Abstract

This research seeks to analyze the spatial and temporal variability of Photosynthetically Available Radiation (PAR), Diffuse Attenuation Coefficient (Kd_490), and Sea Surface Temperature (SST) in the Bangladesh Exclusive Economic Zone (EEZ) from 2016 to 2022. The study tries to explore the ecological consequences of these factors in the context of marine biological processes in the Bay of Bengal. The study utilized data gathered from the NASA Ocean Color website, primarily focusing on PAR, Kd_490, and SST information from the Aqua-MODIS satellite sensor. The data covered a temporal period from 2016 to 2022 and were processed using SeaDAS and ArcGIS software. Spatial and temporal analyses were done to assess these characteristics' yearly and seasonal fluctuation inside the Bangladesh EEZ. The findings demonstrated considerable changes in PAR, Kd_490, and SST across the research period. PAR ranged from 32.47 to 55 Einstein/m²/day, demonstrating fluctuation related to atmospheric and oceanic conditions. Kd_490 data showed trends of increased water turbidity in specific regions, possibly connected to land runoff and anthropogenic activity. SST data ranged from 22°C to 31°C, demonstrating a moderate warming trend throughout the years. The research demonstrates the linked nature of PAR, Kd_490, and SST in marine ecosystems, with their patterns correlated with global environmental changes. It highlights the necessity for regional research to understand changing marine habitat conditions in the context of global climate change and the importance of utilizing these environmental factors for sustainable management and conservation in marine ecosystems.

Keywords: Photosynthetically Available Radiation (PAR), Diffuse Attenuation Coefficient (Kd_490), Sea Surface Temperature (SST), Bangladesh Exclusive Economic Zone (EEZ), Aqua MODIS.

1. Introduction

Photosynthetically available radiation (PAR) refers to the portion of the electromagnetic spectrum that is usable by plants for the process of photosynthesis, which is a vital physiological process in which plants convert light energy into chemical energy to fuel their growth and development (McCree, 1971, 1972). PAR encompasses the range of wavelengths of light that fall between 400 and 700 nanometers, which corresponds to the visible light spectrum (Ferrera-Cobos et al., 2020; M\~ottus Mattiand Sulev, 2012; McCree, 1981). Photosynthesis primarily occurs in chloroplasts, and the pigments responsible for capturing light energy are chlorophylls. These pigments are most receptive to light in the blue (around 400-500 nm) and red (around 600-700 nm) regions of the spectrum. PAR includes these wavelengths, making it essential for photosynthesis. PAR is typically measured in unit Einstein/m^2/day which quantifies the amount of photosynthetically active radiation (PAR) received by a surface over a day (Harmel & Chami, 2016). It is a measure of the total energy from light within the photosynthetically active range (400 to 700 nanometers) that falls on a one-square-meter area during a 24-hour period. Variations in weather, height, latitude, and time of day can all affect how much PAR reaches plants. For example, the PAR available for photosynthesis is impacted when sunlight intensity drops on cloudy days or at higher latitudes. PAR is a key component that affects plant growth and productivity (Pérez-Bermúdez & Rognoni Martínez, 2022).

The light diffuse attenuation coefficient (Kd(λ)) in aquatic systems is determined by the exponential reduction in the amount of light with increasing depth; it is a measure of how light weakens as it travels through a medium like water (Wang et al., 2009a). It's specifically used for photosynthetically available radiation (PAR), which is the range of wavelengths (400-700 nm) that plants and algae use for photosynthesis. The determination of Kd using the ocean color method primarily occurs at a wavelength of 490 nm, particularly in open water (Morel et al., 2007). The reason for this is that Kd (490) is a common parameter that is utilized in numerous ocean color applications. It also has extensive use in the field of water optics and remote sensing (Tiwari et al., 2018). The value of Kd can vary with the wavelengths of light. Different wavelengths are attenuated at different rates, leading to variations in the spectral diffuse attenuation coefficient. The two main processes contributing to light attenuation are absorption and scattering. Absorption occurs when the light is absorbed by molecules in the medium, converting it into other forms of energy(Saulquin et al., 2013). Kd is derived from the inherent optical properties (IOP) and apparent optical properties (AOP) (Setiawan et al., 2021).

Scattering involves the redirection of light by particles in the medium. Both processes contribute to the overall attenuation of light, and their relative importance depends on the characteristics of the medium. It is influenced by the concentration and nature of particles in the medium. Clearer waters with fewer particles may have lower Kd values, while turbid waters with increased particle content may exhibit higher Kd values (Pérez et al., 2010).

Sea surface temperature (SST) is a crucial parameter associated with the worldwide ocean-atmosphere system. Surface Sea Temperature (SST) data are regularly collected from vessels, buoys, and offshore installations (Reynolds et al., 2005). Nevertheless, these conventional observations typically lack the necessary scope for a comprehensive research study. Satellite-derived sea surface temperature (SST) has gained significant interest as a supplementary data source because to its superior spatial and temporal precision, as well as its extensive coverage, which helps overcome the limitations of traditional measures (Kim et al., 2010). Sunlight intensity, ocean currents, and patterns of air circulation are some of the variables that naturally affect sea surface temperature variations. Events such as El Niño and La Niña are linked to the regular warming and cooling of the eastern and central Pacific Ocean, which affects the patterns of the world's weather (Chen et al., 2016). To differentiate between short-term variations and long-term trends, it is essential to look into the SST's inherent variability (Wu et al., 2020).

Remote sensing technology stands out as a valuable alternative for monitoring changes in the marine environment over specific time frames. The utilization of this technology brings forth distinct advantages, notably the capacity for wide-ranging observations and high temporal resolution. These attributes make remote sensing particularly effective in capturing dynamic and time-sensitive alterations within marine ecosystems. Among the various applications of remote sensing technology, monitoring different oceanic parameters using the Aqua MODIS satellite emerges as a widely adopted practice (Yunita & Zikra, 2017). With its advanced sensors and data-gathering capabilities, the Aqua MODIS satellite facilitates the acquisition of precise and frequent measurements.

1.1 Objectives

a) To analyze spatial and temporal variability of PAR, Kd_490, and SST in Bangladesh EEZ.

b) To assess the yearly and seasonal fluctuation of PAR, Kd_490, and SST features over 2016–2022.

