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RESEARCH

Observation of the Freshwater Inflow Event Using IoT Devices at an Oyster Farm in the Merbok Estuary During Monsoon

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Abstract

We installed commercially available observation devices with communication functions, such as weather meters, weather cameras, and water temperature buoys, on an oyster farm in the Merbok River Estuary and established a real-time monitoring system in the farm environment using the internet. Additionally, we observed changes in water temperature and salinity at a depth of 1 m, where oysters are mainly cultivated, using a self-recording water temperature and salinity meter and periodically performed vertical measurements using a throw-in water quality meter during the 2024 monsoon season (October-November). Data analyses, including correlation matrix analysis, indicated a strong correlation between the surface water temperature obtained from the water temperature buoy and the changes in salinity at a depth of 1 m obtained from the self-recording salinity meter. Further, the surface water temperature decreased with decreasing salinity. Generally, to obtain appropriate salinity data in a mangrove estuary, the sensor unit needs to be cleaned at least once a week; however, these results suggest that the decrease in salinity in the oyster hanging layer could be detected from the changes in surface water temperature observed by the water temperature buoy, which can be monitored on the network without relying on a self-recording salinity meter. These findings are expected to contribute to improved management of oyster farming environments and provide a scientific basis for decision-making regarding the relocation of farming sites in response to environmental changes.

Keywords Freshwater Inflow · IoT Devices · Oyster Farm · Mangrove Estuary · Rainy Season

Introduction

In recent years, the development of social infrastructure using communication technologies has accelerated, driven by the expansion of internet communication capacity (Thacker et al. 2019; RIS, 2023). Among these advancements, the application of Internet of Things (IoT) devices in environmental monitoring has shown significant promise in promoting environmental protection and energy efficiency. Various IoT devices capable of collecting real-time data on temperature, humidity, and CO_2 concentrations have already been deployed (Govindarajan et al. 2025; Morchid et al. 2024; Ullo and Sinha 2020). These data are transmitted to cloud platforms, where they are accumulated for big data analysis and artificial intelligence (AI)-based predictions of environmental changes, thereby fostering the development of advanced information and communication technology (ICT) ecosystems (Naghib et al. 2023; Miller et al. 2025; Govindarajan et al. 2025). Remote monitoring and control of equipment in distant locations are now feasible, significantly reducing the need for onsite labour (Laha et al. 2022; Yeshaswini et al. 2024). Moreover, IoT-based initiatives aimed at environmental conservation and sustainable development are progressing across various sectors (Zhang et al. 2022; Chiabai et al. 2013).

In aquaculture, the integration of IoT is expected to reduce ship voyages, enhance operational efficiency, and lower CO_2 emissions (Huang and Khabusi 2025; Assaf et al. 2024; Vijaykumar and Goud 2023). And bivalve aquaculture, which is highly sensitive to environmental conditions, stands to benefit significantly from IoT adoption (Abdullah

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and Bronner 2022; Paget et al. 2019). The Merbok River Basin in Malaysia spans approximately 440 km² and features mangrove brackish waters that support diverse fishing activities, including shrimp harvesting and juvenile fish collection (Haron and Ogawa 2003; Mansor et al. 2012; Ismail et al., 2015; Zainal et al., 2021, 2022; Ab-Doroh et al. 2023). Mangrove forests contribute nutrients and organic matter to estuarine waters, boosting primary productivity and supporting rich aquatic biodiversity (Reef et al. 2010; Ishfaq et al. 2025). Thus, preserving mangrove ecosystems and implementing effective fishery resource management are crucial for sustainable fisheries in the region (Yamamoto et al. 2012; Fatema et al. 2013). Oyster farming, which relies on phytoplankton as a food source, has gained popularity in the Merbok Estuary in recent years (Yurimoto et al. 2025). Efforts are underway to balance environmental conservation with sustainable aquaculture practices (Ali et al. 2021). However, during the monsoon season, freshwater inflow can reduce salinity levels below 10 PSU in upstream oyster farms, posing a risk of mass mortality if such conditions persist for over a week (Kamaruddin et al. 2018; Wong et al. 2022; Rybovich et al. 2016; La Peyre et al., 2013; Yurimoto et al. 2024).

Therefore, this study aims to enhance the productivity of local oyster farming and reduce the labour required for environmental management by developing a monitoring system using commercially available IoT devices. The system is designed to improve data collection efficiency and enable timely responses to environmental changes. As part of the research, water quality was measured using self-recording thermometers and salinity meters. These measurements were compared with environmental data collected via IoT devices to evaluate correlations and determine the most suitable monitoring system for the region.

Materials and methods

Regular Observations of Water Quality

Vertical profiling of water quality parameters—including temperature, salinity, chlorophyll-a, turbidity, dissolved oxygen, and light intensity—was conducted at an oyster culture raft near the weather station (WS) (Fig. 1). Measurements were taken using a portable water quality meter (AAQ-RINKO; JFE Advantech, Tokyo, Japan), which features a multi-parameter probe capable of high-resolution data collection at 0.1 m intervals. The device was manually deployed from the raft between 11:00 AM and 12:00 PM on October 5th, 24th, 27th, and November 6th, 2023. These dates coincided with the monsoon season, characterized by increased rainfall and fluctuating salinity levels, which are known to affect oyster viability.

Continuous Monitoring Using IoT Devices

To facilitate long-term environmental monitoring, a series of IoT devices were installed at the oyster farm located at the mouth of the Merbok River in 2022 (Fig. 2). A personal Wi-Fi weather station (WS-2902; Ambient Weather, USA) for was mounted approximately six meters above sea level, while an outdoor Wi-Fi weather camera (AmbientCam; Ambient Weather, USA) was positioned at a height of approximately three meters. These devices continuously recorded meteorological parameters, including air temperature, absolute pressure, hourly rain amount, wind speed, and solar radiation, at five-minute intervals. In addition to atmospheric monitoring, a wireless waterproof floating thermometer (WH31PF; Ambient Weather, USA) was deployed on the sea surface to measure surface water temperature in real time. For subsurface observations, a memory-equipped water temperature and salinity meter (DEFI2-CT; JFE Advantech, Tokyo, Japan) and a wiper-type chlorophyll turbidity meter (INFINITY-CLW; JFE Advantech, Tokyo, Japan) were suspended from the raft at a depth of one meter, corresponding to the typical depth of the oyster farming. These sensors were configured to record data at ten-minute intervals, a frequency selected to ensure sufficient temporal resolution for capturing short-term environmental fluctuations while maintaining battery life and data storage capacity. Furthermore, a depth meter (DFFI2-D10; JFE Advantech, Tokyo, Japan) was installed at the base of bridge pier to monitor tidal variations during low tide. Before deployment, all sensors were calibrated under the manufacturer's specifications. Calibration procedures included zero-point adjustments and cross-validation using standard sample solutions for salinity and chlorophyll, thereby ensuring the accuracy and reliability of the measurements.

