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The Interaction of Chlorophyll-a and Total Suspended Matter along the Western Semarang Bay, Indonesia, Based on Measurement and Retrieval of Sentinel 3

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ABSTRACT

The Kendal Regency area is one of the areas on the northern coast of Central Java that has been experiencing rapid industrial development. The high human activity in this area will impact the quality of water in these surrounding areas and affect the fertility of the waters. The concentrations of chlorophyll-a (Chl-a) and total suspended matter (TSM) are major water quality parameters that can be retrieved using remotely sensed data. The retrieval satellite of the 3 OLCI chosen in this study has a 300 m spatial resolution. This study aimed to see the distribution and effect of total suspended matter (TSM) on chlorophyll-a based on measurement and retrieval of Sentinel 3 imagery using the linear regression method. The results show the chlorophyll-a distribution and the value from retrieval satellite are higher and occur over larger surface area compared to chlorophyll-a measurements. The linear regression model of chlorophyll-a by retrieval satellite imagery and measurement is $y = 0.65x + 4.65$ with $R^2 = 0.54$. The presence of high amounts of suspended solids in the waters causes disturbances in the reflectance values, which are recorded by the retrieval of satellite. The model regression chlorophyll-a with TSM accuracy from retrieval satellite results in the equation $y = -0.0416x + 5.14$ ($R^2 = 0.45$, $p = 0.05$, $n = 13$). The determination (R^2) coefficient value is 0.445, which means that suspended solids have a 44.5% effect on chlorophyll-a and 55.5% is influenced by other factors and not examined in this study. The results show that TSM has an influence on the accuracy of chlorophyll-a and retrieval satellite recording can be disrupted if waters have high turbidity.

Keywords: Sentinel 3, chlorophyll-a, total suspended matter, linear regression.

INTRODUCTION

The Kaliwungu River estuary is located in the western part of Semarang Bay and it is one of 29 estuaries that drain fresh water into Semarang Bay. This bay is part of Kendal Regency, Central Java, which is located at 109°40'–110°18' E and 6°32'–7°24' S, with an ±1,002.23 km^2 area. These waters have high potential for fishing, with catches reaching 307.168 tons/year (Rahman et al., 2013). The increase in anthropogenic inputs of nitrogen (N) and phosphorus (P) into coastal ecosystems through river discharges into coastal ecosystems is the main cause of eutrophication and ecosystem degradation due to coastal ecosystems worldwide (Paerl et al., 2014; Malon & Newton, 2020).

The eutrophication process could cause algae blooms, and further impacts could be decreased oxygen dissolved and high solids suspended in the water. One of the water quality parameters that can be used to determine the level of eutrophication is the abundance of algae in the water (Marlian et al., 2015; Poddar et al., 2019; Moutzouris-Sidiris & Topouzelis 2021), and its abundance can be estimated by using the chlorophyll-a measurement. The chlorophyll-a concentration can describe the various factors that happen because of human activity (Gai, et al., 2020). Besides chlorophyll-a, total suspended materials (TSM) is also a determining parameter for water quality. Both parameters related to its presence in the waters, though the correlation was not always positive (Maslukah et al., 2022).

Determination of the chlorophyll-a concentration in water analysis could be done by field measurements, laboratory measurements, or by monitoring the color of the sea using remote sensing data (Wang et al., 2017; Abbas et al., 2019; Maslukah et al., 2021). One of the remote sensing methods that have been developed to monitor the optical properties of water is using the Sentinel 3 satellite. Filipponi et al. (2015) performed monitoring of chlorophyll-a using Sentinel 3 in the Adriatic Sea and Po River, Northern Italy. Satellite images MODIS and Landsat are also frequently used for chlorophyll-a monitoring. On the north coast of Java, research on chlorophyll-a using MODIS and Landsat has been done by some researchers, including Siregar and Koropitan (2016); Sabrina et al. (2017); Subiyanto (2017); Wirasatriya et al. (2018), and Sentinel 3 by Muhammad et al. (2021) and Habban et al. (2022). The research on comparing Sentinel 3 to field measurements has not been conducted.

Meanwhile, the results of the research by Maslukah et al., (2021) in Semarang waters indicated that the use of MODIS level 3 was not appropriate for monitoring chlorophyll-a in coastal areas or river estuaries. This is related to low spatial resolution (that is 4 km). Moreover, the estuary area is a highly dynamic area that is characterized by its high turbidity and shallow waters. Tarpanelli et al. (2020) explained that high turbidity could cause the existence of disturbance reflectance values that can be captured by the satellite imagery. Water depth can also affect reflectance, which can be measured by satellite (Abbas et al., 2019).