2. Literature Review

Photosynthetically Available Radiation (PAR) is a part of the electromagnetic spectrum (400-700 nm) employed in photosynthesis. PAR is essential for the global carbon cycle as it stimulates photosynthesis in both marine and terrestrial environments. (Behrenfeld et al., 2001) Conducted studies on global primary productivity, explicitly focusing on the variability of photosynthetically active radiation (PAR) in various marine locations and its influence on primary output. It's vital for plant growth, as noted in research by (Ferrera-Cobos et al., 2020; McCree, 1971, 1972). It's quantified in Einsteins/m²/day, a metric representing the quantity of PAR reaching a surface per day. The availability of PAR is prone to changes due to weather, geographic conditions, and temporal variations, as detailed by (Harmel & Chami, 2016; Pérez-Bermúdez & Rognoni Martínez, 2022).

The Diffuse Attenuation Coefficient (Kd) indicates how light intensity diminishes with depth in water, which is vital for calculating PAR in aquatic situations. This topic is detailed in (Wang et al., 2009b)'s research. Kd_490 is important in open water, as (Morel et al., 2007; Tiwari et al., 2018) indicate. Its variability is related to absorption and scattering by particles in water, with clearer waters having lower Kd values and turbid waters having greater values, as mentioned by (Pérez et al., 2010; Saulquin et al., 2013). The extensive study of Kd_490 aims to understand light penetration in oceans, a crucial factor for marine ecosystem survival. Studies such as (Ronald et al., 2001) in "Light Absorption and Scattering" offer valuable information about the worldwide variations in Kd_490. These studies attribute the changes in Kd_490 to factors such as water quality and the occurrence of algae blooms.

Sea Surface Temperature (SST) is a significant metric for determining global weather patterns. Conventional and satellite-derived SST data give valuable insights, as indicated by (Kim et al., 2010; Reynolds et al., 2005). SST is governed by elements including sunlight intensity, ocean currents, and air circulation, with occurrences like El Niño and La Niña affecting it, as (Chen et al., 2016) and (Wu et al., 2020) show. SST is an essential indication of climate change, with research like those in "Global Ocean Temperature Trends" by (Levitus et al., 2012) displaying rising trends worldwide. These changes have significant repercussions for weather patterns, marine biodiversity, and ocean currents. Research particular to the Bay of Bengal, such as by (Vinayachandran & Mathew, 2003) in "SST Variability in the Bay of Bengal", underlines the considerable influence of monsoons and river inputs on SST, affecting regional climate and cyclone development. (Pezner et al., 2021) studied the geographical and temporal variability of solar penetration depths in the Bay of Bengal, emphasizing how chlorophyll affects solar radiation absorption and hence, SST. A study described in the E3S Web of Conferences (2022) assessed the effect of current velocity on the distribution pattern of SST in the Bay of Bengal, applying the results of the Hybrid Coordinate Ocean Model (HYCOM) (Amsalia Nadia et al., 2022). It was shown that current velocity conditions greatly influence SST, with high SST seen during periods of high current velocity. Studies have shown that chlorophyll's impact on regional climate, particularly its impact on solar radiation absorption and SST, is significant. (Nakamoto et al., 2001) and (Wetzel et al., 2006) found that chlorophyll concentration in the Indian Ocean significantly impacts the South Asian monsoon.

PAR, Kd, and SST jointly determine the depth of photosynthesis and the distribution of phytoplankton, as well as the general physical features of saltwater. The relationship between them is vital for understanding the dynamics of marine habitats, as (Son & Wang, 2015) notes.

3. Materials and Methods

3.1 Study Area

Bangladesh's Exclusive Economic Zone (EEZ) is a maritime zone that extends from its territorial waters up to 200 nautical miles from its baselines (*Gazette_Teritorial Waters & Maritime Zones (Amendment) Act, 2021*,). It is situated in the northeastern part of the Indian Ocean (Figure-1). The coordinates of Bangladesh's EEZ are approximately 20° 28' 32.2" N latitude and 90° 33' 41.5" E longitude (*Bangladesh EEZ | ProtectedSeas Navigator*,). To be precise, the northernmost tip of the EEZ lies nestled at 18° 15' 54.12" North, 89° 21' 47.56" East, where the maritime meet. Its southernmost reaches touch 17° 52' 34.06" North, 90° 15' 4.66" East, marking the end of Bangladesh's maritime territory where Myanmar's waters begin(*The Bangladesh Maritime Zones Act, 2018 (Draft) Maritime Affairs Unit Ministry of Foreign Affairs Government of the People's Republic of Bangladesh Dhaka*, 2018) .Total area of Bangladesh's EEZ is approximately 112,116 sq. km. It is characterized by its strategic location between India to the west, Myanmar to the east, and the Bay of Bengal to the south. The management and jurisdiction of Bangladesh's EEZ are governed by The United Nations Convention on the Law of the Sea, treaties, and agreements, ensuring the country's rights and responsibilities in this vast maritime domain (*PREAMBLE TO THE UNITED NATIONS CONVENTION ON THE LAW OF THE SEA*,). It encompasses diverse marine environments, including the continental shelf, deep-sea regions, and the waters of the Bay of Bengal. This zone is rich in marine resources, offering potential opportunities for fisheries, hydrocarbon exploration, and other maritime activities.

