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Assessment of Fisheries Production in the Major Egyptian Fishing Ports of the Mediterranean Sea Using Remote Sensing Data

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ABSTRACT

Fisheries in the Mediterranean Sea play a critical role in Egypt's economy, yet they face growing challenges from environmental changes, overfishing, and habitat degradation. This study assessed the seasonal and interannual variability of fisheries production in four major Egyptian fishing ports—Port Said, El Arish, Ezbet El Borg, and Borg El Burullus—using 20 years of remote sensing data from the MODIS-Aqua satellite. Key environmental variables, such as sea surface temperature (SST) and chlorophyll-a (Chl-a) concentrations, were analyzed to evaluate their impact on fish production. The results indicate significant spatial and temporal variability in both SST and Chl-a concentrations across the study area, with SST showing an increasing trend over the last two decades, while Chl-a concentrations exhibited a general decline. A negative correlation was observed between SST and Chl-a concentration, suggesting potential shifts in marine productivity. Fisheries data reveal seasonal fluctuations in catch rates, with a decline in total fish production in recent years. This study highlighted the utility of remote sensing as a powerful tool for monitoring and managing fisheries, providing insights that can inform sustainable management practices and policy decisions in the face of climate change and other environmental pressures.

INTRODUCTION

Fisheries are a vital source of food security, employment, and economic revenue in many countries around the world, especially those with significant coastal populations **(Lauria *et al.*, 2018)**. The global fisheries sector supports millions of livelihoods and contributes significantly to nutrition through the supply of protein and essential micronutrients **(Muringai *et al.*, 2022)**. However, this vital resource faces growing challenges, including overfishing, climate change, habitat degradation, and pollution, all of which threaten the sustainability of fish stocks. In recent years, there has been a growing emphasis on assessing fisheries production to ensure that resources are managed effectively and sustainably **(Ali *et al.*, 2022)**. Reliable data on fisheries production is critical for policymakers, researchers, and stakeholders to understand the status of fish stocks, the health of ecosystems, and the impacts of environmental changes on marine resources **(Mahdy *et al.*, 2022; Khaled *et al.*, 2023a; Said *et al.*, 2024)**.

Fisheries play a critical role in Egypt’s economy, providing both food security and livelihoods for millions of people. The country’s Mediterranean coastline, stretching over 1,000 kilometers, is home to several key fishing ports such as Alexandria, Damietta, Port Said, and Rosetta **(Samy, 2015)**. These ports are essential hubs for the fishing industry, with commercial activities ranging from artisanal fishing to large-scale industrial fisheries **(FAO, 2024)**. Egypt's fisheries in the Mediterranean Sea primarily target both pelagic species such as sardines and mackerel, as well as demersal species like mullet and sole. However, in recent years, the fishing industry in the Mediterranean and the Red Sea has been under increasing pressure from various environmental and anthropogenic factors, which include overfishing, habitat degradation, climate change, and pollution **(Enric *et al*., 2018; Khaled *et al*., 2023a; Khaled *et al*., 2023b; Said *et al*., 2024)**.

Traditional methods of assessing fisheries production have historically relied on catch data reported by fishing vessels and surveys conducted by governmental agencies. In Egypt, the Lakes and Fish Resources Protection and Development Agency (LFRPDA) is responsible for collecting and reporting fisheries production data. While such data provides valuable insights into fisheries trends, it has limitations **(Mehanna & Salem, 2011)**. Often, catch data lacks spatial coverage and may not capture the full complexity of marine ecosystems, particularly in relation to environmental factors that influence fish abundance and distribution. Furthermore, the reliance on self-reported catch data introduces a risk of inaccuracies, as fishermen may underreport or overreport catches for various reasons, including economic incentives or compliance with regulations. These challenges underscore the need for more comprehensive approaches to assess fisheries production **(Khalfallah *et al*., 2023)**.