This study aimed to see the distribution of chlorophyll-a and TSM between measurement and retrieval satellite imagery and how the correlation of TSM and chlorophyll-a is recorded by satellite imagery. The retrieval satellite that was used in this research is Sentinel 3, considering the spatial resolution (300 m) is smaller than the MODIS level 1 (1 km). It is expected that this research can contribute to developing the use of Sentinel 3 imagery in monitoring the chlorophyll-a value for mapping fishing ground areas or monitoring the eutrophication process.

MATERIALS AND METHODS

This study was conducted in the western part of Semarang Bay, more precisely, close to the Kaliwungu Estuary, Kendal Regency, Central Java. The research location is located at coordinates 6°54’–6°56’ South Latitude and 110°18’–110°21’ East Longitude (Figure 1). The samples were taken at 13 stations. 3A OLCI (Ocean and Land Color Instrument) L2 Sentinel Satellite Imagery Data, retrieved from https://coda.eumetsat.int/.

Chlorophyll–a analysis

The chlorophyll-a analysis method followed Parson et al. (1984). The water sample from each station was taken in the amount of 1 liter, followed by filtration using nitrocellulose membrane (pore size of 0.45 m) with the help of a vacuum pump. During filtering, $MgCO_3$ was added to prevent acidification during filtering. The filtered filtrate was put in a test tube and extracted with 10 ml of 90% acetone, continuing with the incubation process for 12–16 hours. The centrifugation process was carried out at 4000 rpm for 5–10 minutes. The top sample was poured into a 1 cm cuvette and the absorbance value was read using an Optima UV-Vis spectrophotometer at wavelengths of 750 nm, 664 nm, 647 nm, and 630 nm. The wavelength of 750 nm is a correction for turbidity.

The chlorophyll-a value in the cuvette was calculated using equation 1 (APHA, 1991). The absorbance value at a wavelength of 750 nm has been corrected before. Furthermore, the concentration of chlorophyll-a in this sample is calculated by equation 2.

$$\begin{aligned} Chl-a &= 11.85(\lambda\,664) - \\ &-1.54(\lambda\,647) - 0.08(\lambda\,630) \end{aligned} \tag{1}$$

where: *Chl-a* – concentration chlorophyll-a in the cuvette (μg/mL);
11.85, 1.54, 0.08 – constanta;
664, 647, 630 – spectrophotometer wavelength.

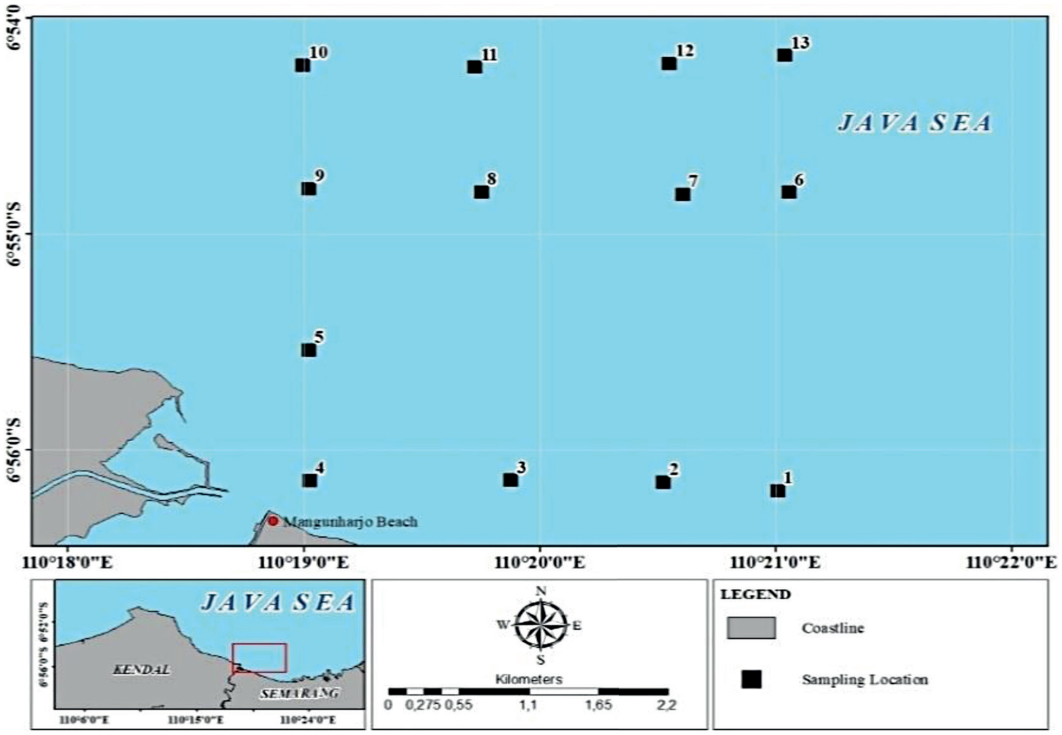

Figure 1. Location of research

$$Chlorophyll - a, \frac{mg}{m^3} = \frac{Ca \times Extract\ volume\ (ml)}{volume\ of\ sample\ (L)} \quad (2)$$

where: Ca – chlorophyll-a concentration in the cuvette; extract volume – acetone (ml)