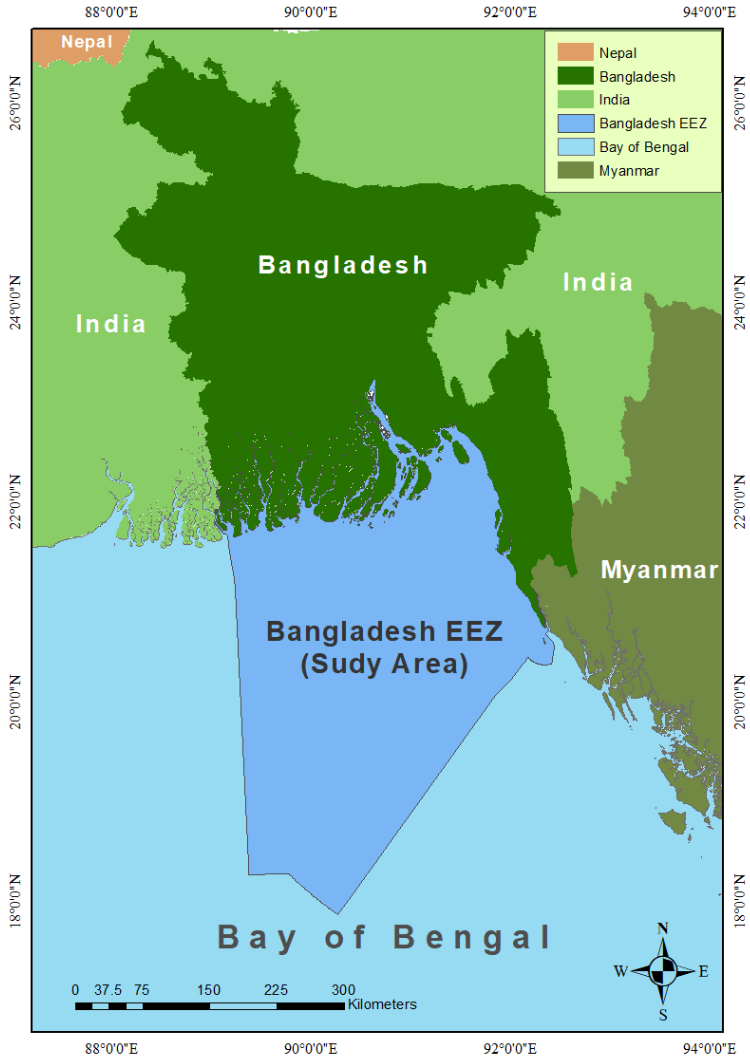

Figure 1: Study area map of Bangladesh EEZ

3.2 Data acquisition

Data for this study were acquired from the NASA Ocean Color website (OCW) (https://oceancolor.gsfc.nasa.gov/), a public repository for oceanographic data, including satellite-derived products. Photosynthetically Available Radiation (PAR) (Einstein/m^2/day), Diffuse Attenuation Coefficient at 490 nm (Kd_490) (m^{-1}) and Sea Surface Temperature (SST) (ºC) of level 3 datasets were downloaded in NetCDF (.nc) format, a standard format for storing and sharing scientific data. The datasets were selected using precise search filters, including the satellite instrument Aqua-MODIS (Moderate Resolution Imaging Spectroradiometer), spatial resolution 4km, and time period (monthly and annual). The datasets cover a global spatial extent and a temporal range from 2016 to 2022.

Table 1: Details of datasets used in this study

Data	Satellite sensor	Time period	Data type	Spatial resolution
Annual & monthly PAR	Aqua MODIS	Jan 01,2016-Dec 31,2022	Mapped	4km
Annual & monthly Kd_490	Aqua MODIS	Jan 01,2016-Dec 31,2022	Mapped	4km
Annual & monthly SST	Aqua MODIS	Jan 01,2016-Dec 31,2022	Mapped	4km

3.3 Data Processing

The downloaded NetCDF files were processed and analyzed using software, such as, SeaDAS (version 8.4.1) for the processing, analysis and Environmental Systems Research Institute's (ESRI) ArcGIS (version 10.8), which is a Geographic Information System (GIS) software for spatial analysis, mapping, and visualization of the downloaded datasets.

Monthly and annual mean values were calculated for PAR, Kd_490, and SST across the years 2016-2022. All the data were projected onto the World Geodetic System (WGS-1984) datum and Universal Transverse Mercator (UTM) zone 46N projection and meticulously clipped to conform to the Bangladesh Exclusive Economic Zone boundary. From these data, the annual variability of Photosynthetically Available Radiation (PAR), diffuse attenuation coefficient at 490 nm wavelength (Kd 490), and Sea Surface Temperature (SST) can be measured.

4. Result and Discussion

4.1 Spatial Variability of PAR, Kd_490 and SST

4.1.1 Annual Photosynthetically Available Radiation (PAR) Variations

The study on annual fluctuations of Photosynthetically Available Radiation (PAR) entailed generating spatial distribution maps for each year spanning from 2016 to 2022. These maps offer an extensive overview of the quantity of solar radiation accessible for photosynthetic activities throughout the Bangladesh EEZ (Figure-2). The maps show that PAR is less than 35 Einstein/m²/day in coastal areas. Based on the annual variability of PAR during 2016-2022, it is observed that the solar radiation flux is 32.47 Einstein/m²/day near the coastal areas, while in the offshore, values reach 54.96 Einstein/m²/day.