Sensor Maintenance

To ensure data accuracy, the installed underwater sensors were regularly cleaned using urethane sponges and nylon brushes to remove biological fouling and sediment. Cleaning was usually performed every 1–2 weeks, but more frequently during periods of high biological activity. Rapid algae growth and sediment accumulation, especially in estuaries with high turbidity, can affect sensor readings and pose operational challenges. In addition, the installed equipment was regularly checked for sensor responses to check for any abnormalities.

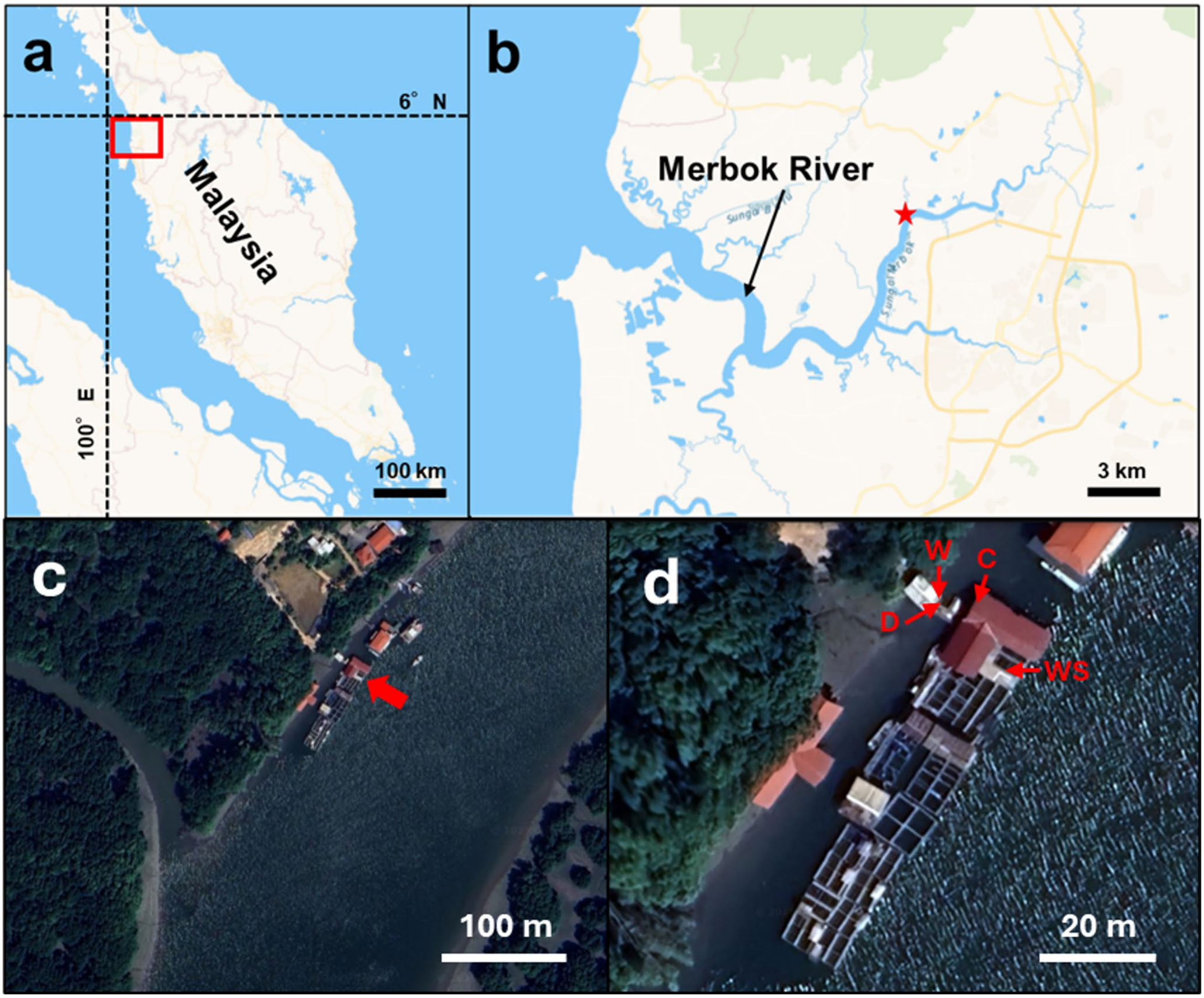


Fig. 1 Location of the oyster farm used as the study site at the mouth of the Merbok River, Malaysia. (**a**) Location of the Merbok Estuary in the Malay Peninsula (red frame), (**b**) location of the oyster farm at the mouth of the Merbok (star), (**c**) an aerial photograph of the oyster farm (arrow), and (d) location of the various equipment installed at the oyster farm: (C) weather camera, (D) depth sensor, (W) weather instrument, and (WS) suspension position of the water quality sensor. Figures a and b were obtained from Sentinel-hub EO Browser (https://apps.sentinel-hub.com/dashboard/#/collections), and Figures c and d were obtained from Google Earth (https://earth.google.com/web)

Data Collection and Analysis

Weather data were automatically stored on a remote server (Ambient Weather Network: https://ambientweather.net), while camera images were periodically downloaded using SeqDownload software (NirSoft, USA: http://www.nirsoft.net/utils/seqdownload.html). Water quality data from the DEFI2-CT and INFINITY-CLW meters were retrieved using dedicated software (DEFI Series, JFE Advantech, Tokyo, Japan). For analysis, vertical and time-series graphs were created using Excel 365 (Microsoft, USA). Hourly averages of weather, temperature, and salinity data from October 26th to 31st were calculated and visualized. Statistical analysis was performed using Jeffreys' Amazing Statistics Program (JASP: https://jasp-stats.org/; V0.18.3), including correlation plots and calculation of Pearson's correlation coefficients and p-values, with statistical significance set at $p < 0.05$.

Ethical Considerations

This study was conducted with consideration for the local marine ecosystem. All monitoring equipment was installed with minimal disturbance to oyster habitats and surrounding benthic communities. No wild specimens were collected during the study. The research aligns with sustainable aquaculture practices and aims to support local fisheries without compromising ecological integrity.