Remote sensing technology, which involves the use of satellite imagery to monitor the Earth's surface and oceans, has emerged as a powerful tool for studying the marine environment **(El Mahrad *et al*. 2020; Ma *et al*. 2023)**. Satellites such as NASA’s Moderate Resolution Imaging Spectroradiometer (MODIS) and the European Space Agency’s Sentinel-3 provide critical data on environmental variables like SST, chlorophyll-a concentration, sea surface height (SSH), and wind patterns **(Gavin *et al*., 2021)**. These data are particularly valuable for fisheries research since they offer comprehensive, continuous, and large-scale coverage of the ocean, allowing researchers to monitor changes in environmental conditions that directly influence fish stocks **(Guillermo & Daniel, 2017)**. By analyzing these variables in conjunction with fisheries catch data, it is possible to identify spatial and temporal patterns in fish productivity, detect the effects of climate variability, and optimize fisheries management strategies **(Gallo *et al*. 2022; Willer *et al*., 2023)**.

The Mediterranean Sea, with its complex oceanographic characteristics, is especially suited for the application of remote sensing in fisheries management **(Emmanuel *et al*., 2011; Amani *et al*., 2022)**. The region experiences a range of seasonal phenomena, including upwelling, changes in water temperature, and nutrient availability, all of which affect fish abundance and distribution. For example, upwelling zones, where nutrient-rich waters rise to the surface, are known to support high levels of primary productivity, creating fertile fishing grounds. Similarly, shifts in SST can cause changes in the migration patterns of pelagic species, while ocean currents and eddies can concentrate fish stocks in certain areas. These factors make the Mediterranean Sea a dynamic environment that requires constant monitoring to ensure the sustainability of fisheries resources **(Bakun *et al*., 2015; Dell’Apa *et al*., 2023)**.

Several studies have demonstrated the utility of remote sensing in fisheries management. For example, SST data have been used to identify suitable habitats for commercially important fish species, while chlorophyll-a concentrations serve as a proxy for phytoplankton abundance, indicating areas of high primary productivity that support fish feeding grounds. Remote sensing also plays a key role in tracking the movement of fish stocks in response to seasonal variations and oceanographic conditions **(Enric *et al*., 2018; Khaled *et al*., 2023a; Khaled *et al*., 2023b; Said *et al*., 2024)**. The integration of remote sensing data into fisheries management frameworks offers an opportunity to address these challenges. By providing large-scale, real-time environmental data, remote sensing can enhance the monitoring of fish stocks, optimize fishing efforts, and mitigate the impacts of overfishing and environmental changes.

This research focused on assessing the fisheries production in Egypt's major Mediterranean ports using remote sensing data. The primary objectives were to: (1) analyze the seasonal and long-term variability in sea surface temperature and chlorophyll-a concentration; and (2) examine the correlation between these environmental factors and fisheries production. Ultimately, the study aimed to provide valuable insights that can guide sustainable fisheries management practices in Egypt's Mediterranean region.

MATERIALS AND METHODS

1 Study area

The study focused on the Egyptian Mediterranean coast, which extended from Ezbet El Borg to El Arish. This region includes key fishing areas, such as the the Nile Delta and its coastal lagoons, where artisanal and commercial fishing activities are concentrated. The Mediterranean waters off the Egyptian coast are characterized by a mix of open sea habitats, coastal ecosystems, and nutrient-rich upwelling zones. The study area was divided into four zones based on the fishing grounds as follows:

1. **Port Said** is located at the northern entrance of the Suez Canal in Egypt and plays an important role in the country's fishing sector due to its strategic position on the Mediterranean Sea.
2. **Ezbet El Borg** includes inland fishing in the Nile Delta, where several canals and freshwater bodies intersect, providing habitats for a variety of fish species.
3. **El Arish** is characterized by its capacity to accommodate a large number of fishing boats.
4. **Port Fouad** is primarily known for its wetland habitats and its significance as a fishing area, rather than for containing several ports (Fig. 1).

