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RESEARCH ARTICLE

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Assessing the water quality dynamics in the coastal waters of Kollam (Kerala, India) using Sentinel images

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Abstract

Coastal waters are complex, dynamic, and sensitive, and any change in the system impacts the marine environment and life. Coastal water quality has been decreasing due to the incursion of anthropogenic derived waste and toxins into the ocean. This study investigates water quality along the Kollam coast of Kerala State, India, using Sentinel-2 Multispectral Imager (MSI) data for the period of 2019–2022. Four key water quality parameters, chlorophyll (Chl-a), total suspended matter (TSM), turbidity, and coloured dissolved organic matter (CDOM), were analysed for seasonal variations and driving factors. The study highlights the potential of web-based platforms like Google Earth Engine for facilitating large-scale water quality assessments. The results reveal a distinct seasonal pattern in all parameters, primarily influenced by monsoonal riverine discharge and anthropogenic activities as contributing factors to water quality degradation. Overall, the study emphasises the need for comprehensive monitoring and management strategies to ensure the long-term sustainability of the coastal ecosystem.

Keywords Google earth engine, Kollam coast, Sentinel imagery, Seasonal variation, Water quality

1 Introduction

Coastal areas are highly sensitive ecosystems vulnerable to both natural and anthropogenic disturbances, impacting the marine environment significantly (Gholizadeh et al. 2016). With approximately 40% of the world's population residing near coastlines (Nicholls et al. 2007), increasing urbanisation, industrialisation, and tourism are degrading water quality (Vikas and Dwarakish 2015), negatively affecting aquatic life and the dependent economy (Xu and Zhang 2022). Consistent monitoring of various ocean water quality parameters, including physical, chemical, and biological factors, plays a key role in resolving the intricacies of marine ecosystem health (Mohseni et al. 2022). By systematically observing and analysing these parameters, scientists and environmental researchers gain valuable insights into the dynamic nature of the ocean environment (Sharma et al. 2020). This proactive approach enables the identification of potential threats, such as pollution or changes in biodiversity, allowing for timely intervention and management strategies (Kvamsdal et al. 2023). Additionally, a comprehensive understanding of ocean water quality parameters contributes to the formulation of sustainable conservation practices, ensuring the long-term well-being of marine ecosystems and the myriad species that inhabit them (Galal Uddin et al. 2023). Further it also ensures sustainable resource utilisation, and protecting coastal communities' livelihoods (Tornero and Hanke 2016). Therefore, the ongoing vigilance in monitoring these

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parameters is fundamental for the preservation and protection of oceans (Briciu-Burghina et al. 2023).

Due to the limitations associated with traditional methods, such as their time-consuming nature, high costs, and impracticality for temporal mapping, the utilization of remote sensing technology has emerged as a practical solution for monitoring and characterizing biophysical and chemical parameters within ocean hydro systems (Manikiam 1988). The advent of diverse satellite data, encompassing spatial, spectral, and temporal resolutions, has significantly transformed the study of ocean water quality parameters (Hafeez et al. 2019). These remote sensing technologies enable efficient and timely data collection, providing researchers with information about the dynamic characteristics of ocean environments (Rani et al. 2021). Prominently, the availability of satellite-derived products as open resources has facilitated researchers in conducting experiments, thorough analyses, and comprehensive understanding of various ocean phenomena (eg. Liu and Wang 2022). This accessibility not only promotes scientific exploration but also fosters collaborative efforts in addressing the complexities of oceanic processes and their associated features.

Numerous researchers have employed different water quality measures, such as Chlorophyll-a (Chl-a), coloured dissolved organic matter (CDOM), turbidity, total suspended matter/solid (TSM/TSS), dissolved organic carbon (DOC), suspended sediment concentration, sea surface temperature (SST), etc. (Li et al. 2022; Aswathy et al. 2021; Poddar et al. 2019; Chen et al. 2017; Gholizadeh et al. 2016). They have combined these parameters with other ocean related factors (eg. Wind, sea surface height (SSH)) to examine the biophysical and chemical conditions in ocean hydrology, particularly in the context of climate change scenarios (García-Soto 2021; Kang and Moon 2022). These studies highlight the importance of accurately assessing and validating remote sensing-derived products for estimating the overall water quality of oceans on a global scale. Researchers emphasize the reliability of these remote sensing tools in providing effective understandings into the environmental changes affecting oceans (Sharma et al. 2023).

Recognizing the critical significance of maintaining healthy water systems, the United Nations' Sustainable Development Goals (SDGs) place a high priority on their conservation. Specifically, SDG 14 focuses on the preservation of vulnerable coastal areas, realizing the unique challenges they face (unstats.un.org n.d.). Additionally, SDG 6 stresses the importance of ensuring access to clean water and emphasizes the necessity for enhanced water quality to promote sustainable development (Kulk et al. 2021). These goals collectively reflect a global commitment to safeguarding water resources, addressing environmental challenges, and fostering sustainable practices for the well-being of present and future generations.

1.1 Rationale of the study

The Kollam coast of Kerala State, India, bordering Ashtamudi Lake and the Arabian Sea, has a rich history of trade and commerce, maintaining maritime connections globally (Shaji and Adabiya 2020; Kumar 2018). Nevertheless, the coastal waters of Kollam have been substantially affected by extensive industrial, tourism, and modernization activities, with adverse impact of industrial waste, sewage, and pollutants on the area's coastal flora and fauna (Cyril 2010). The occurrence of Harmful Algal Blooms (HABs), characterized by the rapid proliferation of algae and the production of toxins that can adversely affect aquatic ecosystems, leads to detrimental consequences for both marine life and the well-being of human populations in contact with affected waters (D'Silva et al. 2012). In 2019, the Kollam coast witnessed the occurrence of a gelatinous white foam bloom identified as *Phaeocystis globosa*, marking the first reported case in India. This phenomenon is known to have a negative impact on shellfish and shore-based fisheries (Madhu et al. 2020). While the Kollam coast experiences strong monsoonal upwelling, which brings nutrients and economically valuable fish species (Smitha et al. 2008), anthropogenic activities pose a threat to its ecological balance and the entire marine food web (Sreedevi and Harikumar 2023). Continuous monitoring of the Kollam coast is, therefore, critical for improving water quality and supporting marine life.

Despite the necessity for consistent water monitoring, there is a limited number of comprehensive studies on the Kollam marine environment. Existing studies rely on conventional in-situ sampling methods, which, while offering accurate data, are labour-intensive, time-consuming, and expensive (Mumthas and Miranda, 2016; Cyril 2010). Additionally, the spatial and temporal coverage of data is limited, hindering comprehensive monitoring of various parameters (Bhuyan et al. 2020). Satellite remote sensing offers a viable alternative for continuous, systematic, and cost-effective water quality monitoring across vast spatial and temporal scales (Sharma et al. 2023). The increasing availability of satellite data and free access platforms like Google Earth Engine (GEE) empowers researchers to assess water quality and its long-term variations (Kwong et al. 2022).

This rapidly growing city (Kollam), recognised by the Economist Intelligence Unit (EIU) survey (2015–2020), encompass rich mineral sand resources and diverse marine life, including approximately 45 seaweed species and economically important crustaceans like prawns, lobsters, and shrimp (Manilal et al. 2010). Therefore, it is essential to ensure sustainable use of resources and maintain the quality of the waters to avoid any further overexploitation and degradation. In this context, the current study assesses the spatiotemporal seasonal variations in optically active water quality parameters, including Chl-a, TSM, turbidity, and CDOM, along the Kollam coast. The objective was achieved by conducting a time series analysis of Sentinel-2 MSI images using the GEE platform.

1.2 Study area

Kollam, located on the southwest coast of India between 8°45' and 9°10' North latitude and 76°30' and 76°50' East longitude (Fig. 1), is a significant urban agglomeration in Kerala (Kovoor and Panjikaran 2021). The Ashtamudi wetland, a Ramsar site and the second-largest estuary in Kerala, empties into the ocean through Neendakara, a major fishing harbour (Saranya and Lancelet 2020) (Fig. 1). Additionally, the Paravur estuary, is closed during most seasons due to sandbars, opens into the sea primarily during the monsoon (Cyril 2010). Sand mining is prevalent in the region, with Panmana and Chavara being major mining areas (Nadayil et al. 2021). These areas also house large industries like Kerala Minerals and Metal Limited (KMML) and Indian Rare Earths Limited (IREL) (Abraham et al. 2021). Kollam's robust fishing industry significantly contributes to its economy (Sumer and Sajesh 2023). However, rapid industrial growth, tourism activities, fishing, sand mining, terrestrial runoff, and urbanisation negatively impact the coastal water quality (Humsa and Srivastava 2015). Kollam experiences two distinct periods of monsoon rainfall: the Southwest monsoon from June to September and the Northeast monsoon from October to November (kerenvis.nic.in n.d.) . The average annual rainfall is 270 cm (kollam.nic.in n.d.). The climate can be categorised into four seasons: spring-inter monsoon (March to May), summer monsoon (June to September), fall-winter monsoon (October to November), and winter monsoon (December to February) (Bhuyan et al. 2020).