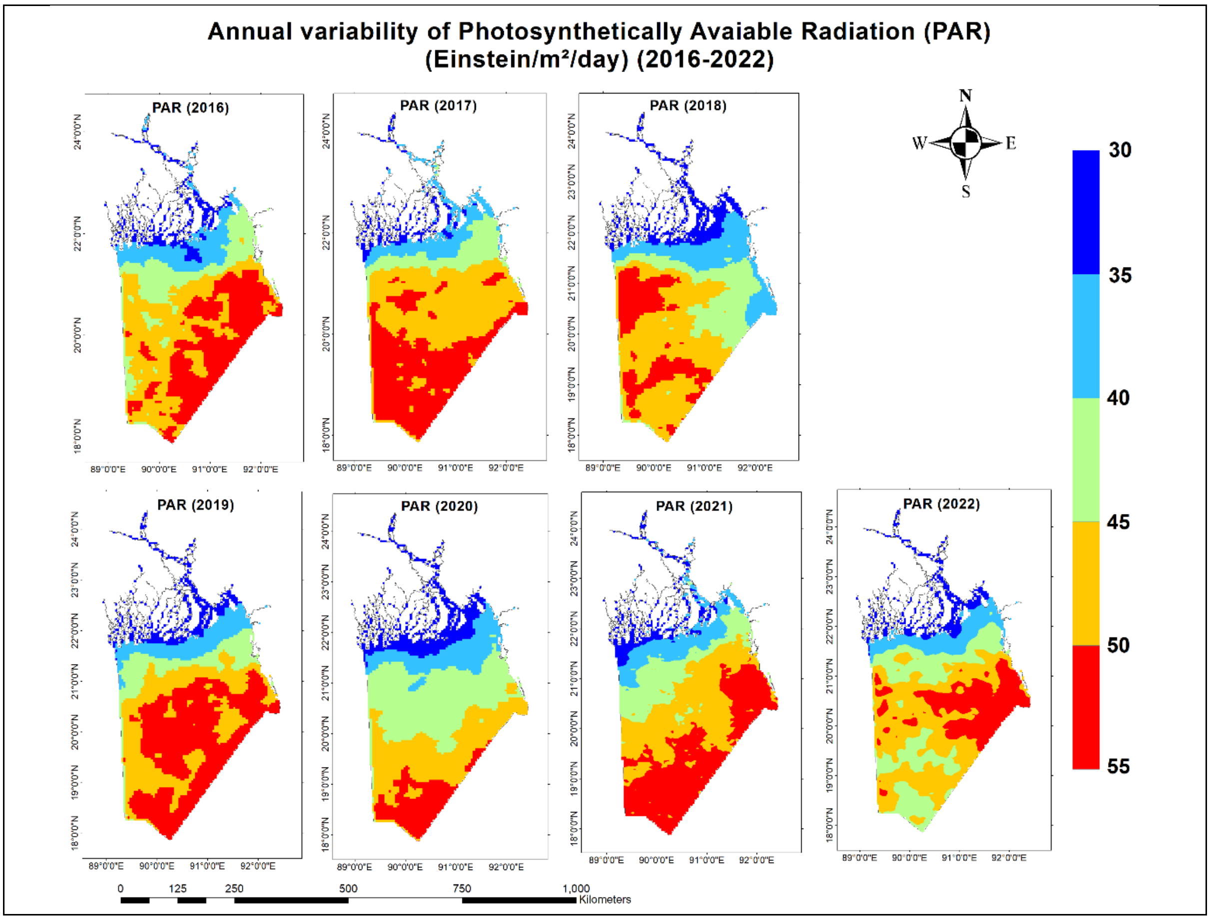

Figure 2: Annual variability of PAR (2016-2022)

4.1.2 Annual Diffuse Attenuation Coefficient Variations

The annual variability of the diffuse attenuation coefficient at a wavelength of 490 nm (Kd_490) has a significant impact on marine ecosystems. It is observed in the maps of Kd_490 between 2016 and 2022 (Figure-3), its values fluctuated between 0.01 m^{-1} and 0.33 m^{-1}. In coastal areas, Kd is generally greater than 0.15 m^{-1} compared to offshore regions. This is mostly attributed to elevated concentrations of suspended particles, organic matter, and phytoplankton in the water. These elements can enhance the phenomenon of light scattering and absorption, resulting in an elevated Kd value. Additionally, coastal areas may encounter increased input of terrestrial materials and contaminants, further contributing to the higher Kd.

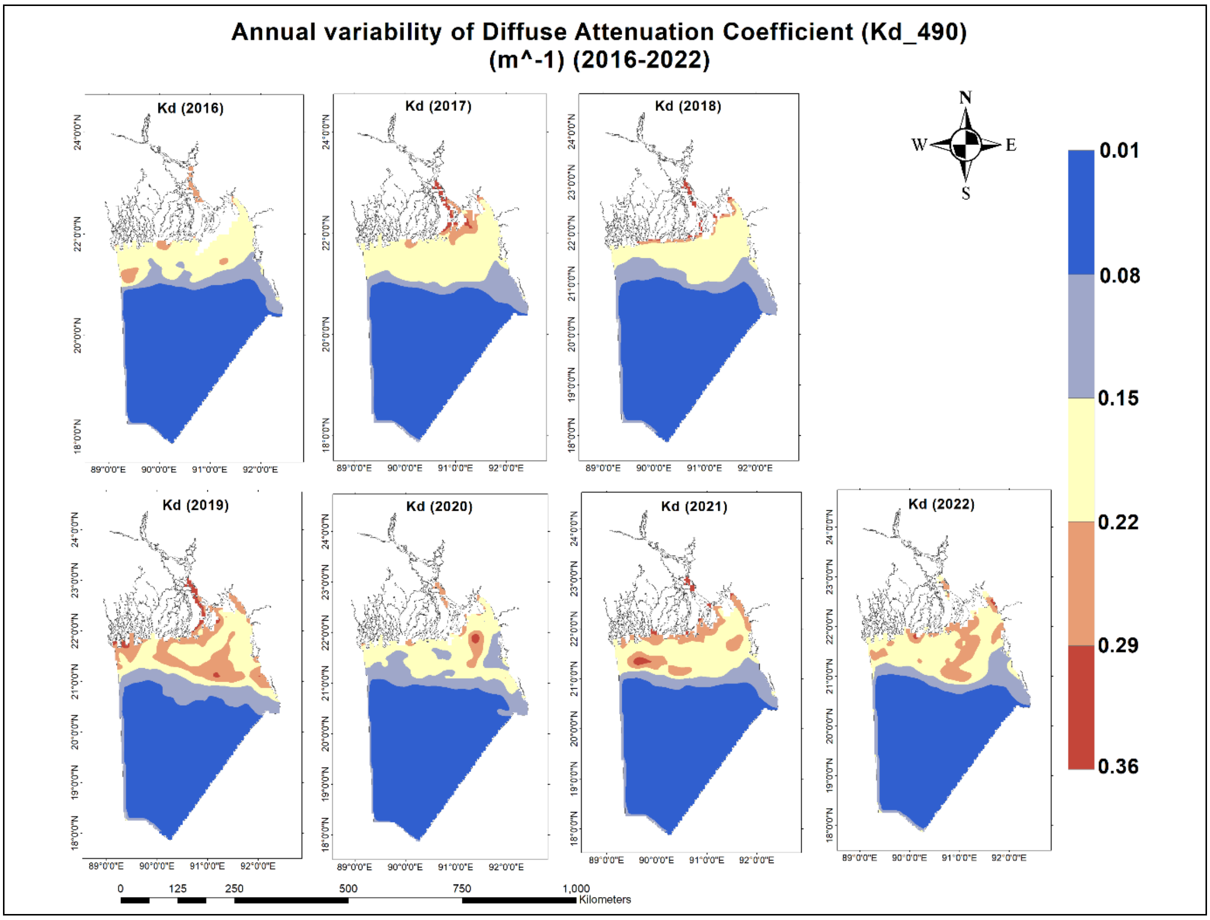

Figure 3: Annual variability of Kd_490 (2016-2022)

4.1.3 Annual Sea Surface Temperature (SST) Variations

The maps reveal distinct spatial and temporal patterns in Sea Surface Temperature (SST) across Bangladesh's Exclusive Economic Zone (EEZ) from 2016 to 2022 (Figure-4). Spatially, a continuous pattern is observed throughout the chosen time period, with the northernmost region of Bangladesh's EEZ consistently exhibiting temperatures around 30°C. The temperatures in this area, which is close to where rivers pour into the ocean and where coastal activities take place, are higher. This may be because the water is not as deep, allowing more sunlight to heat it up, and because warm water from the rivers flows into the area. On the other hand, the southern regions, which go deeper into the Bay of Bengal, exhibit lower SST, around 25°C, because of the existence of deeper oceanic waters and the impact of monsoonal currents.