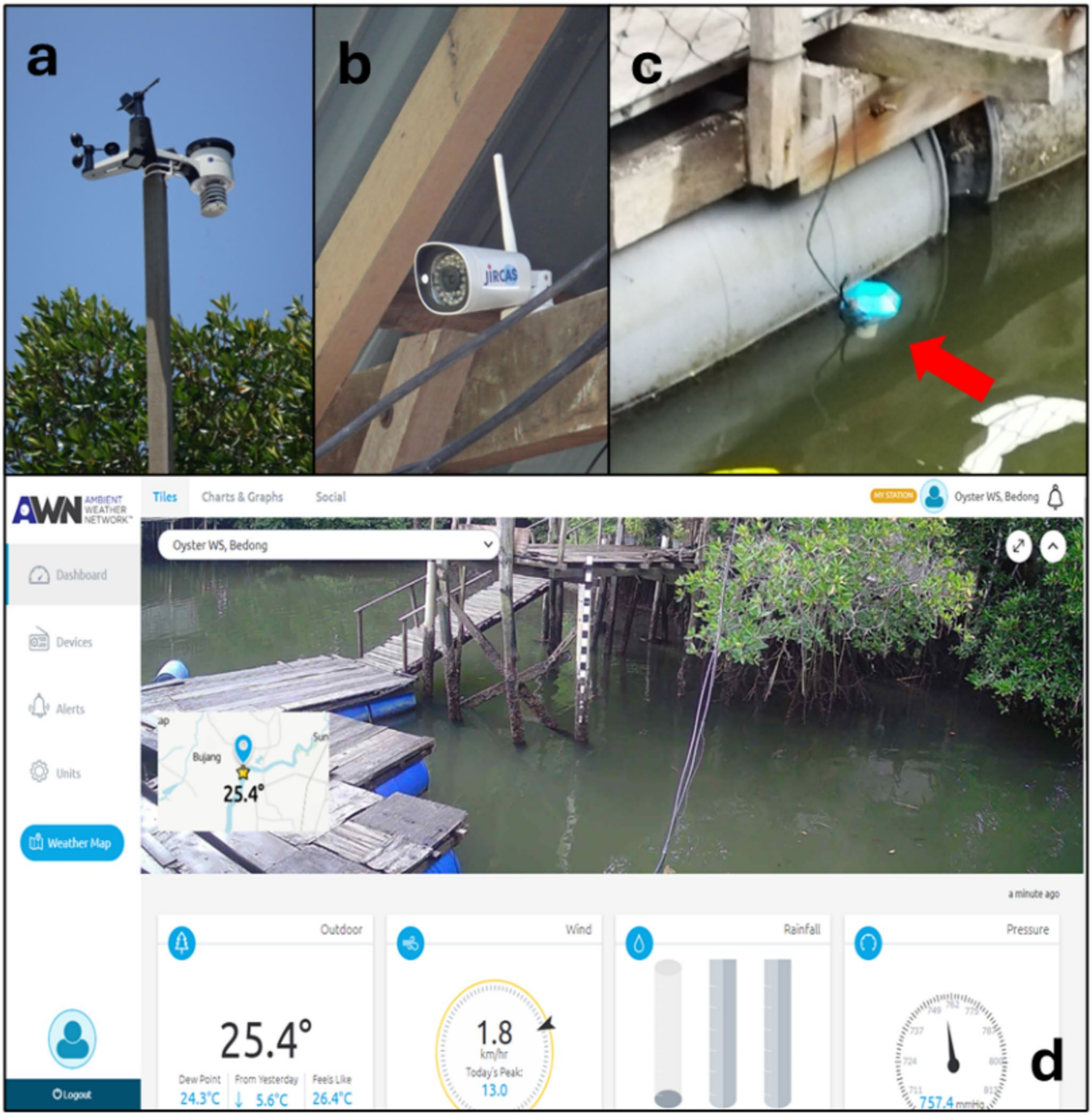


Fig. 2 Installation overview of various IoT devices and the internet homepage screen that records them. (**a**) Weather meter, (**b**) weather camera, (**c**) water temperature buoy, and (**d**) home page screen displaying live data

Results

Vertical Observations of Water Quality

Figure 3 presents the vertical distribution of water quality parameters obtained during regular surveys. Surface water temperature peaked at approximately 31 °C on October 5th, while temperatures at depths of 1 m or more remained around 29.5 °C. From October 24th to November 6th, surface temperatures were lower than those at deeper layers. Surface salinity dropped below 10 PSU on October 5th, October 24th, and November 6th, whereas salinity at depths of 1 m or more remained relatively higher on those same days. Chlorophyll-a concentrations were highest on October 5th, exceeding 6 μg/L at approximately 1.5 m depth, but declined to below 3 μg/L from October 27th onward.