2 Materials and methods

2.1 Data acquisition and processing

This study utilises multi-temporal Sentinel-2 Multispectral Instrument (MSI) data acquired from 2019 to 2020. Sentinel-2 MSI offers high spatial resolution (10 m, 20 m, and 60 m) and a wide swath, making it ideal for continuous monitoring of coastal and inland waters. However, a lack of regionally specific bio-optical algorithms and in-situ data for the Kollam coast necessitated the use of established algorithms proven effective in coastal waters, particularly along the Kerala

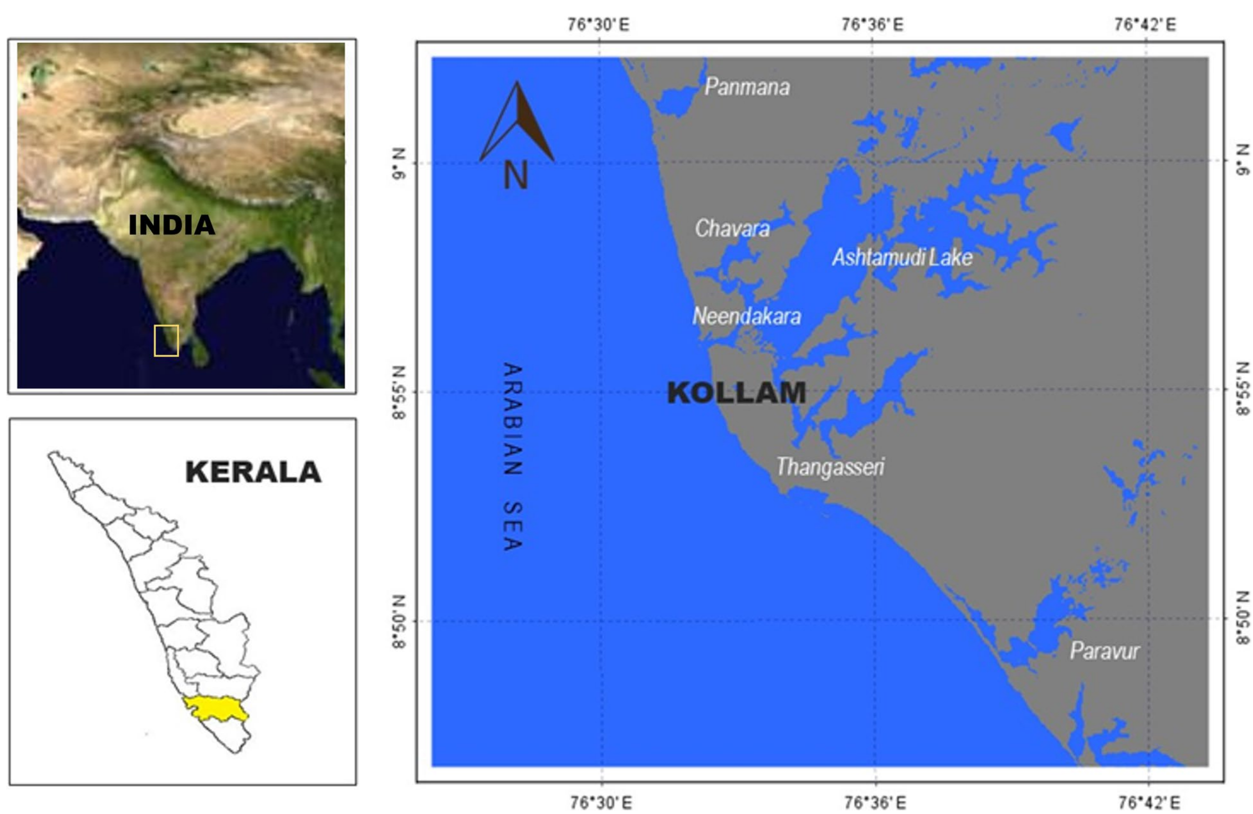

Fig. 1 Study area, Kollam coast, south-west coast of India

coastline (Sarangi and Mohammed 2011; Shanmuga and Jena 2021; Bhuyan et al. 2020). Sixteen Sentinel-2 Level 1C images with minimal cloud cover over the area of interest were downloaded from the Copernicus Open Access Hub (scihub.copernicus.eu). Table 1 shows the acquired sentinel 2 data. These datasets were processed using the Sentinel Application Platform (SNAP) for resampling (to 60 m resolution), subsetting, and atmospheric correction. The Case-2 Regional Coast Colour (C2RCC) processor within the SNAP Sentinel toolbox was employed for atmospheric correction, as it has demonstrated superior performance in retrieving water quality parameters in coastal waters compared to other methods like Polymer atmospheric correction (Sent et al. 2021; Mograne et al. 2019). C2RCC utilises an artificial neural network (ANN) to generate remote sensing reflectance (Rrs) and other products for various sensors (Sent et al. 2021).

Table 1 Data sets used in the study

S.No	Date	Season	Satellite
1	25–03-2019	Spring inter Monsoon	Sentinel 2A
2	08–07-2019	Summer Monsoon	Sentinel 2B
3	20–11-2019	Fall inter Monsoon	Sentinel 2B
4	24–01-2020	Winter Monsoon	Sentinel 2B
5	08–04-2020	Spring inter Monsoon	Sentinel 2A
6	07–07-2020	Summer Monsoon	Sentinel 2A
7	05–10-2020	Fall inter Monsoon	Sentinel 2A
8	24–12-2020	Winter Monsoon	Sentinel 2A
9	04–03-2021	Spring inter Monsoon	Sentinel 2A
10	17–07-2021	Summer Monsoon	Sentinel 2B
11	25–10-2021	Fall inter Monsoon	Sentinel 2B
12	29–12-2021	Winter Monsoon	Sentinel 2A
13	03–04-2022	Spring inter Monsoon	Sentinel 2B
14	16–08-2022	Summer Monsoon	Sentinel 2A
15	24–11-2022	Fall inter Monsoon	Sentinel 2A
16	29–12-2022	Winter Monsoon	Sentinel 2B

We conducted an analysis on the Sentinel 2 level 2A dataset spanning from 2019 to 2022, using different algorithms to compute the water quality parameters. The procedural flowchart, as depicted in Fig. 2, outlines these steps along with the ensuing spatiotemporal and time series analyses. The mean values of each remotely sensed image were graphed over time, and the time series data was processed using R and Excel to derive the monthly averages of the variables. This approach allowed for a comprehensive examination of the data. Simultaneously acquired time series data of runoff and precipitation from the HYCOM model, SST from the Aqua-MODIS satellite, and SSH from NASA's Giovanni

