real-time sensing of turbidity changes in indoor and outdoor aquaculture tanks, recirculating aquaculture systems, marine cage sites, and environmental monitoring in both marine and freshwater environments.

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DATA AVAILABILITY STATEMENT

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Figure Captions

FIGURE 1. The photonic sensor used in detecting turbidity changes in seawater. (a) The top unit and its main and auxiliary parts, (b) schematic sensor probe

FIGURE 2. Polynomial fitting calibration curve (Polynomial IR) prepared by comparing the number of photons detected by the photonic sensor with the nephelometric turbidity unit (NTU) values measured using a handheld turbidimeter in samples with different turbidities to test the sensitivity of the photonic sensor probe's infrared channel (IR).

FIGURE 3. Photon counts detected by the infrared (IR) and ambient light (C) channels of the photonic sensor at 15-minute intervals for 52 hours in the Gilthead Seabream (a), Sea Cucumber (b) and the control (c) tanks. Zero photons for ambient light channel corresponds to total darkness in the tanks.

FIGURE 4. Nephelometric turbidity unit (NTU) values measured by a handheld turbidimeter at random times and corresponding photon counts measured by the infrared channel (IR) of the photonic sensor in Gilthead Seabream tank during the trial period. Dotted lines show the linear trends of both measurements.

FIGURE 5. Box-plot showing the distribution of average NTU values measured by the turbidimeter in 21 random measurements from Sea Cucumber (SC), Gilthead Seabream (GS), and control (CN) tanks. The box extends from the lower to upper quartile values of the data, with the line inside the box representing the median. The whiskers extend to 1.5 times the interquartile range from the edges of the box, and data points beyond this range are considered outliers (represented as individual points).