The chlorophyll-a data were obtained from the Sentinel-3 OLCI in the CHL_NN band. The data was downloaded on April 9th, 2021, together with field data collection. This satellite imagery data was processed based on the algorithm of Moutzouris-Sidiris and Topouzelis, 2021, using equation 3.

$$C = 10^{A_0 + A_1 \times R + A_2 \times R^2 + A_3 \times R^3 + A_4 \times R^4} \quad (3)$$

where: R = log10 (MBR);
A_0 = 0.450; A_1 = -3.259; A_2 = 3,522;
A_3 = -3.359; A_4 = 0.949;
C – chlorophyll-a concentration (mg/m ^{3});
R443, R490, R510, and R555 are reflectants radiation at the 443, 490, 510, and 555 nm wavelengths. The nominally relevant band used by Sentinel-3 OLCI at a 555 is 560 nm wavelength;
MBR = $(\frac{R_{443}, R_{490}, R_{510}}{R_{555}})$.

Afterwards, the data was processed using SNAP software for correcting, masking, and cropping in accordance with the research area to make it easier to render. Then the data is reprojected so you can process it using ArcGIS to make layers scatter chlorophyll-a.

Total suspended matter analysis

The sample is filtered in the amount of 500 mL through a pre-ash, pre-weighed 47 mm, 0.7 m pore size glass fiber filter (GF/F). The samples were dried at 100 °C was then put in a desiccator for storage. TSM is calculated by subtracting post-weight from filter pre-weight for each sample.

Data analysis

The correlation of chlorophyll-a retrieval satellite precision, chlorophyll-a measurement, the TSM satellite imagery, and the TSM measurement is explained using regression and correlation analysis to determine the significance of the relationship between both variables. To validate this Chl-a and TSM, the reflection value is also calculated. The index applied is as follows (Table 1).

Table 1. Statistical indices (Moutzouris-Sidiris and Topouzelis, 2021)

Statistical index	Equation	Index
R^2	$R^2 = \left(\frac{\sum_{i=1}^{N}[(y_i - \hat{y})x(x_i - \hat{x})]}{\sqrt{\sum_{i=1}^{N}[(y_i - \hat{y})]^2 \sum_{i=1}^{N}[(x_i - \hat{x})]^2}} \right)^2$	-
r	$r = \frac{\sum_{i=1}^{N}[(y_i - \hat{y})x(x_i - \hat{x})]}{\sqrt{\sum_{i=1}^{N}[(y_i - \hat{y})]^2 \sum_{i=1}^{N}[(x_i - \hat{x})]^2}}$	-
Bias	$\text{Bias} = \frac{1}{N} \times \sum_{i=1}^{N} (y_i - x_i)$	mg/m^3

Note: y – the value of Chl-a calculated from the satellite data; $\hat{y}$ – the mean value of y; x – the measurement.

The coefficient of determination (R^2) indicates that an independent variable (x) has an influence on the dependent variable (y). The determination coefficient is useful to look at the relationship model and how much influence is given by variable x on variable y simultaneously. The t test statistics were used to test hypotheses for coefficients m (gradient) and c (constanta), and SPSS 24 (Statistical Package for the Social Sciences) software was used for data analysis. The accuracy testing in this study involved root-mean-square error (RMSE) (equation 4) and mean absolute relatif error (MARE) (equation 5), while the t-test (Student's T-Test) was used to determine the significance level of the correlation coefficient. The t-statistics were calculated using the following equation 6.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left(Chla_{i,meas} - Chla_{i,retr}\right)^2}{N}} \quad (4)$$

$$\text{MARE} = \frac{1}{N} \times \sum_{i=1}^{N} \frac{\left| \begin{pmatrix} Chla_{i,meas} - \\ -Chla_{i,retr} \end{pmatrix} \right|}{Chla_{i,meas}} \quad (5)$$

where: $Chla_{i,meas}$ and $Chla_{i,retr}$ refer to the measured (in-situ) and retrieved (estimated) Chl-a respectively;
N is the total number of samples.

$$t = \frac{r \times \left(\sqrt{n - 2}\right)}{1 - r^2} \quad (6)$$

where: n – the number of measurements,
r – the Pearson correlation,
R^2 – the coefficient of determination.