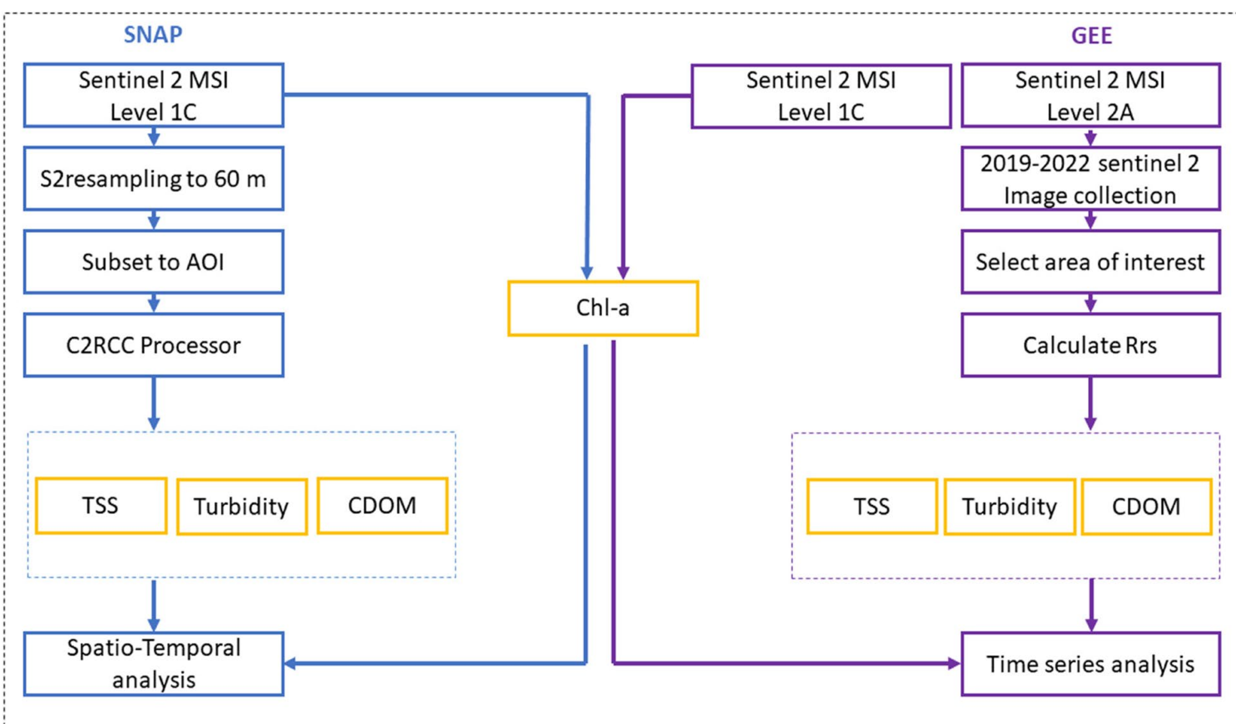

Fig. 2 Flow chart of the processing steps involved in SNAP and GEE to evaluate the spatiotemporal and time series variation of the water quality parameters

portal ((http://giovanni.gsfc.nasa.gov/giovanni/) and performed a comparative analysis with the water quality indicators.

2.2 Methodology

2.2.1 Time series analysis in Google Earth Engine (GEE)

The extensive geospatial research capabilities of GEE were leveraged for the time series analysis. This cloud-based platform facilitates access to open satellite data and provides powerful processing capabilities for diverse applications (Kwong et al. 2022). GEE efficiently manages the computational burden associated with downloading, processing, and analysing large datasets (Sherja et al. 2023). However, despite its potential for water applications, few studies have explored GEE's capabilities in developing remote sensing-based water quality monitoring systems. Kwong et al. (2022) successfully utilised GEE to develop a cost-effective and efficient workflow for improved water quality monitoring. Nevertheless, the limited availability of atmospheric corrections specifically tailored for water applications on GEE remains a challenge (Sherja et al. 2023). Addressing this challenge, the study employed readily available Sentinel-2 MSI Level 2A data from the GEE catalogue, which provides bottom-of-atmosphere reflectance after Sen2cor atmospheric correction. This data was used to analyse the temporal variations of Chl-a, TSM, turbidity, and CDOM (Fig. 7).

2.2.2 Parameters retrieval using bio-optical algorithms

We applied bio-optical algorithms based on remote sensing reflectance (Rrs) to estimate the water quality of case-2 water. These algorithms derived the optically active parameters (Chl-a, TSM, turbidity, and CDOM) that influence the water quality (Gholizadeh et al. 2016).

a) Chlorophyll-a (Chl-a)

Chl-a is a proxy for phytoplankton biomass and algal bloom events in the marine environment (Poddar et al. 2019). It also reflects the nutrient status at a given time (Gholizadeh et al. 2016). Algal blooms can have beneficial or detrimental effects on fisheries, marine ecosystems, and human health (Berdalet et al. 2015). Elevated and persistent Chl-a levels in a region indicate eutrophication, which can impair the marine ecosystem. Hence, Chl-a is an essential water quality parameter for coastal and inland water management. The rising frequency of algal blooms over time may be attributed enhanced methods for detecting and monitoring previously unreported blooms, alongside factors like species dispersal, introduction of new algal species, long-term climatic changes, and cultural eutrophication (D'Silva et al. 2012).

Chl-a is an optically active parameter that alters the ocean colour by absorbing blue and red wavelengths of visible light and reflecting green (Poddar et al. 2019). Several algorithms based on band ratio can quantify Chl-a. The algorithms that use log-transformed band ratios of blue and green spectral bands perform well in complex case-2 waters for different Chl-a concentrations (Sarangi and Mohammed 2011). The atmospheric influence on the remote sensing reflectance (Rrs) decreases when spectral band ratios are used (Gholizadeh et al. 2016). We use the OC2V2 (Ocean Chlorophyll 2 Version 2) algorithm to calculate the Chl-a concentrations in Kollam coastal waters. Sarangi and Mohammed (2011) applied the algorithm to analyse the seasonal algal bloom in the Kerala coast. This algorithm uses a band ratio of the blue band at 443 nm and the green band at 560 nm.

$$C = 10^{(a_0+a_1R+a_2R^2+a_3R^4)} + a_4$$

$$R = log(\frac{Rrs_{443}}{Rrs_{560}})$$

$$a_0 = 0.1977 =, a_1 = -1.8117, a_2, = 1.9743, a_3 = -2.5635, \text{and}, a_4 = -0.7218$$

C is the Chl-a concentration in mg/m3, a_0, a_1, a_2, a_3, and a_4 are the sentinel-2 specific coefficients (Kulk et al. 2021). The available atmospheric corrections (AC) assume that water absorbs all the incident radiation in the NIR. However, in complex waters, the water leaving radiance (Lw) in the NIR is not zero due to the presence of optically active Chl-a and suspended solids. These AC may overestimate Chl-a in complex waters (Aranha et al. 2022). To avoid such uncertainties, we use Sentinel-2 level 1C TOA (top of the atmosphere) bands for the Chl-a concentration.

b) Total Suspended matter (TSM)

TSM indicates the amount of suspended matter in the water, which includes sediments, clay, silt, sewage disposal, pollution, organic matter, microbial pollution, plankton, mineral fragments, etc. (Sakthivel and Kirthiga 2022). TSM affects the coastal ecosystem and biodiversity by increasing in coastal water (Chapman et al. 2017). It also reduces the sunlight penetration to the bottom, which impairs the primary productivity and aquatic life in high concentrations (Aswathy et al. 2021). TSM in the coastal waters of India is rising due to anthropogenic activities such as tourism and industrial activities. Other factors that contribute to water quality concerns are untreated sewage and municipal solid waste, leakage from ships, river inflow with nutrients during monsoons, stormwater inflow, and dredging (Sakthivel and Kirthiga 2022; Kulk et al. 2021).

The red band in the visible spectrum can distinguish between Chl-a, turbidity, and TSM (Shanmuga and Jena, 2021). In their research, Shanmuga and Jena (2021) implemented the Miller TSS model, (Miller and McKee 2004) utilizing the red band at 665 nm, to quantitatively assess TSM in the southern Kerala coast. The application of this model demonstrated a notable correlation with in-situ field data, indicating its efficacy in accurately estimating TSM levels. This established correlation is crucial as it serves as a foundational aspect integrated into the methodology of the present study, ensuring the reliability and relevance of the TSM evaluations conducted in the current research context.

$$\mathrm{TSM} = -1.91 + (1140.25 \times Rrs_{665})$$

c) Turbidity

Turbidity measures the water's relative transparency or light-scattering capability, directly linked to TSM levels and their impact on light transmission (Schroeder 2003). TSM represents the amount of substance in the water, while turbidity is an optical property that depends on the concentration, shape, size, and distribution of the substance (Sakthivel and Kirthiga 2022). Nechad et al. (2009) proposed a bio-optical algorithm that calculates turbidity in Nephelometric Turbidity Units (NTU), which is the measure of light scattered at 90° relative to a reference solution. This algorithm has shown excellent results with different types of turbid waters (Bhuyan et al. 2020). In this study, the turbidity algorithm from Kulk et al. (2021) was applied as follows:

$$Turbidity = \frac{A * Rrs_{665}}{1 - \frac{Rrs_{665}}{C}}, \mathrm{A} = 228.1\mathrm{and}\mathrm{C} = 0.1641$$

d) Coloured Dissolved Organic Matter (CDOM)

CDOM is the biogenic organic material found in both fresh and saline water, often referred to as the yellow substance due to its ability to impart a yellowish-brown hue to the water when present in high concentrations (Bonelli et al. 2021). CDOM, serving as a measure of dissolved organic carbon in water, facilitates the examination of the carbon cycle and its dynamics across various scales, with origins either from terrestrial sources, characterized as allochthonous inputs, or from phytoplankton and algae, identified as autochthonous inputs (Chen et al. 2017). CDOM can be removed by photobleaching or microbial decomposition (Kragh et al. 2022). CDOM is an important water quality metric because it relates to aquatic ecosystem processes, drinking water safety, and pollutant transport (Chen et al. 2017). CDOM also determines the physical and chemical conditions of the water and its suitability for different aquatic species (Gholizadeh et al. 2016).