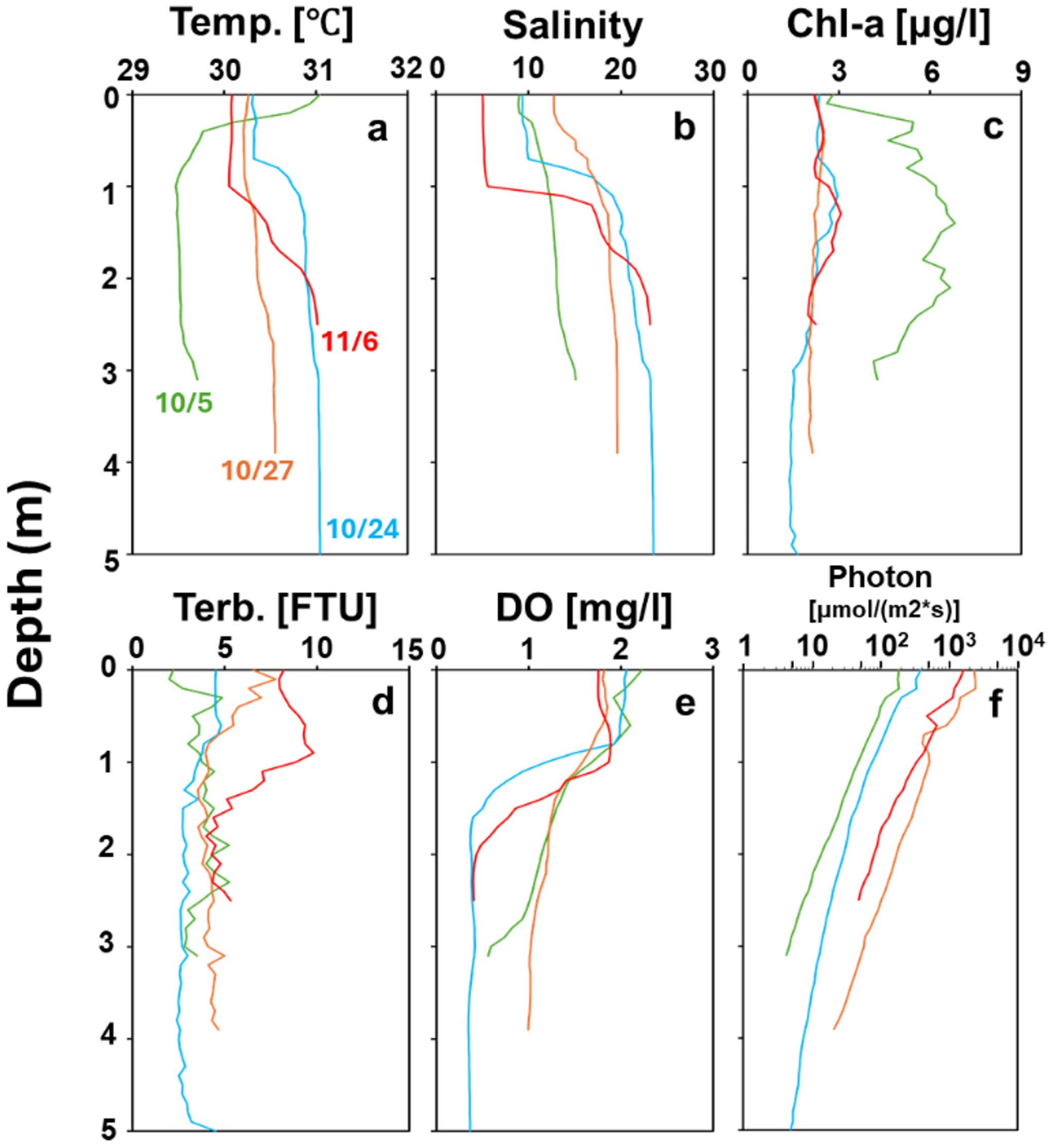


Fig. 3 Changes in (**a**) water temperature, (**b**) salinity, (**c**) chlorophyll concentration, (**d**) turbidity, (**e**) dissolved oxygen, and (**f**) photon quantity measured using a throw-in water quality meter. Green: Measured on October 5th, Blue: Measured on October 24th, Yellow: Measured on October 27th, and Red: Measured on November 6th

Turbidity remained elevated (up to 10 FTU) from the surface to 1 m throughout the observation period, with the highest value recorded on November 6th. Dissolved oxygen levels were approximately 2 mg/L at the surface but dropped below 0.5 mg/L at depths of 2 m or more on October 24th and November 6th, indicating hypoxic conditions. Light intensity was high at the surface, occasionally exceeding 1000 μmol/(m²·s), but decreased sharply below 100 μmol/(m²·s) at depths ≥ 3 m.

Time-Series Observations of Water Quality

Figure 4 illustrates the temporal changes in water quality parameters. Water temperature fluctuated periodically around 30 °C but dropped to 28 °C on the night of October 29th and further below 27 °C on October 30th. It recovered to approximately 29 °C after November 3rd and reached 30 °C by November 4th. Salinity remained stable at around 15 PSU until October 29th, then dropped sharply to nearly 0 PSU on October 30th. It gradually increased after November 3rd, stabilising around 10 PSU. Chlorophyll-a concentrations remained relatively constant at approximately 3 µg/L throughout the study period. Turbidity was generally below 10 FTU until October 29th, but exceeded 100 FTU on October 30th–31st before declining below 10 FTU by November 5th. Water depth at the observation site showed regular tidal fluctuations, exceeding 2 m around October 30th. However, the amplitude diminished over time, and periodicity was nearly absent by November 5th–6th. Notably, water temperature and salinity tended to decrease during low tide, while chlorophyll-a and turbidity increased.

Weather Camera Observations

Figure 5 shows sea surface conditions captured by a weather camera. On October 26th, the weather was stable, and the sea surface appeared green. Although rain on October 29th was not recorded due to communication issues, rainy condition was documented on October 28th. On October 30th, despite stable weather, muddy water was observed flowing into the farming area, particularly during low tide. By November 5th, the influence of turbid water had largely dissipated.

Environmental Changes Prior To Inundation

Figure 6 presents hourly average changes in water temperature and salinity at a depth of 1 m, surface water temperature, air temperature, atmospheric pressure, precipitation, wind speed, and light intensity. Salinity decreased from approximately 15 PSU on October 26th to below 5 PSU on October 29th. Water temperature at 1 m dropped from 30 °C to 27 °C on October 30th, while surface temperature fell from 29 °C to 26 °C. Air temperature showed diurnal variation, peaking at 32 °C during the day and dropping to 25 °C at night. On October 28th, daytime temperatures reached only 30 °C. Atmospheric pressure, which had exceeded 1010 hPa earlier in the month, declined after October 28th. Precipitation increased significantly on October 28th and peaked at 35 mm/h on October 29th. Wind speed remained below 1.5 m/s, and light intensity dropped below 80,000 lx on October 28th.

Correlations between Environmental Parameters

Figure 7 summarises the correlation analysis among observed parameters. Salinity at 1 m depth showed positive correlations with water temperature at 1 m depth, sea surface temperature, air temperature, air pressure, and light intensity. Water temperature at 1 m depth was positively correlated with sea surface temperature, air temperature, and air pressure. Sea surface temperature correlated positively with air temperature and light intensity. Air temperature was negatively correlated with air pressure and positively correlated with light intensity. Air pressure showed no significant correlation with sea surface temperature, rainfall, wind speed, or light intensity. Rainfall and wind speed did not exhibit significant correlations with all other parameters. Importantly, the correlation coefficient between sea surface temperature and salinity at 1 m depth—where farming oysters were suspended—was $r = 0.867$ ($p < 0.01$), with the regression equation $y = 3.7896x - 96.331$ (Figs. 7 and 8), indicating a strong predictive relationship.

Discussion

Oyster Farming and Water Quality

In the oyster farms surveyed in this study, oysters were cultivated in suspended cages positioned at a depth of one meter. This depth is considered optimal for oyster growth and survival, based on both previous studies and local farmers' experience (Sun et al. 2024; Le et al. 2025). High survival and growth rates are essential for improving aquaculture efficiency, and these are closely linked to several water quality parameters, including temperature, salinity, dissolved oxygen, chlorophyll-a concentration, and turbidity (Turner et al. 2019; Crockett et al. 2012). To evaluate environmental conditions at various depths, vertical profiles of water quality were regularly measured. The one-meter depth layer, where oysters were cultivated, generally exhibited high levels of dissolved oxygen, likely due to gas exchange at the air–water interface (Iriarte et al. 2010). Chlorophyll-a concentrations, which indicate phytoplankton abundance—the primary food source for oysters—also tended to peak at this depth (Boyer et al. 2009). However, this layer was also subject to fluctuations in salinity and turbidity, with occasional exposure to low-salinity and high-turbidity conditions. Below two meters, salinity and turbidity were relatively stable (approximately 20 PSU and <5 FTU, respectively), but dissolved oxygen levels dropped sharply, often falling below 1 mg/L. Such hypoxic conditions can impair oyster feeding and respiration, potentially leading to stunted growth or mortality if