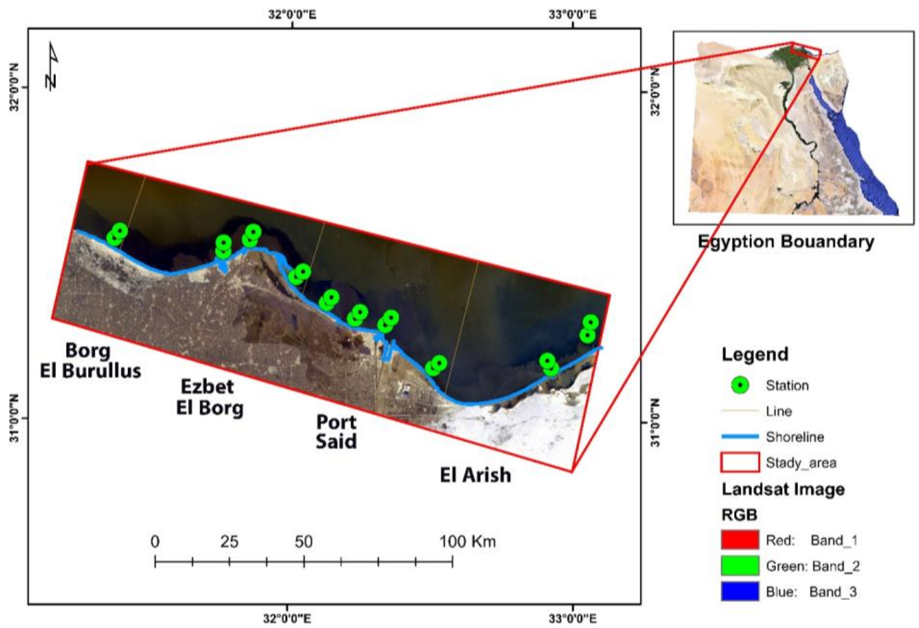


Fig. 1. Map of study area along the Northern Egyptian Mediterranean Coast for fisheries assessment

2. Remote sensing data

The sea surface temperature (SST) and chlorophyll a concentration (Chl-a) data in this study were acquired from MODIS-Aqua (MODIS-A) satellite. Daily data with a spatial resolution of 4km of sea surface temperature and chlorophyll-a from July 2002 to December 2022 (over a 20-year period) were provided from Ocean Color (https://oceancolor.gsfc.nasa.gov/) (Table 1).

3. Fisheries data

Catch data for the most key fish species (sardines, mackerel, and mullets) were obtained from the Lakes and Fish Resources Protection and Development Agency (LFRPDA) and local fisheries organizations. This data were used to correlate environmental conditions with fish catch rates, allowing for the identification of environmental factors influencing fish productivity. Catch data were available monthly, and seasonally from 2002 to 2021 for all fishing ports at the study sites (Table 1).

Table 1. Summary of data sources and parameters used for fisheries assessment

Parameter	Sensor / In situ	Source	Resolution		Period	Image NO.
			Temporal	Spatial		
SST (°C)	MODIS-A	OceanColor Data	Daily	4 Km	2002-2022	7083
Chl-a (mg/m^3)						7100
Fish data (Ton)	Statistical reports /In situ	LFRPDA	Monthly	-	2002-2021	-

4. Data processing and analysis

4.1. Time series analyses of SST and Chl-a

Daily mapped data of SST and Chl-a concentration were atmospherically corrected and subset to the study area using MATLAB and the equation of the time series analyses was performed to calculate seasonal average, climatology and anomalies, as shown in the following equations where Xd = daily average in season; nd = number of days in season; Xs = seasonal average in year i; ns= number of seasons in year; nc = Count of specific season x; i= seasons; j= number of years:

$$\text{Seasonal Mean } (Xs) = \frac{\sum_{i=1}^{n_d} Xd_i}{n_d}$$

$$\text{Climatology } (SC) = \frac{\sum_{i=1}^{n_c} Xs_i}{n_c}$$

$$\text{Anomalies } (A) = Xs_{ij} - Sc_i$$

Temporal analysis was performed to assess seasonal variations in these parameters over the course of the study period by using MATLAB programming code script **(Hu *et al*., 2002; Khaled *et al*., 2023b; Khaled *et al*., 2023a., Said *et al*, 2024)**.

5. Statistical analysis

Correlation analysis and regression was performed to evaluate the relationship between environmental variables (SST, chlorophyll-a) and fish catch rates. Seasonal trends were analyzed to identify key periods of high productivity and suitable fishing grounds.