The p-values were then calculated using the student t distribution output. A two-way distribution with a 0.05 (α = 0.05) significance level was chosen. There is a significant linear relationship between Chl-a and TSM calculated from in situ and retrieval of satellite if the p value is less than the significance level. In ArcGIS, the modelbuilder was used to generate spatial patterns for the resulting image fields and images.

RESULTS AND DISCUSSION

According to the study, the measurement field for chlorophyll-a and TSM was in the range of 0.7–9.07 mg/m^3 and 9.40–106.60 mg/dm^3, and the estimated Sentinel 3 satellite was between 3.87–9.47 mg/m^3 and 11.77–48.42 mg/dm^3. Full results per station are presented in Table 2.

Chlorophyll–a distribution

According to Table 2, the average value of the satellite data is higher at 6.74 ± 1.99 mg/m^3. Figure 2 shows the spatial distribution of chlorophyll-a field measurement and satellite measurement. The highest chlorophyll-a concentration by field measurement (observation) was found near the estuary with a value of 9.07 mg/m^3, while the lowest was found far from the estuary with a value of 0.70 mg/m^3. The high input of nutrients from land, estuary and coastal areas has the highest chlorophyll concentration (Malon and Newton, 2020; Maslukah et al., 2018).

Chlorophyll-a satellite distribution (Figure 2a), demonstrating the difference from the measurement field data (Figure 2b). In Figure 2a, the highest chlorophyll-a value has shifted to the north estuary. Chlorophyll-a satellite value was shown at 9.47 mg/m^3, while at the station close to the estuary, the value was in the range of 8.81 mg/m^3. Figure 3 depicts a scatter plot of the chlorophyll-a field measurement and satellite data.

Figure 3 shows the equality obtained by the regression is $y = 0.65x + 4.65$, with coefficient determination $R^2 = 0.54$. On the basis of the equation model obtained a 0.74 coefficient correlation (r)

Table 2. The concentration of chlorophyll-a and TSM

Stations	Longitude	Latitude	Chlorophyll-a (mg/m^3)		Total Suspended Matter (mg/dm^3)	
			Measurement	Retrieval of satellite	Measurement	Retrieval of satellite
1	-6,936 5	110.3502	4.24	6.83	17.29	15.73
2	-6.9358	110.3421	3.70	8.19	35,80	21.81
3	-6,935 7	110.3313	4.04	8.49	56.50	34.94
4	-6,935 7	110,317 1	9.07	8.81	106.60	48.42
5	-6.9256	110.3171	5.49	9.47	52.70	41.88
6	-6,9134	110.3509	1.12	5.11	21.70	13.61
7	-6,913 6	110,343 5	1.78	5.91	17,20	14.11
8	-6,913 4	110.3292	3.58	7.35	23.80	16.92
9	-6.9132	110,317 1	3.05	7.90	43.60	21.81
10	-6.9036	110.3166	1.83	7.90	9.40	18,19
11	-6.9038	110,328 8	0.70	3.83	51.30	13.13
12	-6,903 5	110.3425	1.26	3.83	43.30	11.77
13	-6,902 9	110,350 7	2.01	3.97	37,20	11.77
Average			3.22	6.74	39.72	21.85
Std dev			2.26	1.99	25,19	12.11