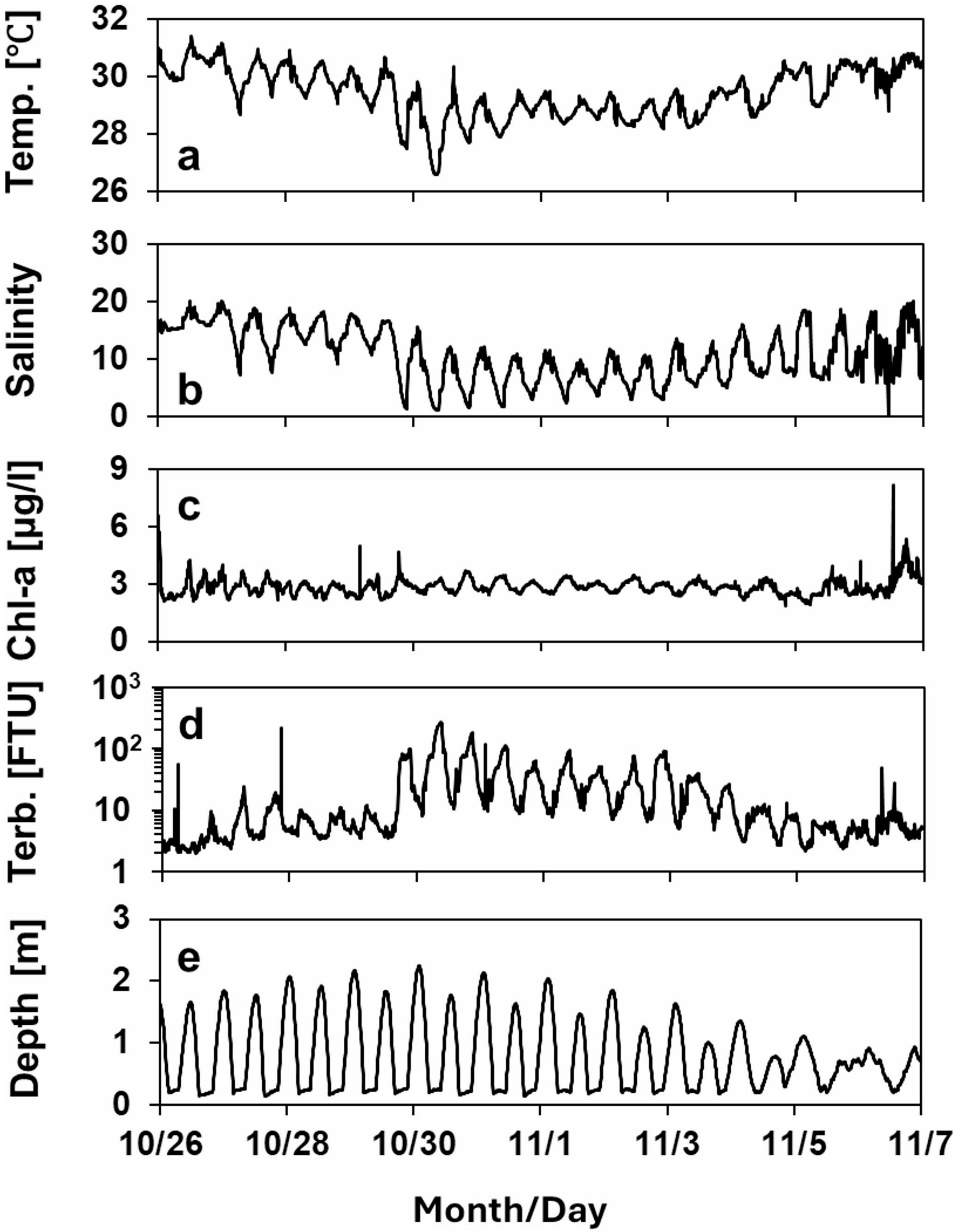


Fig. 4 Changes in water quality at a depth of 1 m measured using a self-recording water quality meter. (**A**) Water temperature, (**B**) salinity, (**C**) chlorophyll-a concentration, (**D**) turbidity, and (**E**) water depth

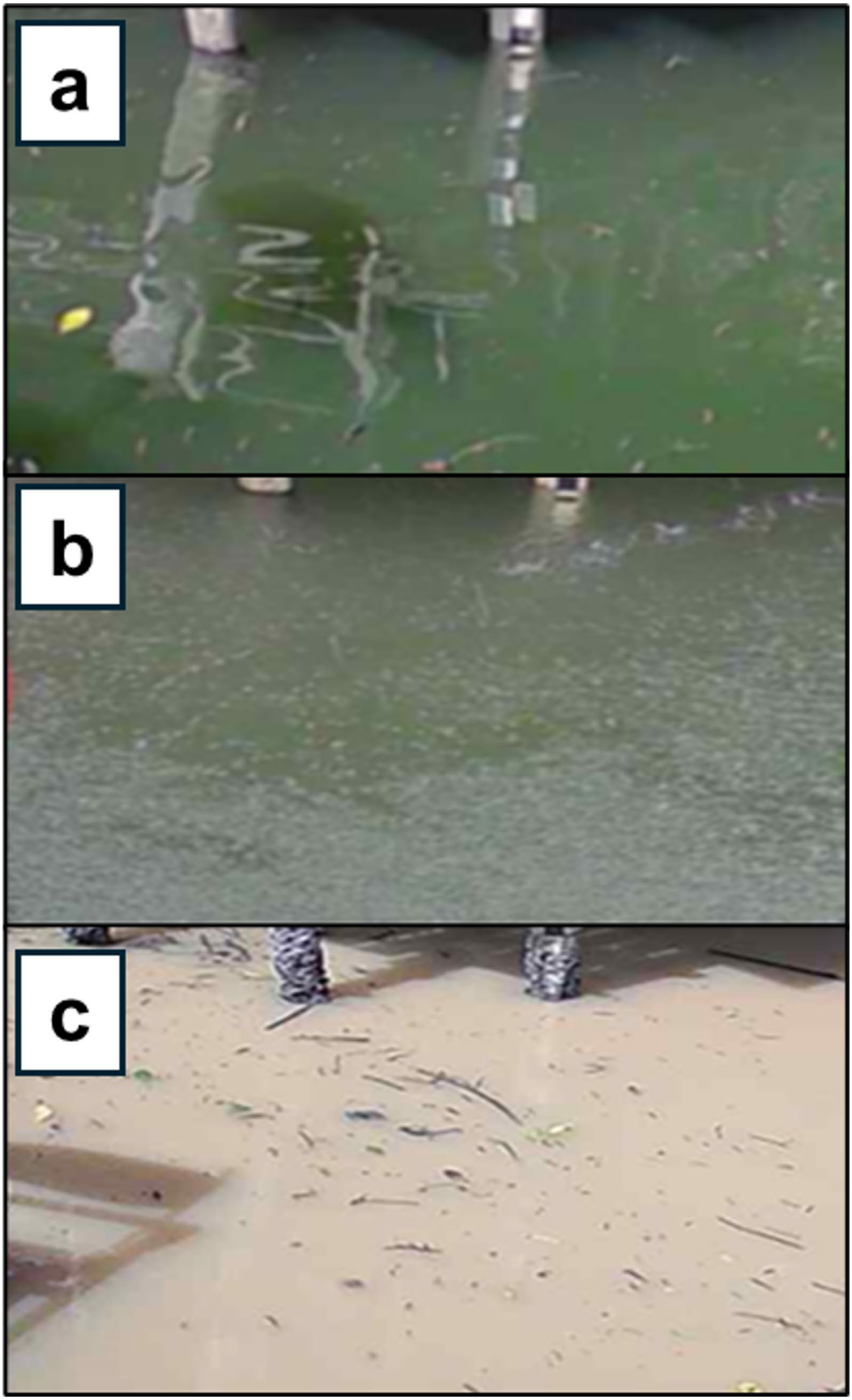


Fig. 5 Daytime sea surface photographed using a weather camera. Photographs on (**a**) October 26th, (**b**) October 28th, and (**c**) October 30th