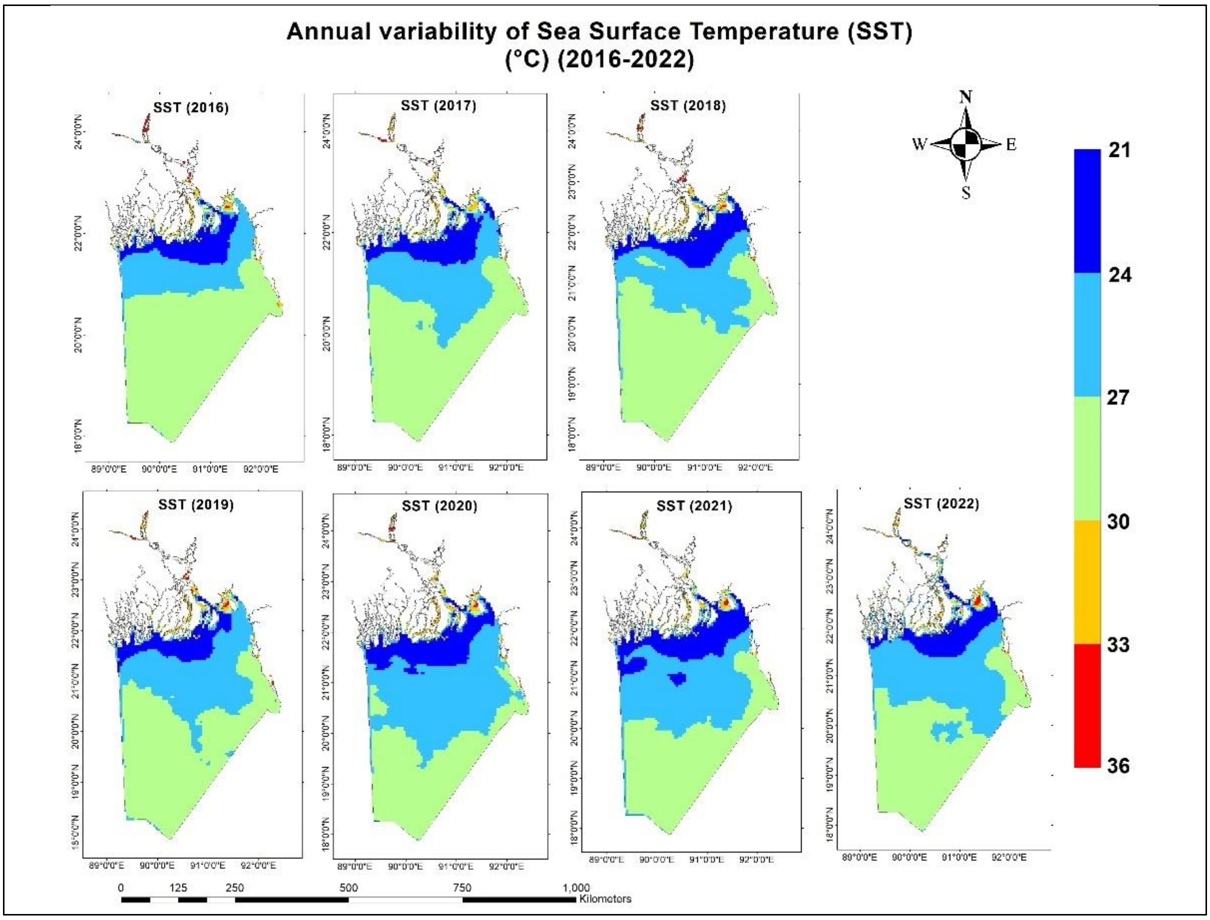

Figure 4: Annual variability of SST (2016-2022)

4.2 Temporal Variability PAR, Kd_490 and SST

4.2.1 Visualization of Annual PAR Variations

PAR values exhibit a distinct seasonal trend, characterized by elevated values during the spring & summer period (around May to July) and reduced values during the winter period (around November to February). This pattern remains constant across all years. From the annual variability graphs (Figure-5), it is observed that the range of PAR values fluctuated between 32.47-54.96 Einstein/m²/day.

From the time series graphs of PAR (2016-2022) (Figure-6), each line has a different seasonal pattern, with the maximum values of PAR around 55 Einstein/m²/day, often occurring during the mid-year months. This correlates to the summer season in the Northern Hemisphere, when the sunshine is more direct and the days are longer, leading to more available light for photosynthesis. The lowest values around 32 Einstein/m²/day exist throughout the late and early months of the year, corresponding with the winter season when there is less sunshine due to shorter days and a lower solar angle.