CDOM is optically active and absorbs strongly in the ultraviolet and blue bands of the visible spectrum (Li et al. 2022). The CDOM concentration is calculated by its absorption coefficient at 440 nm ([a]CDOM 440). The CDOM absorption decreases exponentially with increasing wavelength (Ruiz et al. 2017). Therefore, the blue band is the best band for CDOM concentration, but Chl-a also absorbs strongly in the blue region, which reduces the water-leaving radiance in the blue band, resulting in a low signal-to-noise ratio (Gholizadeh et al. 2016). Chen et al. (2017) developed an exponential model that uses a green–red band ratio algorithm for complex waters, which calculates the CDOM absorption coefficient at 440 nm.

$$a_{CDOM} = 40.75 * e^{-2.463X}$$

$$X = \frac{Rrs_{560}}{Rrs_{665}}$$

The green band is at 560 nm, and the red band is at 665 nm in Sentinel-2. This exponential model reduces uncertainties and eliminates negative outcomes, making it better than a linear or logarithmic model (Chen et al. 2017).

3 Results and discussion

Limited attention has been given to the assessment of water quality along the Kollam coast, with only a few notable studies available. Cyril (2010) conducted a study that concentrated on seasonal variations in vital water parameters, including surface water temperature, dissolved oxygen, pH, turbidity, nutrients, and various biological factors such as phytoplankton, zooplankton, and coliforms. Another study by Madhu et al. (2020) explored the occurrence of foam formation attributed to the blooming of *Phaeocystis globose* on the beaches of Kollam (Mundakkal), Kerala. Furthermore, Dilipkumar and Shanmugam (2023) contributed to the global water quality assessment discourse, specifically discussing CDOM in the Arabian Sea, with a focus on the Kollam coast. These studies collectively highlight the lack of comprehensive investigations into the water quality of the Kollam coast. The current study, assessing monthly and annual variations in water quality parameters (using remote sensing technology), emerges as an establishing

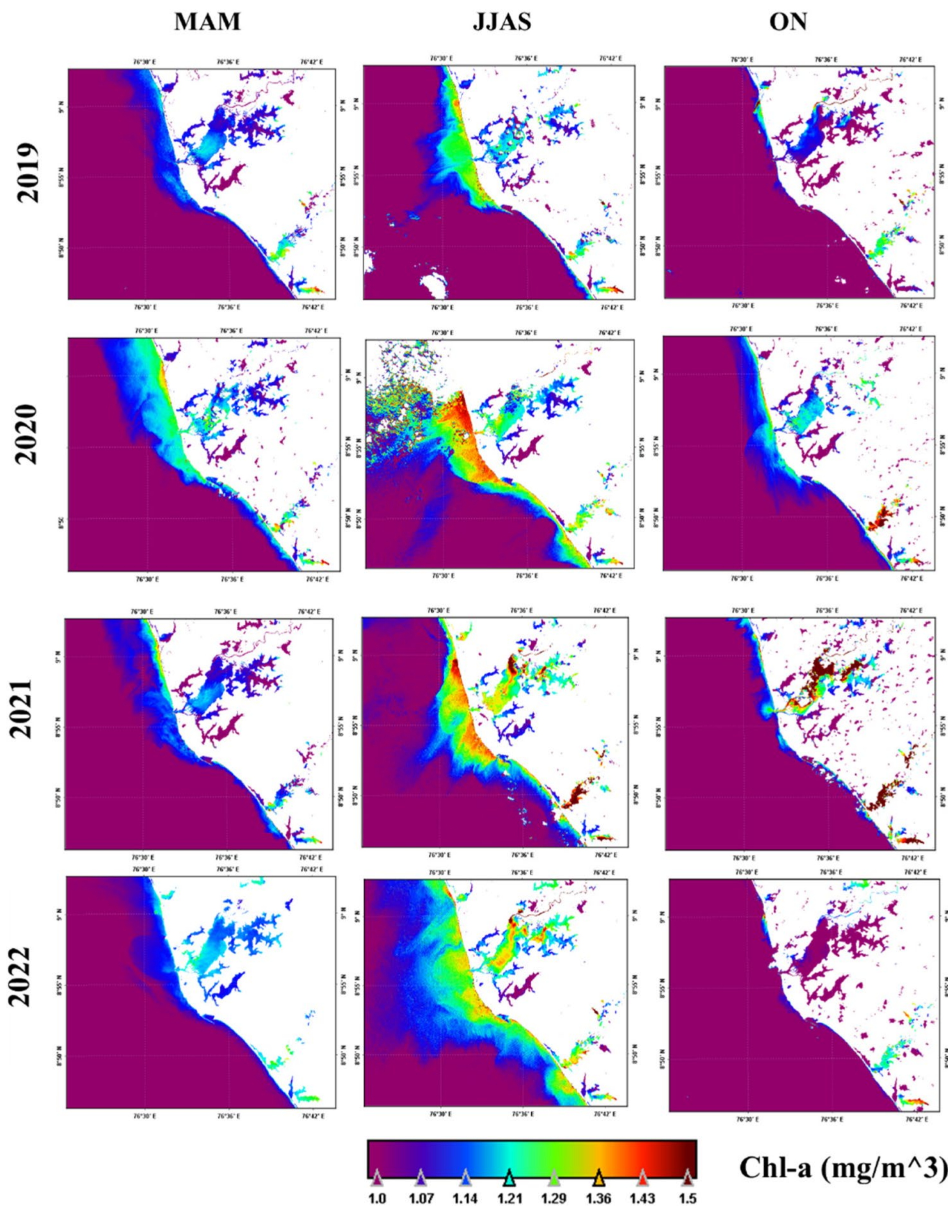

Fig. 3 Seasonal variation of Chl-a for the period 2019 to 2022 for the Kollam coast

effort, filling a notable gap in the understanding of the region's aquatic ecosystem.

In the course of conducting a comprehensive spatiotemporal analysis (Figs. 3, 4, 5 and 6), this study precisely examined four key water quality indicators—Chl-a, TSM, turbidity, and CDOM—in the coastal waters of Kollam, India, throughout the distinctive seasons of the Indian subcontinent: spring-inter monsoon (MAM: March–May), summer monsoon (JJAS: June–September), fall-winter monsoon (ON: October–November), and winter monsoon (DJF: December-February), covering the timeframe from 2019 to 2022.

The investigation probed the impact of environmental drivers, encompassing precipitation, run-off, SST and SSH, on these indicators. The findings revealed pronounced seasonal fluctuations in the water quality indicators intricately associated with monsoon dynamics and thermal regimes. Moreover, noteworthy inter-annual variations surfaced, exemplified by an aberrant Chl-a bloom in MAM 2020 and a conspicuous upsurge in TSM during MAM 2022, the origins of which could be attributed to climatic, anthropogenic, or oceanographic anomalies (Ma et al. 2022; Lyngsgaard et al. 2017; Thushara and Vinayachandran 2020; Wang et al. 2021; Pathirana et al. 2023).