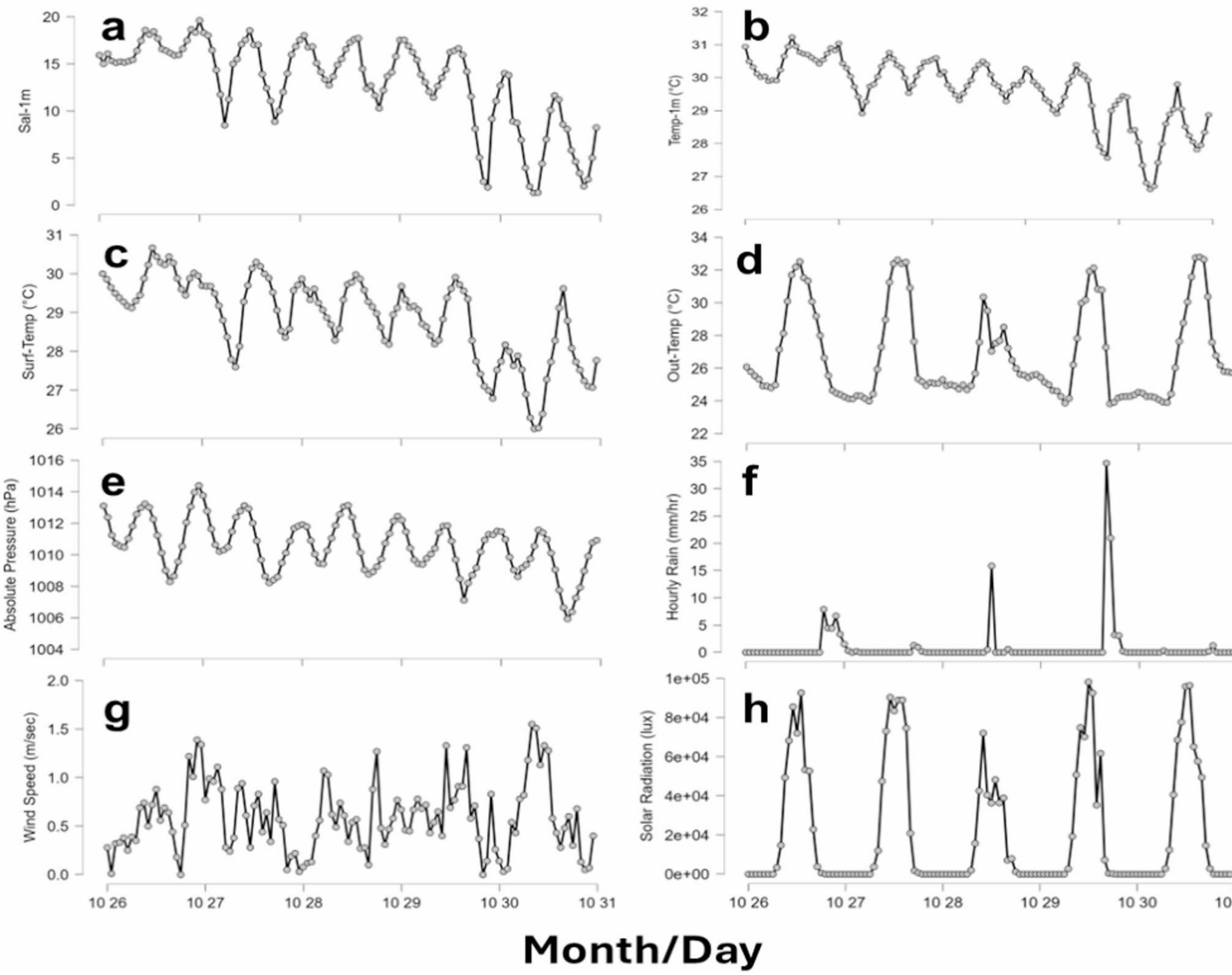


Fig. 6 Trends in the hourly average values of various environmental factors from October 26th to 30th. (**a**) Salinity at 1 m depth, (**b**) water temperature at 1 m depth, (**c**) surface water temperature, (**d**) air temperature, (**e**) atmospheric pressure, (**f**) hourly precipitation, (**g**) average wind speed, and (**h**) solar radiation

prolonged (Davis et al. 2024; Le Moullac et al., 2007). The surrounding mangrove forests may contribute to these low oxygen levels through the decomposition of organic matter, which consumes oxygen in the water column (Dubuc et al. 2019; Lake et al., 2015). Although continuous monitoring of dissolved oxygen was not conducted in this study, it is presumed that oxygen concentrations fluctuated significantly due to tidal and diurnal cycles. Future research should focus on capturing these fluctuations in greater detail, particularly at the one-meter depth where oyster cultivation is concentrated.

Inflow of Turbid Water

On the night of October 29, 2025, a significant inflow of freshwater was observed in the oyster farming area, leading to a rapid drop in water temperature and salinity, along with a sharp rise in turbidity. These changes were closely associated with tidal dynamics, as continuous water quality observations revealed that temperature and salinity tended to decrease while turbidity increased during low tide. Conversely, during high tide, warmer and clearer seawater entered the area, mitigating the effects of the turbid inflow (Fatema et al. 2014; Karati et al. 2021). This event occurred during a spring tide, a period characterised by active seawater intrusion into estuarine zones, which promotes mixing between freshwater and suspended sediments. As a result, the turbid water was more effectively dispersed (Burchard et al. 2019; Veerapaga et al. 2020). Water quality data from October 29 to the early morning of October 30 confirmed these trends, showing sudden shifts in temperature, salinity, and turbidity levels. Despite the turbid conditions persisting for approximately six days, interviews with local oyster farmers indicated that no oyster mortality occurred during