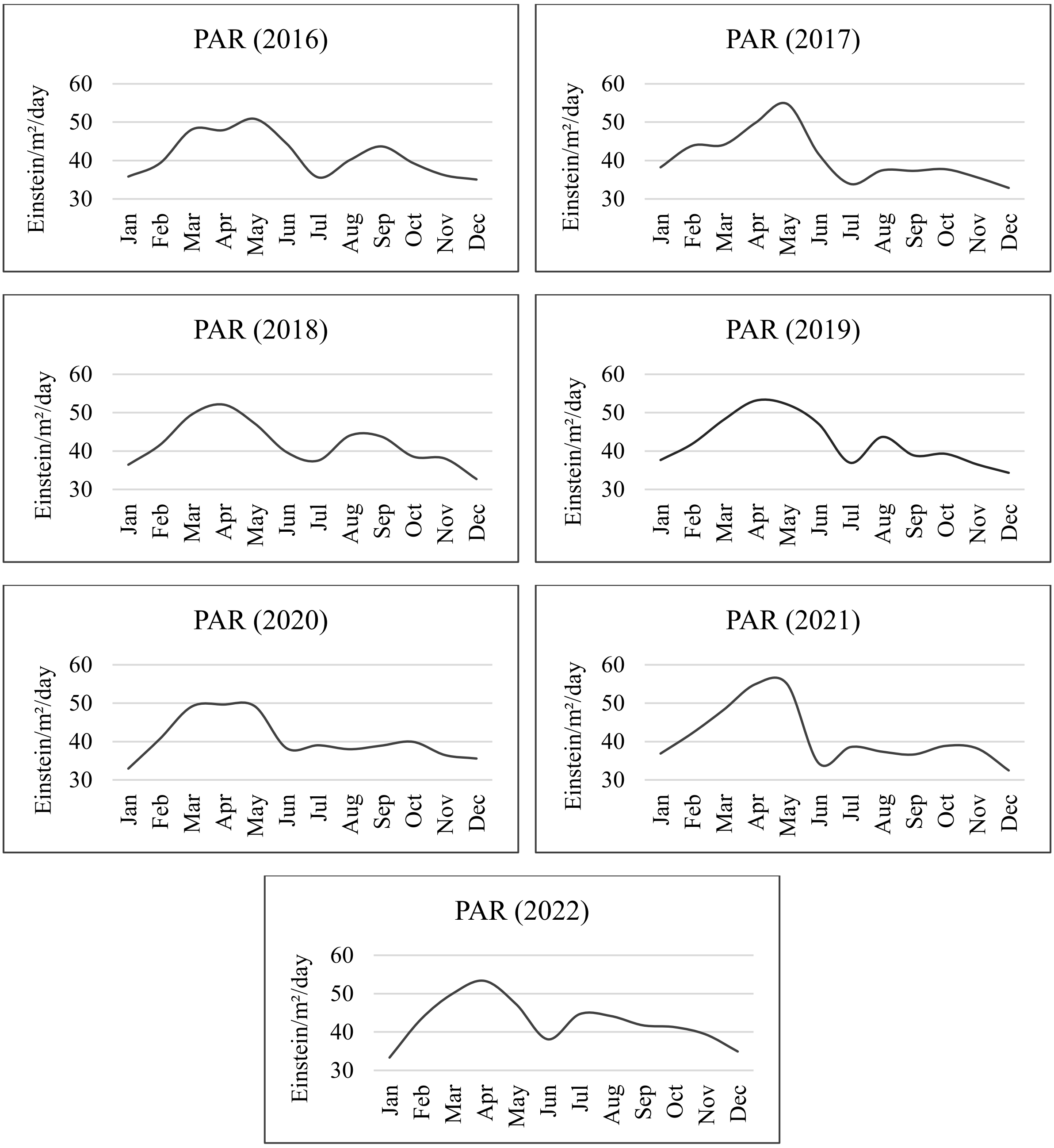

Figure 5: Graphs of annual PAR (2016-2022)

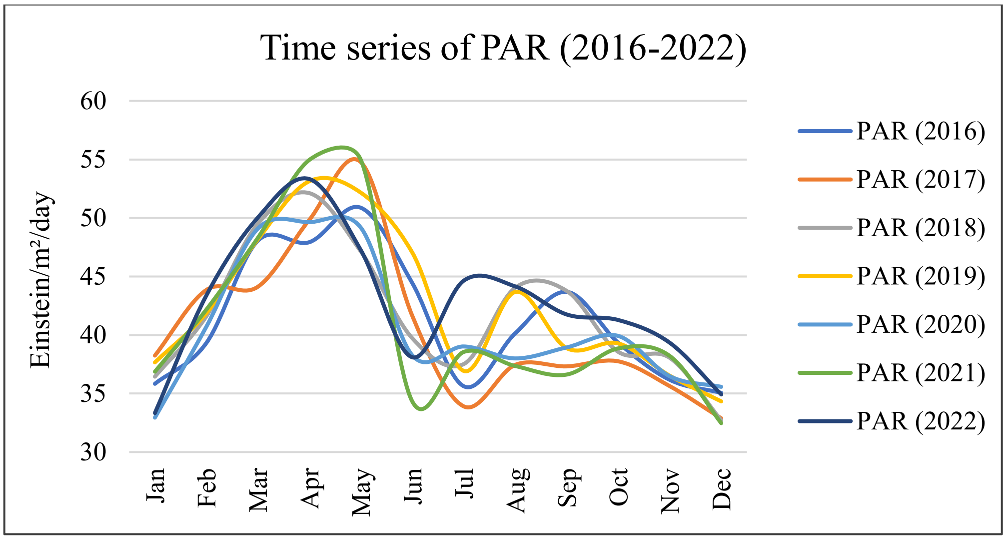

Figure 6: Time series of PAR (2016-2022)

4.2.2 Visualization of Annual Kd Variations:

Graphs of annual Kd variability showed the variation of Kd_490 throughout the year from 2016 to 2022 (Figure-7). There was a seasonal pattern evident in the graphs, with Kd values fluctuating between 0.01- 0.33 m^{-1} throughout the year. The graphs show different patterns each year, suggesting variability in the factors affecting water clarity. For example, higher Kd values indicate more light being absorbed or scattered per meter. These changes are likely related to seasonal climatic factors affecting water transparency, such as monsoons, river runoff, and algal blooms, which are common in marine environments like the EEZ of Bangladesh.

Time series graphs of Kd across the years (2016-2022) (Figure-8) showed more fluctuations. A common feature across the years is that the Kd values tend to increase around the middle of the year, particularly in the months of May through August, which suggests a seasonal influence. Towards the end of the year and the beginning of the next year, the Kd values generally decrease, suggesting clearer water conditions.