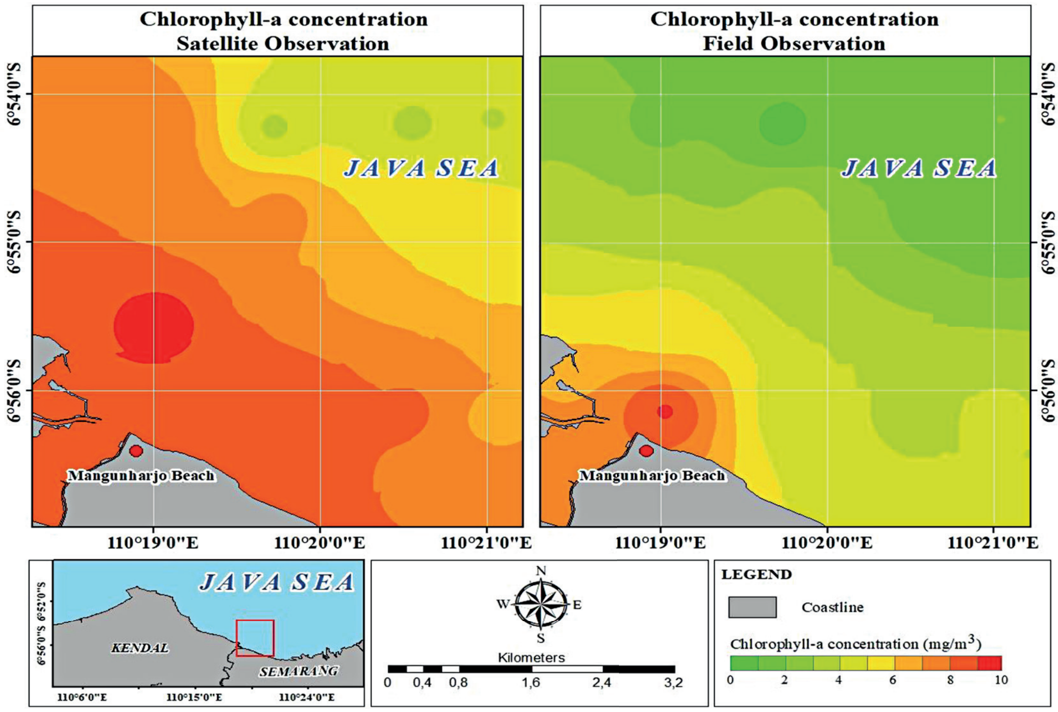

Figure 2. Distribution of chlorophyll-a satellite data (a) and the field measurement (b)

with a 0.004 significance level (α). The 4.65 constant with the 0.00 significance level (α) indicates that the satellite data differs from the field data by more than 4.65. The coefficient of $m = 0.65$, with the 0.004 significance level (α), indicates that the chlorophyll-a field is underestimated for the value. Underestimation occurs at the stations furthest from the beaches (11, 12, and 13), where the value of Chl-a ≤ 2.0 mg/m^3 is recorded.

Spatial distribution of total suspended matter

The TSM average value from field measurements (observation) was 39.72 ± 25.19 mg/dm^3. The field measurement of TSM distribution map is presented in Table 2, and the spatial distribution is shown in Figure 4. At the closest station, the estuary had the highest value, reaching 106.6 mg/ dm^3, and the farther offshore, the lower it is.