RESULTS

1. Seasonal patterns of sea surface temperature

The analysis of SST data revealed significant seasonal variations along the Egyptian Mediterranean coast. The SST shows an upward trend in all regions and seasons over the 20-year period. This is especially evident in summer and autumn where the temperatures have increased significantly. In 2022, summer SSTs reached 28.2 to 29.3°C, compared to the lower values in the early 2000s, showing a general warming of around 1°C over two decades (Table 2). El Aresh consistently records higher temperatures compared to the other regions, especially during summer and autumn. Borg El Burullus tends to show slightly cooler temperatures in comparison to the other regions, particularly during winter and spring. Summer has the highest SST values, with El Aresh reaching temperatures as high as 29.7°C in 2012 (Fig. 2), which is also the warmest summer for all regions. Winter has the lowest SSTs, with Port Said reaching as low as 15°C in 2011. The temperatures in spring and autumn act as transition points, with increasing trends, though they are milder than in summer.

The winter season shows relatively stable SSTs across all regions, with an average around 16 to 18°C. Notable lows in 2011, with Port Said registering the lowest SST at 15°C. The warmest winters were observed in 2017 and 2020, where temperatures ranged between 17.8 and 18.3°C. Spring shows gradual warming over the years, with SSTs around 21 to 24°C by 2022. The highest spring SSTs were observed in 2017 in El Aresh at 23°C. Port Said shows a relatively higher increase compared to the other regions, with its SST rising from 22.4 in 2002 to 23.7°C in 2021. Summer SSTs exhibit the highest values, with temperatures reaching up to 29.7°C in 2012 for El Aresh. Port Said and Izbet el Borg follow closely behind, with temperatures ranging around 28.7 to 29.5°C in the later years. Summer SSTs in Borg El Burullus have been consistently cooler, but even here, they rose from 29°C in 2002 to 29.3°C in 2022. Autumn SSTs are close to those in summer but slightly cooler, ranging from 23.3 to 25.5°C over the years. 2020 was an unusually warm autumn, especially in El Aresh, where temperatures reached 25.5°C. Borg El Burullus again shows cooler SSTs but still follows the warming trend over time. The year 2012 was the warmest year overall for all regions, especially during the summer and autumn months. El Aresh consistently shows the highest SSTs across seasons, with temperatures regularly exceeding those in the other regions, likely due to its geographical location. Port Said also shows significant warming, particularly in summer, where it frequently reaches 29°C and above. Borg El Burullus, while cooler in comparison, shows a consistent increase in SST over the years, indicating that the warming trend affects all regions. The total means indicate the overall trends of sea surface temperature (SST) across all regions in winter, with the average SST being about 17.3 ± 0.67°C, and El Arish being the warmest on average. In spring, the SST rises to around 22 to 23°C, with Ezbet El Borg slightly warmer than the other regions. The highest SSTs are observed in summer, averaging around 28.1 to 29°C across all regions, with El

Arish consistently being the hottest. SSTs drop slightly in autumn but remain warm, averaging around 24°C across the regions (Figs. 2, 4).

2. Seasonal patterns of chlorophyll-a concentrations

Chlorophyll-a, an indicator of phytoplankton abundance, helps assess the health of aquatic ecosystems. Port Said consistently has the highest concentrations, especially in spring and autumn, indicating high phytoplankton productivity. In contrast, El Arish shows lower, more stable values. Izbet El Borg and Borg El Burullus have intermediate levels, fluctuating between El Arish and Port Said. Winter and spring generally have higher concentrations, with spring being the most productive season. Summer has the lowest values, likely due to higher temperatures reducing phytoplankton growth, while autumn shows a slight rebound as temperatures cool (Table 3). Chl-a concentrations remain relatively stable across all locations from 2002 to 2009, with moderate values across all seasons. While the years 2010 and 2013 are notable for sharp increases in spring Chl-a concentrations, particularly at Port Said, where the concentration reached 7.2mg/ m^3 in 2010 and 8.2mg/ m^3 in 2013 (Table 3). These spikes could indicate environmental changes, such as nutrient upwelling or shifts in oceanographic conditions that promoted phytoplankton blooms. A dip in Chl-a concentrations is evident across locations at 2017 and 2018, especially in winter and spring. This decline may point to changes in water quality, temperature, or other environmental factors limiting phytoplankton growth. On the other hand, a resurgence in Chl-a concentrations at 2020 and 2021, particularly at Port Said during winter and spring, is observed, with concentrations as high as 6.5mg/ m^3 in spring 2020 and 6.8mg/ m^3 in winter 2021 (Figs. 3, 4).