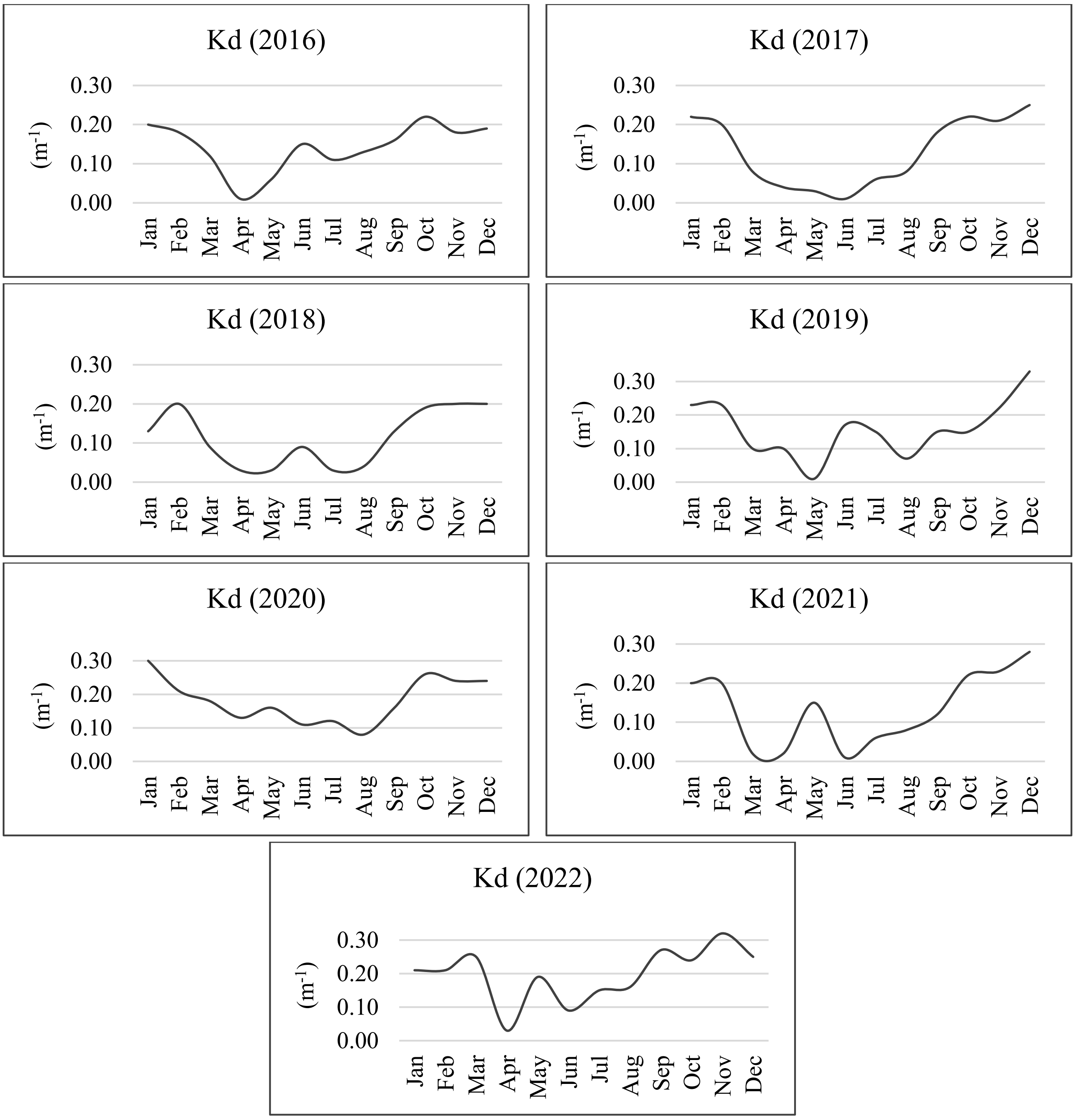

Figure 7: Graphs of annual Kd_490 (2016-2022)

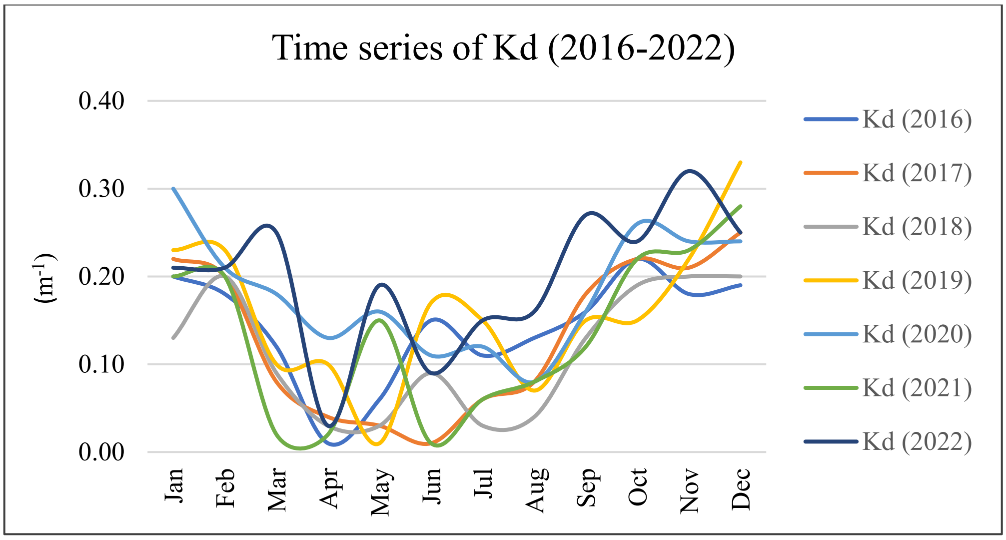

Figure 8: Time series of Kd (2016-2022)

4.2.3 Visualization of Annual SST Variations:

There is a strong seasonal pattern evident in each year's graph, with SST typically peaking in the middle months, suggesting summer circumstances, and reaching its lowest points during the early and later months, suggesting winter conditions. Although the seasonal trend is stable, the peak and trough temperatures fluctuate from year to year (Figure-9). This suggests that each year may encounter slightly varying oceanic and atmospheric conditions impacting SST.

While there is some variation in the exact temperatures, fluctuated between 22 °C to 31 °C observed from the time series graphs of SST between 2016 and 2022 (Figure-10), the overall seasonal pattern is remarkably consistent from year to year. There are subtle differences in the peak temperatures reached in different years and the timing of these peaks.