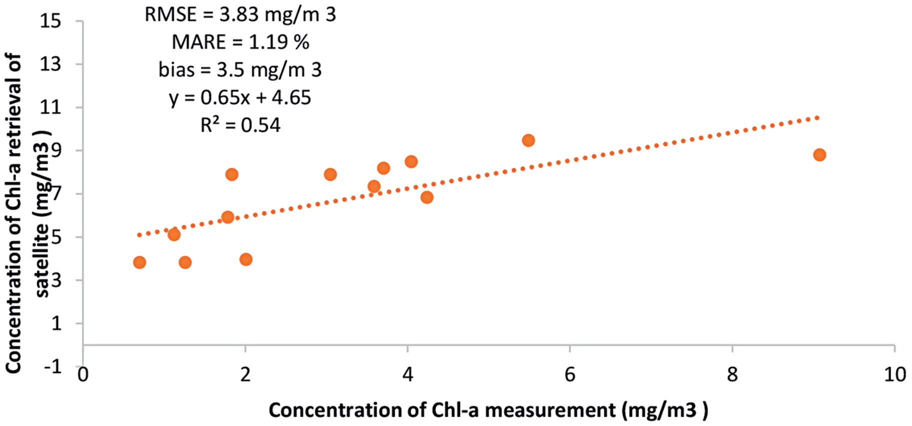

Figure 3. Scatter Plot of chlorophyll-a retrieval satellite and measurement

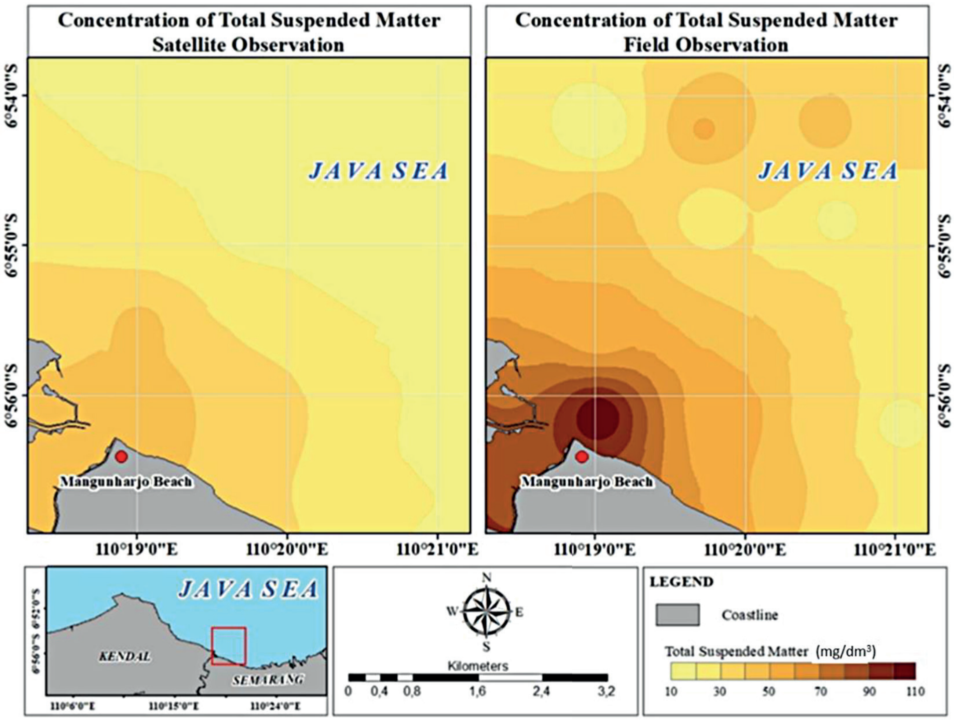

Figure 4. Total suspended matter distribution based on retrieval satellite and measurement

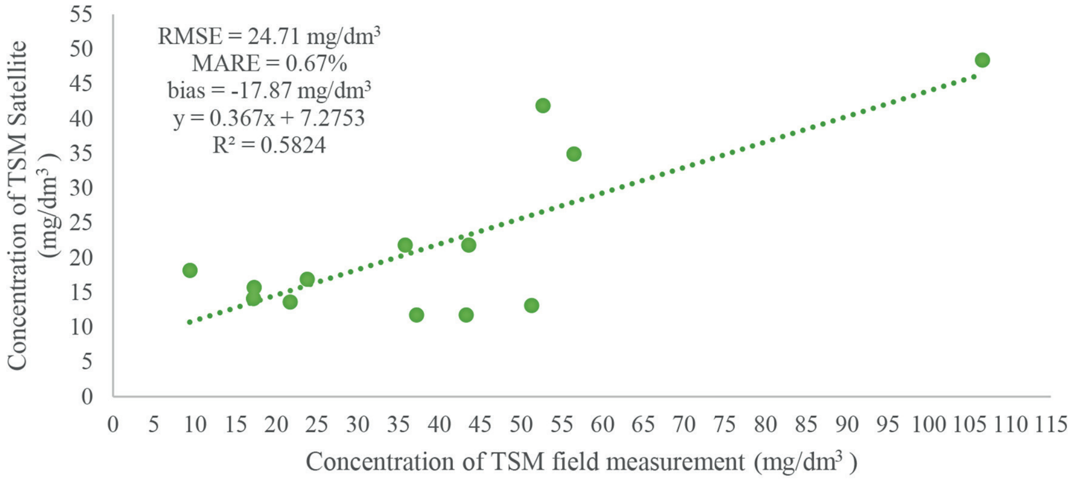

Figure 5. Scatter plot of satellite TSM to field measurement

This thing describes that the main source of TSM comes from the estuary river. Riverine input has an effect as a source of suspended material and affects the distribution pattern in coastal waters (Utama et al., 2021). The scatter plot of satellite TSM to field observation (measurement) is presented in Figure 5.

Figure 5 shows the positive correlation between TSM from satellite imagery and TSM field measurement. This pattern shows high TSM field measurement followed by the highest TSM concentration of retrieval of satellite. Figure 5 also shows the regression model, root mean square error (RMSE), mean absolute relatif error (MARE), and the bias.

The model regression chlorophyll-a with TSM accuracy

The difference between chlorophyll-a concentration by satellite and field measurement is used to calculate the accuracy estimation value of chlorophyll-a concentration by retrieval satellite. The regression results between the TSM and chlorophyll-a difference revealed an equality regression $y = -0.0416x + 5.169$ with a 0.445 determination coefficient (R^2). In this case, TSM has a 44.5% effect on chlorophyll-a accuracy, while the rest (100% - 44.5% = 55.5%) is influenced by other factors. According to Santoso (2017), R^2 is typically between 0 and 1, with the value closest to 0, indicating a weaker relationship between the two variables.

The coefficient regression test hypothesis has $a < 0.05$ sig value (Table 3). This item explains how equality leads to regression, which is a sufficient connection between the second and third variables. Although the value of R^2 is less than 0.5 (Figure 6) the results of hypothesis testing on the coefficients are significant. This study shows that TSM influenced the accuracy of the chlorophyll-a concentration. The gradient coefficient is m = -0.042 with a 0.013 significant level. This means that when the TSM is low, the chlorophyll-a satellite value is higher than the field measurement, and when the TSM is high, the chlorophyll-a satellite value is lower than the field measurement. The accuracy test of chlorophyll-a on TSM can be studied by plotting the difference between chlorophyll-a satellite reduced and chlorophyll-a measurement as the y-axis and TSM field concentration as the x-axis.