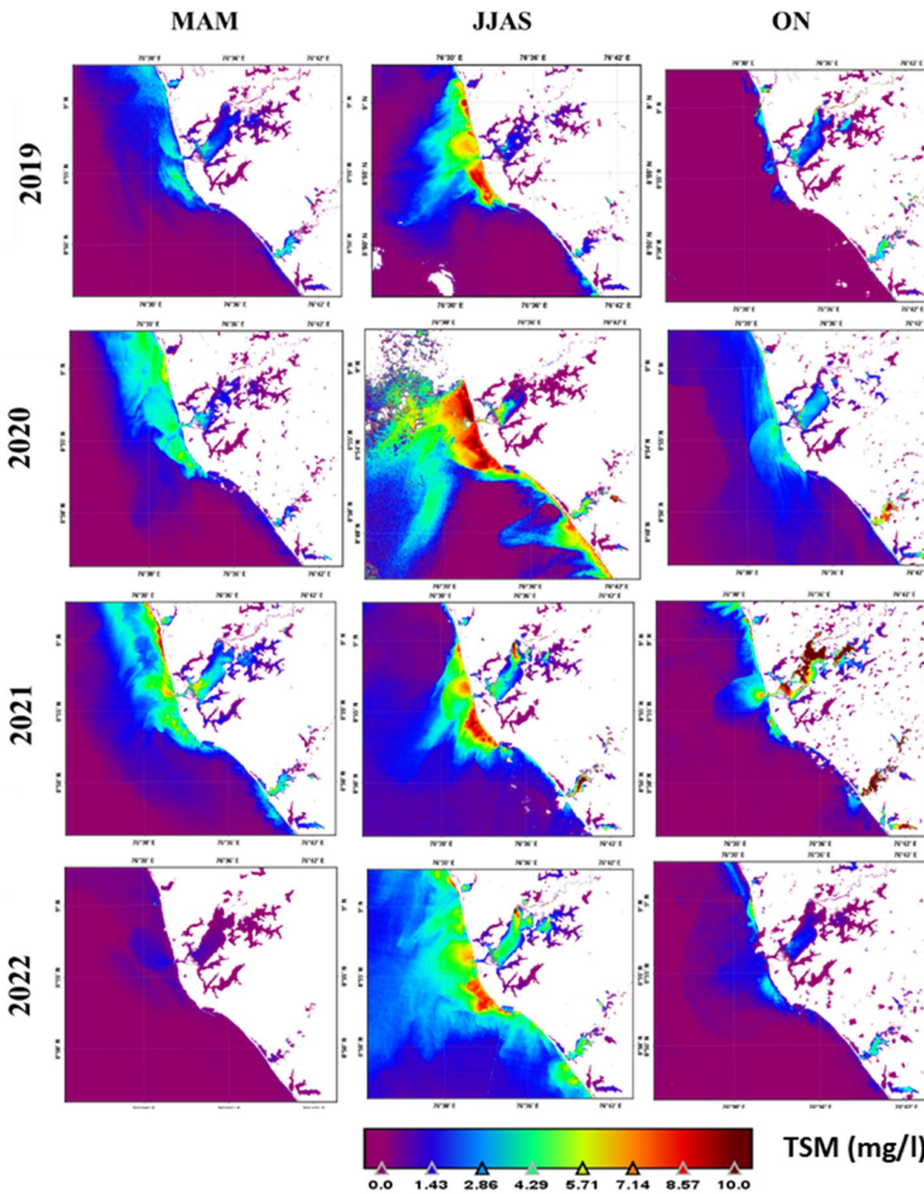

Fig. 4 Seasonal variation of total suspended matter (TSM) for the period 2019 to 2022 for the Kollam coast

3.1 Seasonal and inter-annual variability in Kollam coastal water quality (2019–2022)

The water quality indicators under investigation revealed discernible seasonal patterns, each characterized by distinct environmental factors. During the spring-inter monsoon (MAM) period, elevated Chl-a levels were consistently observed across all years, indicating conducive conditions for phytoplankton production attributable to enhanced solar radiation and increased nutrient availability (Helbling and Villafañe 2009). Concurrently, turbidity and TSM also exhibited an upswing during MAM, likely attributed to augmented run-off and sediment load in the coastal waters (Misra et al 2014; Bayram and Kenanoğlu 2016). These findings align with the observations of Shi and Wang (2010), who reported that elevated ocean turbidity may result from increased levels of TSM and high concentrations of algae (Chl-a) in the water, attributable to various atmospheric, oceanic, and terrestrial processes. Further, Nair et al. (1988) states that intensified wave activity during the pre-monsoon season leads to turbulent conditions in coastal waters, promoting the resuspension of bottom sediment primarily through the stirring action of the waves and consequently reducing water transparency (Gadhia et al. 2013).

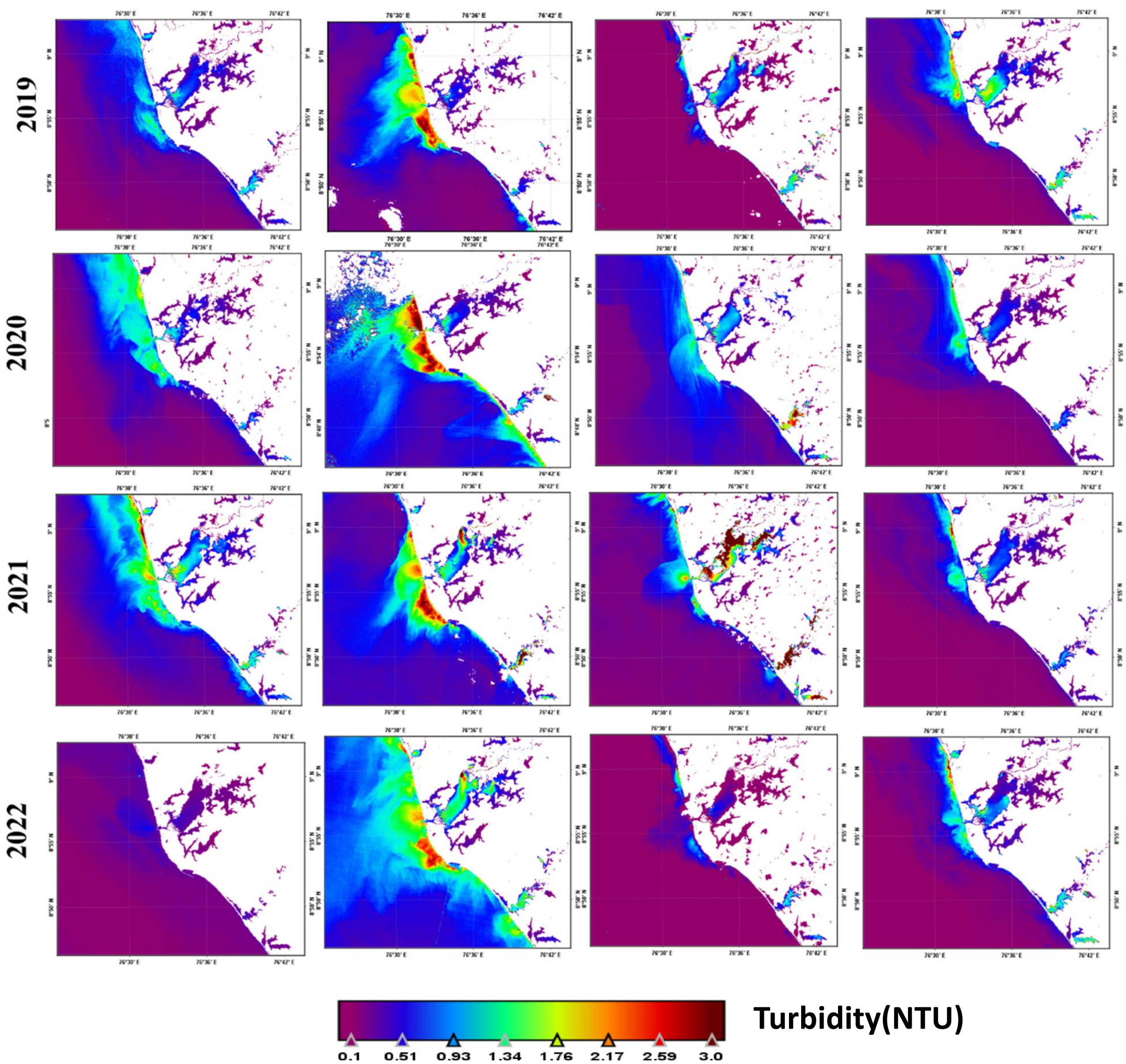

Fig. 5 Seasonal variation of turbidity for the period 2019 to 2022 for the Kollam coast

In the summer monsoon (JJAS), TSM levels remained consistently high across all years, reflecting intensified monsoon precipitation and subsequent increased run-off. Parida et al. (2019) also made similar observation of elevated TSM concentrations along the western coast of the Bay of Bengal during the monsoon period, attributing them to precipitation-induced river and terrigenous discharge. Chl-a, CDOM, and turbidity mirrored this trend, displaying elevated levels during JJAS. Notably, the fall-winter monsoon (ON) was characterized by raised CDOM levels which may result from human-induced inputs, including industrial or domestic effluents discharged through rivers (Bricaud et al. 1981), as well as in situ production originating from the remains of phytoplankton (Carder et al. 1989; Parida et al. 2019). Conversely, Chl-a, turbidity, and TSM levels experienced a decline during ON. Specifically, CDOM affects Chl-a by diminishing the availability of photosynthetically active radiation for the phytoplankton community (Bidigare et al. 1993). In the winter monsoon (DJF), the water quality indicators exhibited the lowest levels for Chl-a, turbidity, and TSM in all years, indicative of reduced solar radiation, diminished nutrient supply, and decreased run-off (Lévy et al. 2007). CDOM levels were