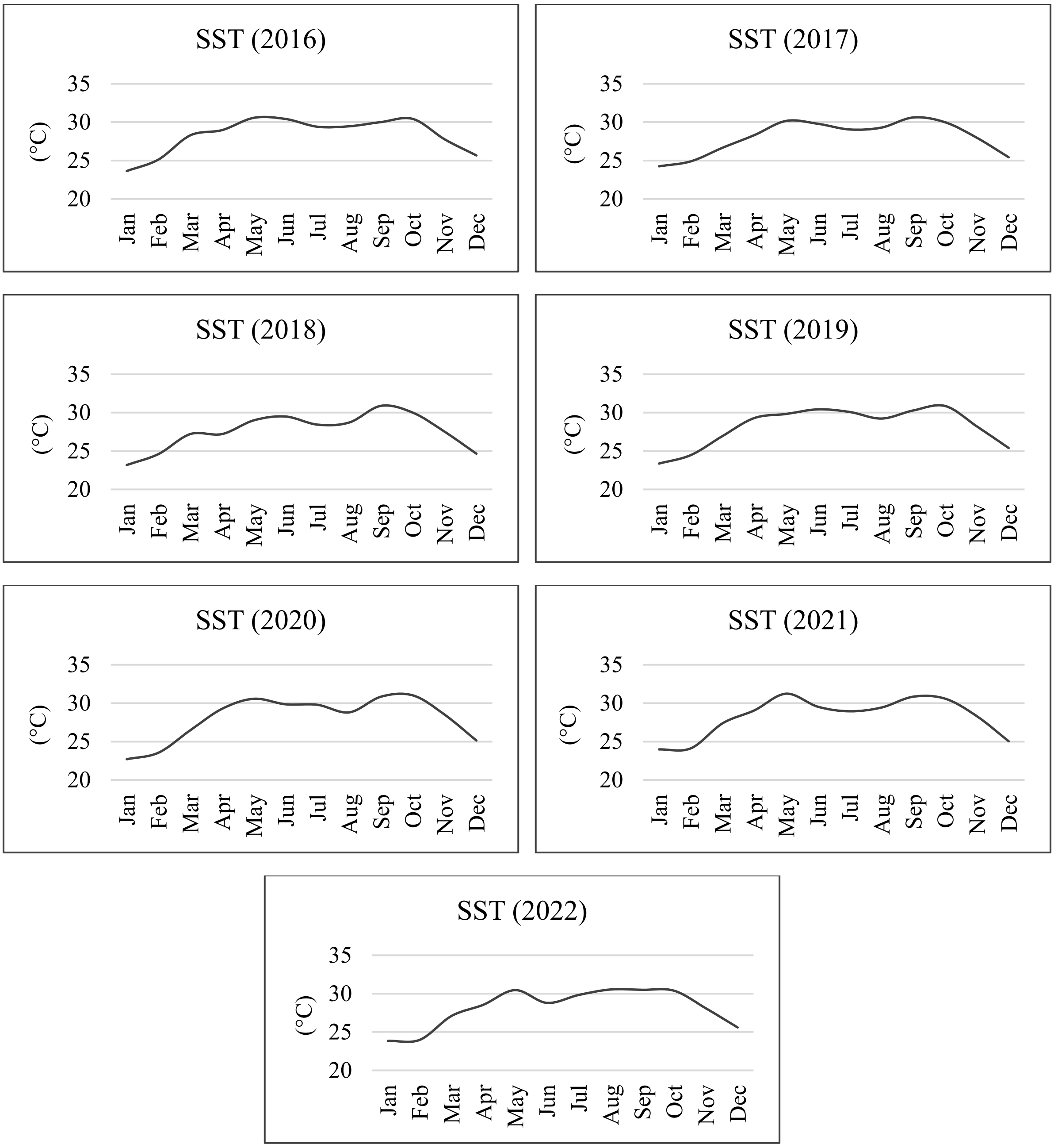

Figure 9: Graphs of annual Kd_490 (2016-2022)

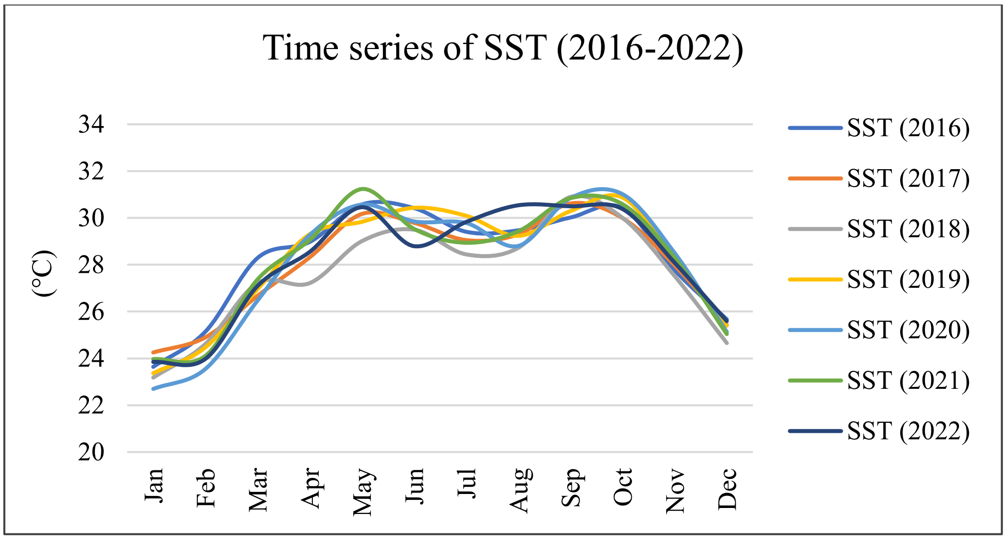

Figure 10: Time series of PAR (2016-2022)

This study presents a comprehensive analysis of the spatial and temporal variability of Photosynthetically Available Radiation (PAR), Diffuse Attenuation Coefficient (Kd_490), and Sea Surface Temperature (SST) in the Bangladesh Exclusive Economic Zone over the period from 2016 to 2022. The findings reveal significant fluctuations in these parameters, which are essential for comprehending the marine biological dynamics in this area.

The observed variability in PAR across the study period, with a high PAR of 55 Einstein/m²/day and low PAR of 32 Einstein/m²/day, suggests a dynamic interplay of atmospheric and oceanographic conditions. (Ocean et al., 2012) observed a high PAR of 47 Einstein/m²/day during 1998 and 2002. Fluctuations in solar radiation have direct implications for primary productivity in the marine ecosystem. Periods of low PAR are indicative of reduced photosynthetic activity, which can impact the base of the food web. This variability might be attributed to monsoonal cycles, cloud cover, and anthropogenic factors like pollution.

In terms of Kd_490, the data shows a trend of increasing water turbidity in certain areas. This increase could be related to land runoff, particularly post-monsoon, and possible anthropogenic activities like overfishing and pollution, leading to changes in phytoplankton composition. The impact of such changes is profound, as it impacts the upper ocean thermodynamics (Mallick et al., 2019) and strongly affects light penetration, influencing both the ecological balance and the heat absorption of the ocean.

The SST data range 22 °C to 31 °C observed from this study indicates a gradual warming trend over the years between 2016-2022, while (Shuva et al., 2022) observed 29.613 °C to 23.446 °C during daytime in the northern Bay of Bengal over the time period of 2000-2019. This subtle rise in SST can have far-reaching consequences, including altering species distributions, impacting weather patterns, and potentially contributing to more frequent and severe tropical storms.

5. Conclusion

The comprehensive analysis of the spatial and temporal variability of Photosynthetically Available Radiation (PAR), Diffuse Attenuation Coefficient (Kd_490), and Sea Surface Temperature (SST) in the Bangladesh Exclusive Economic Zone from 2016 to 2022 reveals critical insights into the dynamic state of this marine environment. This study underscores the interdependent nature of these key environmental parameters and their collective influence on marine ecosystems. The observed trends, particularly the gradual increase in SST and variability in PAR and Kd_490, align with broader global environmental changes, emphasizing the significance of regional studies in global climate change.

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