According to Tarpanelli et al. (2020), water turbidity is caused by sediment suspended in the water column and can affect the surface reflectance in satellite recordings. If not corrected properly, it can worsen the measurement quality. Doerffer and Schiller (2010) explain that in the areas with low TSM concentrations, the error for chlorophyll-a uptake was in the order of 10–20%, while in very turbid waters it could exceed 100%. Suspended material in the water is not always represented by phytoplankton. However, there is inorganic sedimentary material by land input (Kratzer et al., 2020). These two materials have different reflectances in nature. As a result, not all of the determination algorithms used to extract chlorophyll-a in water could be applied to other waters. This will result in an overestimation or underestimation of the value.

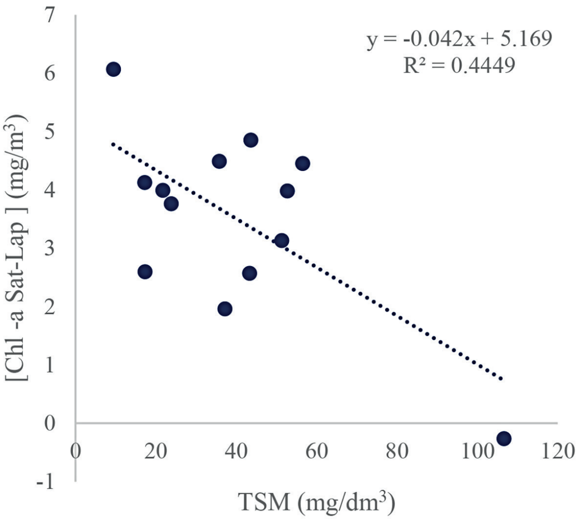

Figure 6. The scatter plot of chlorophyll-a and TSM accuracy

Table 3. Coefficient value

Model	Unstandardized coefficients		Standardized coefficients	t	Sig.
	B	Std. Error	Beta		
Constant	5.169	0.652	-	7.933	0.000
TSM	-0.042	0.014	-0.667	-2.969	0.013
a. Dependent variable: accuracy					

The relationship between the chlorophyll-a and TSM measurement

The relationship between chlorophyll-a and TSM could describe how TSM influences the presence of chlorophyll-a. Incoming light from total suspended mater (TSM) causes turbidity, reducing the intensity of incoming light and disrupting the photosynthesis process. However, if the connection between them is positive, things like this describe what is measurable in TSM and can explain why water suspension is dominated by phytoplankton, whose biomass can be determined through the chlorophyll-a measurement. The relationship between chlorophyll-a and TSM in this study is presented in Figure 7.

Figure 7 depicts how increasing the TSM value at the research site increases chlorophyll. This thing describes that the measured TSM was dominated by the phytoplankton, whose contribution reached 49.69%. Every water has the characteristics of each related relationship between TSM and chlorophyll-a. Positive relationship results were also found by Maslukah et al., (2022) in the waters of Barrangcaddi Island, where phytoplankton had contributed by 23.04%.

DISCUSSION

Chlorophyll-a [Chl-a] is the most abundant component of phytoplankton, and its presence is critical to the food chain in the sea ecosystem (Shaik et al., 2020). The abundance of phytoplankton is greatly influenced by nutrients and light intensity (Sidabutar et al., 2016). Riverine input contributes significantly to nutrient concentration and suspension material on the beach. High nutrient concentrations may cause phytoplankton blooming and cloudiness in the water and cause the solid suspension in the water become high. However, suspension in column waters includes not only phytoplankton but also inorganic sediment, riverine input, resuspension, and coastal abrasion (Kratzer et al., 2020). This is what causes the optical properties of coastal waters to be very complex.

The satellite-based sensors can be used to assess synoptic Chl-a at large spatial scales. Recording optical properties of water can be extracted and produce the quality of water parameters, such as chlorophyll-a, using an algorithm. Every algorithm is not yet suitable for each region, so that is known as validation value. Validation could be calculated based on the RMSE value, bias, and coefficient determination (R^2).