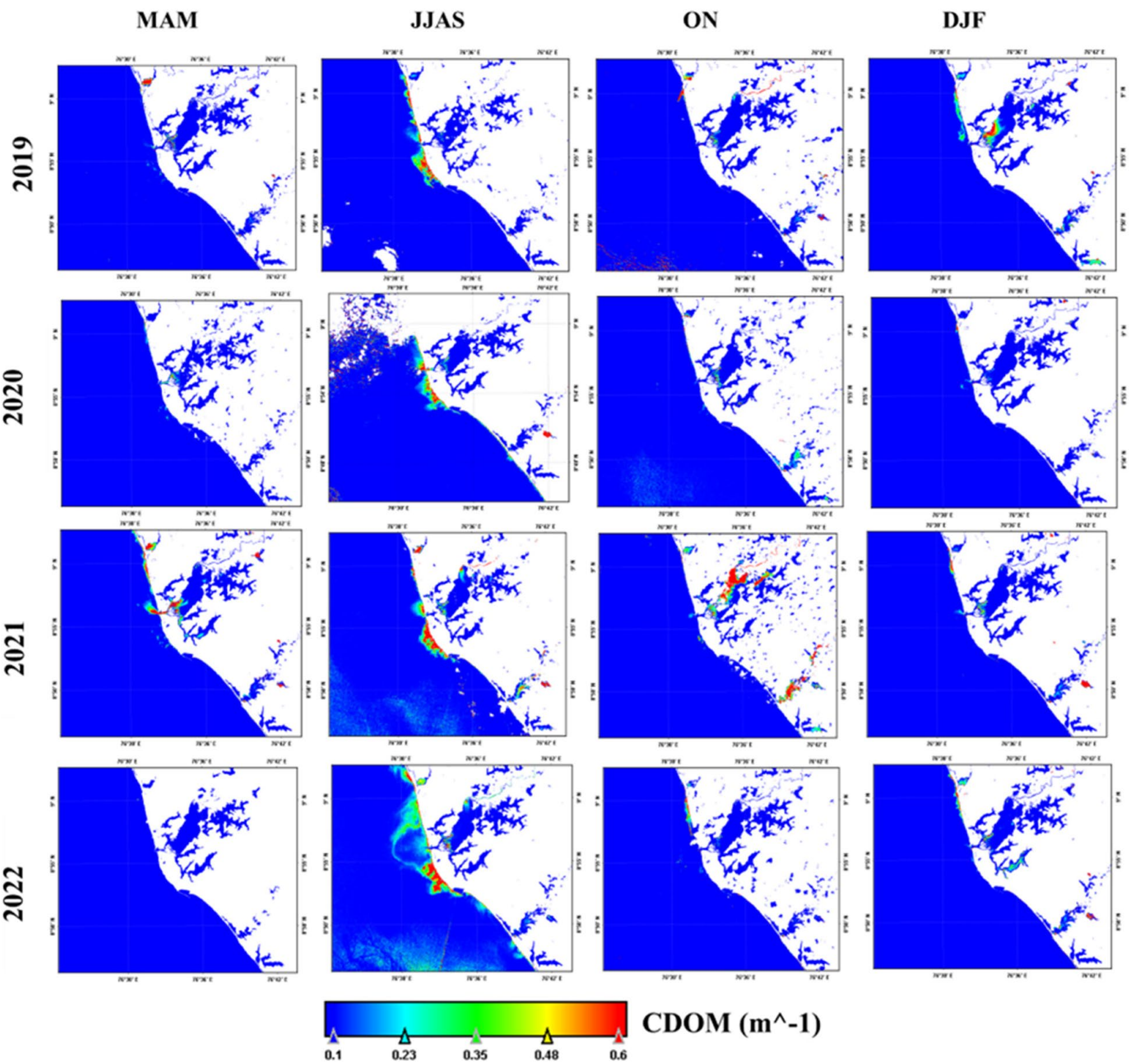

Fig. 6 Seasonal variation of CDOM for the period 2019 to 2022 for the Kollam coast

also consistently low during this season. These observed patterns provide insights into the intricate dynamics of water quality variations in the coastal waters of Kollam, India, throughout different seasons.

3.1.1 Annual variations

The analysis of Chl-a concentrations revealed a consistent pattern across all four years, characterized by peaks during the spring-inter monsoon (MAM) followed by a gradual increase during the monsoon (JJAS) and subsequent decline during fall-winter monsoon (ON) and winter monsoon (DJF). During JJAS, the increase in Chl-a levels aligns with Fardoshi et al.'s (2023) findings in Bay of Bengal, indicating that increased wind-driven upwelling during the summer monsoon (June to September) brings nutrient-rich waters to the surface, resulting in elevated Chl-a concentrations. Especially July to September period sees increased river discharge with higher nutrient content due to monsoonal rainfall-induced river runoff, contributing significantly to the rise in Chl-a abundance. Notably, the year 2020 exhibited a higher MAM peak, indicative of enhanced phytoplankton growth during that season, while 2022 displayed an overall lower Chl-a profile across all seasons compared to previous years.

Previous research conducted in the Arabian Sea has put forth a hypothesis that emphasizes the significant

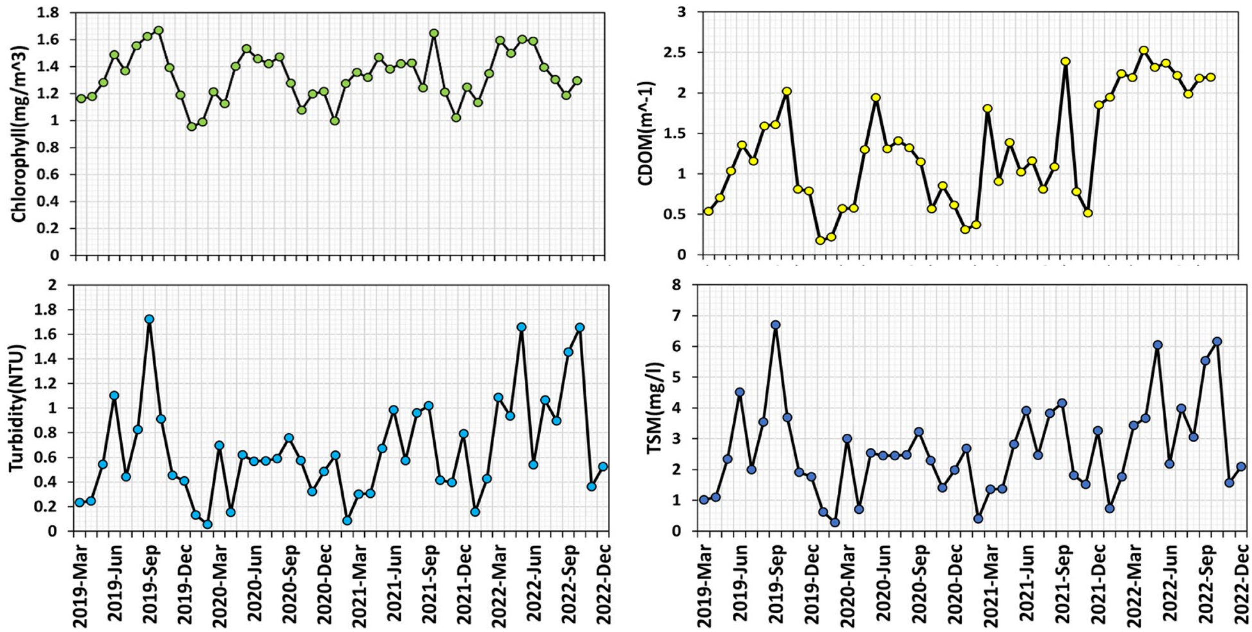

Fig. 7 Time series of monthly average of Chlorophyll, CDOM, Turbidity, and TSM

influence of the Southwest (SW) monsoon climatology on the extent of TSM influx into the sea (Nair et al. 1989; Haake et al. 1993, 1996). TSM concentrations in 2019 and 2020 showed similar peaks during the summer monsoon (JJAS) exceeding 5 mg/L, followed by declines in other seasons. However, 2021 exhibited a notably higher JJAS peak, exceeding 7 mg/L, suggesting a more substantial monsoon impact on sediment transport. In 2022, although the JJAS peak was lower than in previous years, a higher MAM peak was observed. Similar to our findings for JJAS, Raghavan and Chauhan (2013) also observed seasonal fluctuations in TSM, indicating high values during the SW (June–September) monsoon and lower levels during other non-monsoon months in the coastal waters of the Arabian Sea. Contrastingly, they also reported that this pattern is absent in the deeper waters of the outer shelf, where there is a consistent lack of variation in TSM content throughout the year; thereby, indicating that the deeper regions of the Arabian Sea do not experience significant transport of TSM from local rivers.