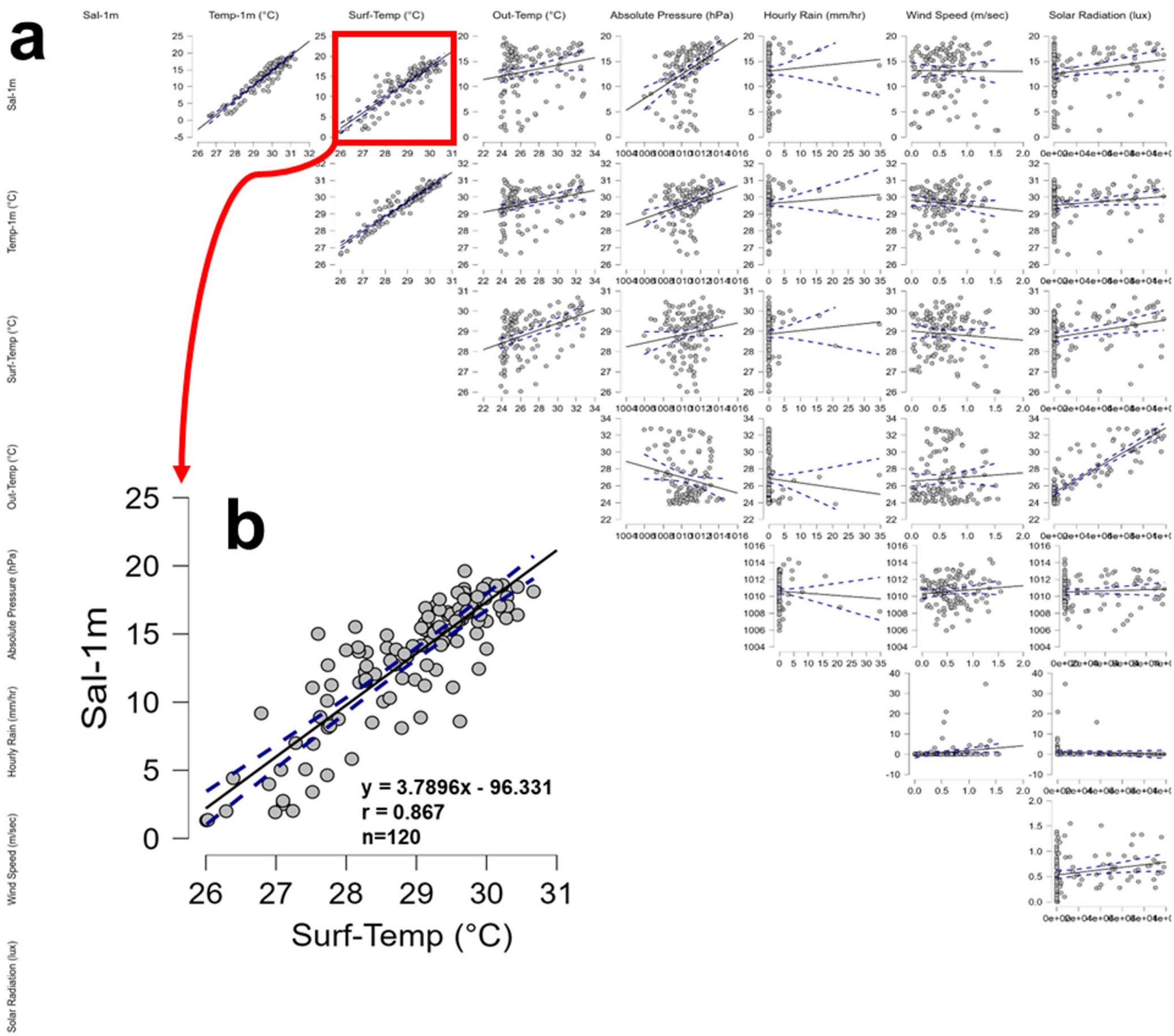
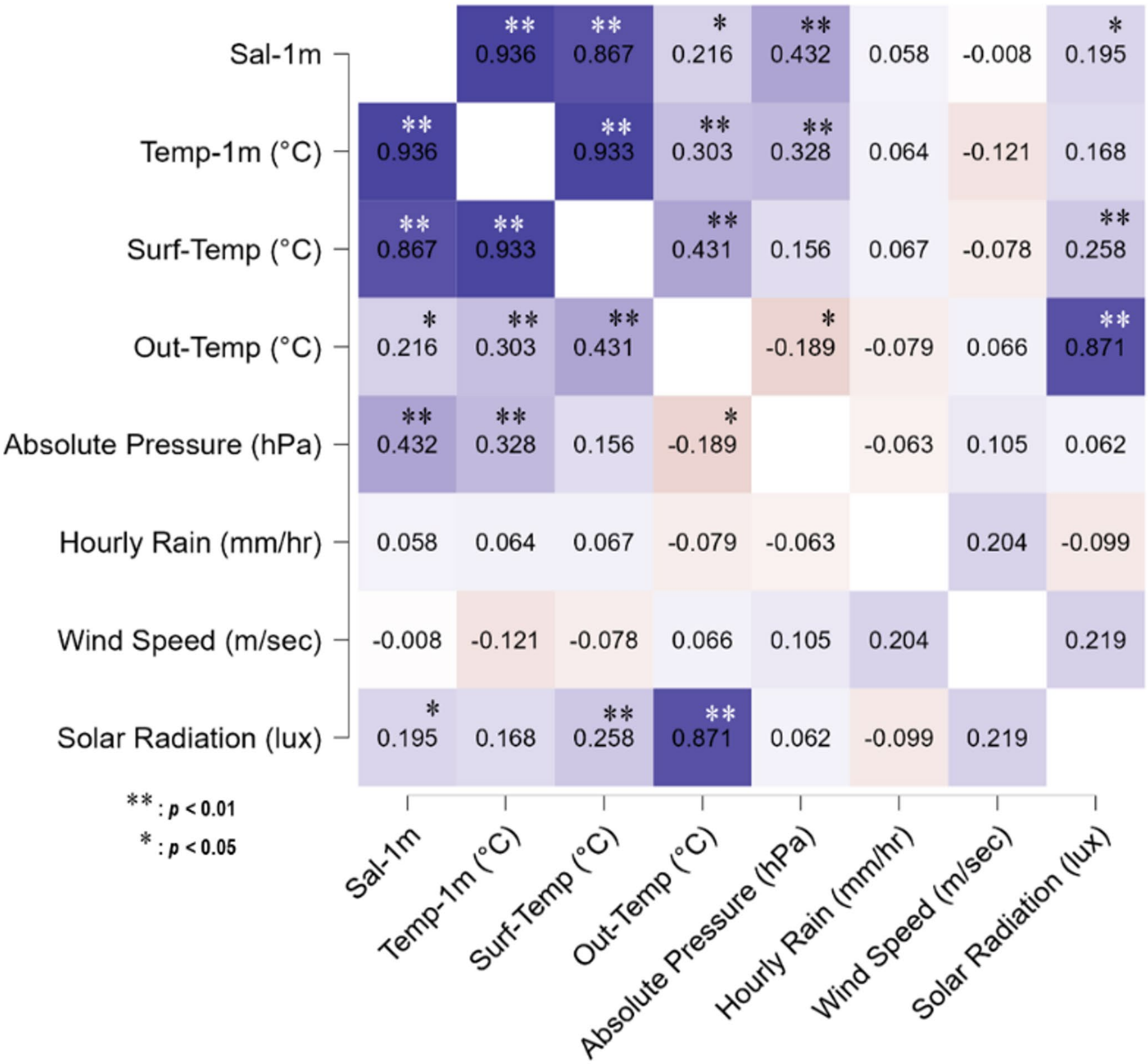