This study used the chlorophyll retrieval from Sentinel 3, using OC4Me algorithm (Moutzouris-Sidiris and Topouzelis) and compared the measurement results with chlorophyll-a. The effect of the presence of suspended solids is seen as its impact on the working properties resulting from the data taken by the Sentinel 3 satellite. According to this research, the chlorophyll-a estimation from the Sentinel 3 retrieval satellite has a higher value than the measurement (Table 1). The RMSE analysis in this study is 3.65 mg/m^3 and the bias is 3.43. Figure 2a depicts the existence of this difference by spatial distribution. Tilstone et al. (2017) explained that satellite imagery using OC4Me was 5 to 10 times higher in the coastal areas of the North Sea and the

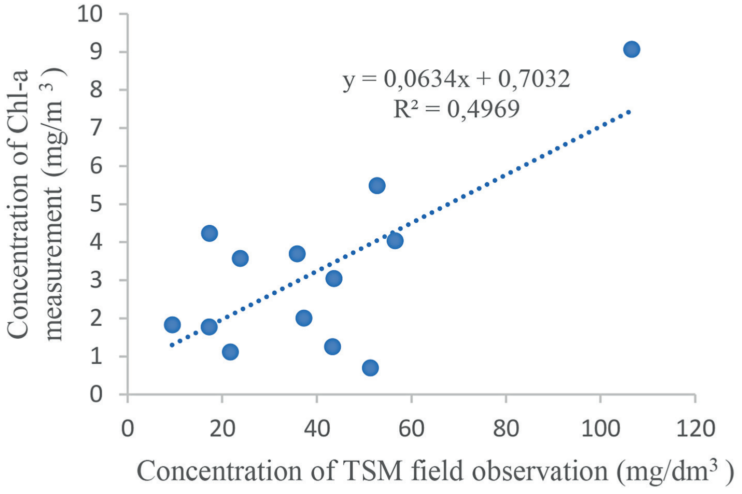

Figure 7. The scatter plot of chlorophyll-a and TSM

English Channel. This is caused by an error in OC4Me which varies with TSM.

The correlations between retrieval chl-a satellite estimates and chl-a measurement are moderate ($R^2 = 0.54$, $r = 0.7$, $n = 13$). The same result was also shown by Moutzouris-Sidiris and Topouzel (2021) in the Mediterranean Sea with an RMSE of 3.83 mg/m^3 and a bias of 3.5 mg/m^3. The RMSE value of the research results is lower than Watabene et al. (2018), but the bias is smaller (1.02 mg/m^3).

The estimated satellite data (Figure 2) shows that the high values have a larger distribution than the field measurement. This could happen because Sentinel 3 algorithm is insufficient for the west areas of Semarang Bay. The algorithm used in this study is from Moutzouris-Sidiris et al. (2021), and the wavelength range is 555–560 nm. According to Tistone et al. (2017), when using Chl-a data from satellites to monitor the environment, selecting the most accurate color algorithm is critical in order to obtain more value.

The complex optical properties may be due to the turbidity research area, as indicated by the TSM value in this study. The difference in interpretation of the chlorophyll-a value in retrieval satellite and measurement was caused by the high TSM. The difference between the concentration of chlorophyll-a satellite data and the measurement was then used in this study to estimate the accurate value of chlorophyll-a concentration by retrieval satellite. The regression model calculation result shows that TSM has a 44.5% effect on the chlorophyll-a accuracy and that it has a significant effect ($p < 0.05$) (Table 2). The analysis of t-students test results also shows that chlorophyll-a and TSM measurement differed with satellites ($p < 0.05$, $n = 13$, Table 2).

Different things happen between field and satellite measurements of suspended solids (TSM). When compared to the field measurement, the TSM estimation from the Sentinel 3 satellite yields a lower value. However, the results show a moderate correlation between the TSM field observations and the satellite observations ($R^2 = 0.58$, $r = 0.76$). The RMSE value is 24.71 mg/m^3 and the bias is -17.87 mg/m^3. According to Toming et al. (2017), the research on the Brazilian coast also reveals a moderate correlation, R^2 (0.42–0.69). On the basis of the findings of this study, an algorithm must be developed in Indonesian waters, particularly in Semarang Bay.

CONCLUSIONS

The TSM and chlorophyll-a field measurement distribution results show that the highest concentration is near the estuary and decreases towards the middle. Different patterns emerge from satellite estimations. The chlorophyll-a measurement is lower than the satellite estimation, and the TSM measurement is higher than the Sentinel 3 satellite estimation. The TSM concentration influences the accuracy of estimating chlorophyll-a using satellite imagery. When the TSM is low, there is an overestimation in which the chlorophyll-a value in the satellite image is greater than the field data. This also occurs in the opposite direction, where the chlorophyll-a value in satellite imagery is lower than the field data at high TSM. Further research is needed to develop an algorithm for Sentinel 3 so that for future monitoring, the concentration of chlorophyll-a can be obtained with less error.

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