Turbidity trends are similar to those of TSM, with 2019 and 2020 showing analogous JJAS peaks and subsequent declines in other seasons. 2021 had the highest JJAS peak in turbidity, while 2022 had a lower JJAS peak but a higher MAM peak across all years. Kalharo et al. (2017) study on Indus River Estuary also observed high turbidity in the month of September – wet season (akin to current study JJAS) primarily from sediment input from the Indus River, while lower turbidity values in the dry season resulting from decreased freshwater and sediment discharge from the river, accompanied by higher salinity levels.

Minu et al. (2020) in their study on coastal water of southern east Arabian sea, categorized the sources of CDOM into three classifications: terrestrial origin (such as river discharge) during the monsoon (JJAS) period, organic decomposition in the pre-monsoon season (MAM), and a combination of both sources during the post-monsoon period (ON). CDOM consistently displayed elevated levels during the summer monsoon (JJAS) throughout all four years, particularly near estuarine waters, indicating runoff of sewage and organic wastes. Peaks in CDOM occurred during the fall-winter monsoon (ON) in 2019 and 2021, potentially associated with organic matter decomposition. Another peak in CDOM was noted during the MAM season of 2020, likely linked to increased runoff. Sanyal et al. (2020) reported high to extremely high levels of CDOM during the post-monsoon and monsoon periods in the Hooghly estuary. This was attributed to the increased riverine discharge during these seasons, indicating a substantial influence of intensified river activity on the CDOM concentrations in the estuarine environment.

Global warming and extreme events are anticipated to lead to rising SST, variations in SSH, Chl-a levels, salinity, pH, rainfall, and other oceanic conditions, affecting the overall health of marine ecosystems (Akash et al. 2021). Figure 8 presents a comprehensive analysis, illustrating the annual and monthly fluctuations in SST,

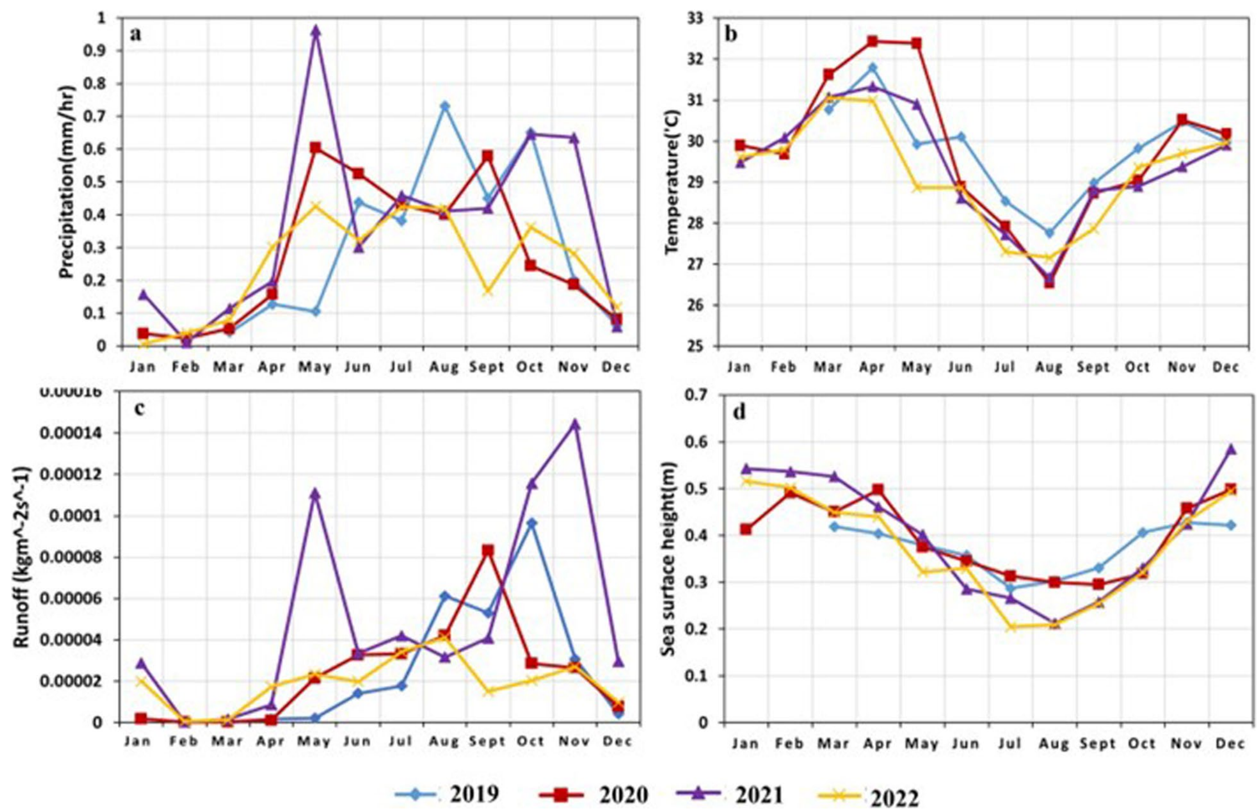

Fig. 8 Annual variation of precipitation, runoff, temperature, and sea surface height over the Kollam coastal waters for the four years (2019, 2020, 2021 and 2022)

precipitation, runoff, and SSH providing valuable insights into the dynamic environmental conditions influencing the studied coastal water parameters.

SST is a key metric intricately tied to marine productivity, pollution dynamics, and global climate change, strongly influencing habitat and life cycles, impacting fisheries and biodiversity, and serving as a sensitive marker for pollution that contributes to the formation of HAB (Azmi et al. 2015; Fingas 2019). A strong correlation exists between SST and Chl-a, with SST being a key factor influencing both the abundance and biomass of phytoplankton (Hidayat 2023). Elevated SST can hinder vertical mixing, leading to increased water column stratification and subsequently diminishing critical nutrients necessary for photosynthesis from sub-surface waters (Behrenfeld 2014). SST typically ascends from March, reaching its zenith in April, followed by a decline through May and June and attaining its lowest in August. April 2020 stands out with the highest recorded SST of the period at 32.5˚C, while the lowest temperatures occurred in August of both 2021 and 2020, measuring 26.5˚C. August 2019, however, exhibited a slightly higher temperature of 28.2˚C compared to other years.

Runoff data closely aligns with precipitation trends, showcasing similar variations. Precipitation significantly impacts TSM concentrations through the increase in riverine influx (Misra et al. 2014). Except for 2019, precipitation consistently attains its peaks during the pre-monsoon and post-monsoon periods, exhibiting comparatively lower values during the summer monsoon. However, 2019 deviates from this pattern, showcasing its peak precipitation during the summer monsoon, moderately diminished values in the post-monsoon, and notably reduced levels in the pre-monsoon in comparison to other years. The winter monsoon consistently registers the least amount of rainfall throughout the four-year period. The inverse correlation between local SST and rainfall, linked to variations in solar radiation and evaporative cooling above the sea surface, underlines the notion that SST is predominantly influenced by atmospheric factors, highlighting the importance of comprehending robust air–sea coupling processes for accurate predictions of monsoon rainfall (Takahashi and Dado 2018).

The fluctuation of SSH varies with seasons due to thermal expansion and contraction, with additional influences from factors like wind and tides (Woodworth et al. 2019). SSH consistently experiences a notable decrease during the summer monsoon each year. The summer monsoon, marked by seasonal winds and atmospheric changes, significantly influences SSH variations (Zhang and Mochizuki 2022). Further ocean eddies can substantially stimulate local sea level fluctuations and contribute to narrowly confined anomalies in SSH caused by ocean upwelling (Trott et al. 2019).