Fig. 7 (**a**) The scatter plot matrix between pairs of variables and (**b**) the enlarged correlation graph between sea surface temperature and salinity of 1 m depth. The dotted lines in the scatter plot indicate 95% confidence intervals

this period. However, it is suggested that if similar rainfall had occurred during a neap tide—when seawater inflow is reduced—the exposure to low salinity and high turbidity could have lasted longer (Parada et al. 2012). Under such conditions, salinity levels might remain below 10 PSU and turbidity above 100 FTU for more than a week, potentially posing a serious threat to oyster survival. The surrounding environmental conditions, including tidal fluctuations and the timing of freshwater inflow, play a critical role in determining the resilience of oyster farms to such events. Future monitoring should focus on capturing these dynamics in greater detail to better predict and mitigate risks to aquaculture operations.

Potential of Water Temperature Buoys

A key objective of this study was to explore the use of IoT devices for onsite environmental monitoring in oyster farming. Currently, monitoring water quality data via internet communication requires dedicated underwater sensors and transmitters, which are often costly. To address this, research is underway to reduce these expenses and improve accessibility for general aquaculture operations (Demetillo et al. 2019; de Camargo et al. 2023). However, underwater sensors such as salinity meters are prone to measurement errors due to biofouling and require regular cleaning and antifouling treatments (Delauney et al. 2010; Delgado



	Sal-1m	Temp-1m (°C)	Surf-Temp (°C)	Out-Temp (°C)	Absolute Pressure (hPa)	Hourly Rain (mm/hr)	Wind Speed (m/sec)	Solar Radiation (lux)
Sal-1m		** 0.936	** 0.867	* 0.216	** 0.432	0.058	-0.008	* 0.195
Temp-1m (°C)	** 0.936		** 0.933	** 0.303	** 0.328	0.064	-0.121	0.168
Surf-Temp (°C)	** 0.867	** 0.933		** 0.431	0.156	0.067	-0.078	** 0.258
Out-Temp (°C)	* 0.216	** 0.303	** 0.431		* -0.189	-0.079	0.066	** 0.871
Absolute Pressure (hPa)	** 0.432	** 0.328	0.156	* -0.189		-0.063	0.105	0.062
Hourly Rain (mm/hr)	0.058	0.064	0.067	-0.079	-0.063		0.204	-0.099
Wind Speed (m/sec)	-0.008	-0.121	-0.078	0.066	0.105	0.204		0.219
Solar Radiation (lux)	* 0.195	0.168	** 0.258	** 0.871	0.062	-0.099	0.219	

Fig. 8 Correlation heat map between pairs of various variables. The dark purple items indicate $r=0.8$ or higher. Statistical significance levels were set at *: $p<0.05$ and **: $p<0.01$

et al. 2021). In tropical mangrove brackish waters, fouling organisms and sediment flux tend to accumulate rapidly, necessitating cleaning at least once per week. Moreover, the use of antifouling agents is discouraged on oyster cultivation rafts, making long-term maintenance labour-intensive. In contrast, commercially available weather meters, cameras, and buoys equipped with communication functions are relatively affordable (total approximately 100,000 JPY) and can be maintained more easily, especially when installed on land and near shore. Although issues such as poor electrical contact, Wi-Fi failures, and lightning-induced power outages were encountered, land-based installations allowed for straightforward maintenance. Over time, algae and other organisms may adhere to surface buoys, and in severe cases, the accumulated weight can cause the buoy to sink (Venkatesan et al. 2017; Thomson et al. 2015). Therefore, it is recommended to remove surface debris every 1–2 months, a frequency significantly lower than that required for underwater sensors. This study demonstrated the effectiveness of water temperature buoys as low-cost, low-maintenance tools for environmental monitoring. A strong correlation was observed between surface water temperature and salinity at a depth of one meter—the typical depth for oyster cultivation. This suggests that surface temperature can serve as an early indicator of freshwater inflows, such as those caused by rainfall. In tropical regions, surface water temperatures are generally stable throughout the year (Satheeshkumar and Khan 2014; Itsukushima et al. 2024), but rainwater inflow can cause a rapid temperature drop. In the observed case, surface temperature fell from approximately 29 °C to below 27 °C, while salinity at the cultivation depth dropped below 10 PSU. These findings highlight the potential of using surface temperature data as a proxy for salinity changes, enabling oyster farmers to develop early warning systems that enhance the resilience and sustainability of aquaculture operations.

Challenges for Stable Aquaculture

The introduction of commercially available IoT-based water temperature buoys enables oyster farmers to detect sudden environmental changes in real time. This allows for timely interventions, such as relocating oysters to safer marine areas or transferring them to land-based tanks with controlled salinity. However, the findings of this study are based on data collected at limited sites during the monsoon season, and it remains unclear whether the same monitoring approach is applicable under different seasonal or geographical conditions. While surface water temperature proved to be a useful indicator of salinity changes, other important environmental parameters such as dissolved oxygen and turbidity were not covered in this study. To enhance the reliability and generalizability of this monitoring method, future research should focus on long-term data collection and validation across multiple sites and environmental contexts.

Conclusion

This study demonstrated that changes in surface water temperature, measured by a buoy, can effectively indicate salinity decreases in the sub-surface and bottom layers of oyster farms. This approach enables real-time monitoring via networked systems, eliminating the need for high-maintenance salinity meters. However, the findings are based on limited data collected during a specific monsoon season, and their applicability to other seasons or regions with different hydrological and ecological conditions remains uncertain. Additionally, while surface temperature served as a useful proxy for salinity, it does not capture other key environmental factors such as dissolved oxygen and turbidity. To improve the reliability and broader applicability of this method, further long-term, multi-site validation is necessary. Future work will focus on analysing the collected environmental data in greater detail, identifying critical indicators for site assessment, and exploring predictive techniques—such as multiple regression analysis—to enhance environmental forecasting in oyster farming areas.

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Author Contributions T. Y. planned the monitoring system, performed the data analysis, and drafted the manuscript. F. M. K. was responsible for equipment status management and data collection. M. A. R. decided on the location of this study and supervised the promotion of the study. All authors collaborated to improve the content of the manuscript.

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Data Availability The datasets generated and analysed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Declarations

Competing Interests The authors declare no competing interests.

Clinical Trial Number Clinical trial number: not applicable.

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