3.2 Dwindling water quality parameters

The southwestern coast of India experiences pronounced upwelling phenomena driven by monsoon winds from June to September (Sarangi and Mohammed 2011). Typically commencing in late March and persisting until September (Hareesh and Anand 2016), these vigorous upwellings bring forth cold, dense subsurface water enriched with nutrients to the ocean's surface, creating conducive conditions for potential algal blooms in coastal waters (Vishnu et al. 2022). This coastal upwelling serves as a substantial nutrient source along the southwest coast of India, facilitating the proliferation of phytoplankton in coastal waters (Retnamma et al. 2020). The emergence of a *P. globusa* bloom at Mundakkal Beach, Kollam, reported on June 10, 2019, was investigated by Madhu et al. (2020). Their findings suggested that the *P. globosa* bloom, a relatively uncommon event in low-latitude seas, might have been induced by nutrient enrichment facilitated by coastal upwelling and prevailing water column turbulence preceding the monsoonal winds associated with rainfall. In addition to the escalation of Chl-a levels, the upwelling contributes to increased sediment accumulation as water ascends from the ocean depths. This phenomenon accounts for increased concentrations of Chl-a and TSM during the summer monsoon, consequently coinciding with elevated turbidity levels during this period. This complex interplay of upwelling dynamics elucidates the multifaceted impact on water quality indicators along the studied coastal region (Pati et al. 2023).

In the summer monsoon of 2020, there was a conspicuous peak in the levels of Chl-a, TSM, and turbidity, with 2021 closely following suit, while 2019 recorded the lowest concentrations of these elements. The influence of rainfall on coastal waters manifests in a dual manner: it can both wash away phytoplankton and suspended materials and introduce nutrients and sediments through runoff or erosion (Thompson et al. 2015; Fong et al. 2020; Han et al. 2023). This dualistic impact elucidates the rationale behind the often observed higher concentrations of Chl-a and TSM near the coast, where robust upwelling coincides with significant terrestrial runoff (Li et al. 2023). The summer monsoon period of 2019 (JJAS), experienced increased rainfall compared to other years, resulting in a reduced concentration of Chl-a and suspended matter. Conversely, during the summer monsoon of 2022, Chl-a and TSM exhibited a broader dispersion into the ocean, a phenomenon likely attributed to lower rainfall levels during this period in comparison to other years. This analysis emphasizes the complicated interaction of meteorological factors and coastal dynamics shaping the variability in water quality indicators across different monsoon seasons (Ahmed et al. 2023).

In the pre-monsoon season, coastal waters experience a substantial influx of nutrients from both upwelling processes and anthropogenic sources (Su and Pohlmann 2009; Oduor et al. 2023). The presence of ample sunlight penetrating these waters creates favourable conditions for rapid algae growth and proliferation (Mumthas and Miranda 2016). Particularly noteworthy is the pre-monsoon period of 2020, during which the SST reached a peak of 32.5°C, surpassing temperatures recorded in other seasons. This sharp exposure to sunlight, combined with the influx of upwelled nutrients, likely played a significant role in the observed increase in Chl-a concentration during this pre-monsoon period compared to levels recorded in the pre-monsoon seasons of other years. The synergy of raised SST and nutrient enrichment highlights the complex dynamics shaping the biological productivity of coastal waters during specific climatic periods (Kang and Lee 2023).

In conjunction with natural influences, a persistent rise in TSM and Chl-a concentrations is steadily observed in proximity to the Ashtamudi estuary and along the northern coast near Chavara across all seasons. This enhanced concentration can be largely attributed to the Ashtamudi estuary acting as a conduit for domestic waste, sewage, and pollutants originating from Ashtamudi Lake and entering the sea (Cyril 2010; Krishnan et al. 2015; Lekshmiprasad and Mophin 2017). During the June to September (JJAS) period, the runoff from the lake into the sea intensifies due to increased rainfall, as depicted in Fig. 8. The proximity of Neendakara fishing harbour to the estuary exacerbates the situation, as pollutants and toxins from ships further degrade water quality (Cyril 2010). Industrial influences, particularly from two major industries near Chavara on the northern coast—Kerala Minerals and Metals Limited (KMML) and Indian Rare Earths Limited (IREL)—play a substantial role (Johnson and Muthu 2022). These industries discharge industrial waste into the ocean, contributing to pollution (Abraham and Sivan 2021).

A comprehensive plankton diversity study conducted by Mumthas and Miranda (2016) in two environmentally disturbed sites along the Kollam coast, namely Chavara-titanium and Neendakara, revealed that plankton varieties displaying high tolerance to heavy metals and sewage pollutants were more prevalent during the pre-monsoon period, indicating anthropogenic influences. In contrast, plankton identified during the monsoon season was primarily associated with increased nutrient availability. Tourism activities in these areas exacerbate environmental stress (Sitaram 2014). While the northern coast, particularly around Panmana, is renowned for its abundant mineral deposits, intensive sand mining activities in this region result in substantial mineral dredging and contribute significantly to ocean pollution (Jose 2018). This amalgamation of anthropogenic factors significantly impacts water quality in these regions, exerting a lasting effect on TSM and Chl-a concentrations throughout the year.

The study highlights that during the summer monsoon, areas with substantial anthropogenic activities exhibit notably higher concentrations of CDOM, as depicted in Fig. 6. The intensified land runoff characteristic of the monsoon season, as illustrated in Fig. 8(c), enhances the flow from Ashtamudi Lake, introducing freshwater laden with nutrients, wastes, and organic matter into the ocean. This inflow is a probable contributor to the enhanced CDOM levels observed during the summer monsoon, in addition to the influence from phytoplankton. Notably, the increase in CDOM concentration is not uniformly distributed along the entire coastline, suggesting that anthropogenic inputs exert a more pronounced influence than natural dynamic processes in shaping CDOM levels. The utilization of high-resolution Sentinel imagery facilitates a clear observation of augmented CDOM concentrations near Panmana, a prominent sand mining area in Kollam. This specific detail emphasizes the substantial impact of human activities, particularly those associated with industrial processes like sand mining, on CDOM variations in coastal waters. The findings underline the need for targeted interventions and management strategies to mitigate the human-induced alterations in CDOM concentrations and maintain the ecological balance of the coastal environment.

The water quality parameters in the Kollam coastal waters exhibit a distinct seasonal trend, characterized by higher values during the June to September (JJAS) period. Moreover, the parameters demonstrate notable inter-annual variability, influenced by physio-chemical conditions such as rainfall, monsoon wind forcings, runoff, among others. Although studies focusing on water quality in the Kollam coastal waters are limited, a noteworthy investigation conducted by Dilipkumar and Shanmugam (2023) provides valuable insights. Their study, which specifically emphasized Kollam as a region dominated by CDOM, revealed the poor water quality in Kollam's coastal waters. The study attributed this to the collective impact of various parameters, with higher values observed during the SW monsoon. Overall, the present study sheds light on the complex dynamics of water quality in the region, emphasizing the need for continued monitoring and targeted interventions to address the specific challenges influencing Kollam's coastal water quality, especially during the monsoon season.

4 Conclusions

Traditional methods of water quality testing often fall short in providing a continuous and comprehensive record, highlighting the superior capabilities of remote sensing technologies for a more thorough understanding of specific phenomena. In our study, we utilized Sentinel-2 satellite data to analyse the water quality along the Kollam coast in India over the period from 2019 to 2022. Our focus was on four key parameters: Chl-a, TSM, turbidity, and CDOM. Our findings indicate that water quality on the Kollam coast exhibits both seasonal and inter-annual variations. During the summer monsoon, increased rainfall was associated with higher TSM and turbidity levels. The spring-inter monsoon period was characterized by enhanced phytoplankton growth, as evidenced by elevated Chl-a concentrations. CDOM levels reached their peak in the fall-winter monsoon, likely due to the decomposition of organic matter. The year 2021 was notable for an exceptionally high Chl-a peak during the spring-inter monsoon, which could suggest the occurrence of a harmful algal bloom. In 2022, there was a marked increase in TSM during the spring-inter monsoon, indicative of altered sediment transport dynamics.

Understanding these dynamic patterns in water quality is crucial for effective coastal management. Continuous long-term monitoring and research are necessary to gain a deeper comprehension of this complex coastal ecosystem and to ensure its sustainability for future generations.

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Author's contributions

The first author was responsible for carrying out the data analysis, interpreting the results, and drafting the manuscript. The second author conceptualized and supervised the work and reviewed the manuscript. The third author contributed to the review and refinement process,

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Availability of data and materials
We have provided citations wherever required to download the datasets.

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Ethics approval and consent to participate
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Authors declare no competing interest.

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