Port Said location exhibits the highest Chl-a concentrations throughout the years, particularly in spring and winter, indicating that conditions here favor higher phytoplankton productivity. This might be due to its proximity to nutrient inputs or upwelling zones. El Arish exhibits the lowest Chl-a concentrations, indicating lower productivity levels. This might be due to the eastern location or specific environmental conditions less favorable for phytoplankton blooms. The Chl-a concentrations at Izbet El Borg are relatively stable and close to the values of Borg El Burullus, suggesting a moderate productivity level. However, it does not reach the high productivity of Port Said. While Borg El Burullus shows a slightly higher productivity than El Arish and Izbet El Borg, especially in spring and autumn, but still lower than Port Said. The variability in Chl-a concentrations could be influenced by changes in temperature, nutrient availability, water circulation patterns, and seasonal events (like stratification or upwelling). The higher productivity in spring and winter could be linked to cooler water temperatures and nutrient mixing in coastal waters, promoting phytoplankton growth. The sharp spikes in productivity in some years (e.g., 2010, 2013) suggest the influence of specific events or conditions that promoted unusually high phytoplankton blooms. Port Said stands out as the most productive area, especially in spring. El Arish is the least productive area, indicating different environmental or oceanographic conditions.

There is clear seasonal variability, with higher Chl-a concentrations in winter and spring, and summer consistently showing the lowest values across all locations. The spikes in productivity in 2010 and 2013 are significant, indicating potential events that caused large phytoplankton blooms. The overall long-term trend shows relatively stable productivity, but with occasional notable fluctuations that warrant further investigation into potential environmental drivers.

3. Seasonal patterns of fish production

Seasonal mean fish production (in tons) for the four studied regions along Egypt's Mediterranean coastline from 2002 to 2021 spans spring, autumn, winter, and summer (Table 4). The general trends indicate that Port Said consistently exhibits the highest fish production across all seasons, underscoring its importance in fish productivity. Borg El Burullus tends to have moderate to high fish production, with fluctuations observed between years and seasons. Izbet El Borg shows intermediate production, with noticeable peaks in certain years. El Arish consistently records the lowest production, except for a few years with increases (e.g., 2012, 2017).

In spring, Port Said demonstrates a significant range, with production fluctuating between 1,697 tons in 2007 and 8,135 tons in 2009. El Arish peaks at 575 tons in 2012. Borg El Burullus and Izbet El Borg show more moderate but stable trends, with production increasing in later years, particularly from 2019 to 2021. Notably, Port Said reached its peak in 2009 at 8,135 tons.

In autumn, Port Said again shows the highest production, with peaks of 6,304 tons in 2007 and 7,360 tons in 2017. El Arish maintains low production in most years, with occasional increases, such as 804 tons in 2003 and 883 tons in 2008. Borg El Burullus exhibits consistent autumn production, ranging from 256 tons in 2002 to 3,649 tons in 2020, with a significant increase in 2017 for Port Said (7,360 tons).

In winter, Port Said stands out with peaks of over 5,000 tons in both 2007 and 2008. El Arish shows a notable dip, recording just 7 tons in 2021. Borg El Burullus had lower production in earlier years, but saw a steady increase starting in 2009, peaking at 3,791 tons in 2021. Izbet El Borg also shows a consistent increase, with peaks in 2007 and 2008.

In summer, Port Said remains dominant, with production exceeding 7,000 tons in both 2007 and 2009. El Arish registers notably lower summer production, often below 100 tons in recent years. Borg El Burullus shows variability, with peaks of 3,649 tons in 2020 and 3,440 tons in 2019. Izbet El Borg demonstrates moderate production, with some increases in later years (Table 4).

Table 2. Seasonal means ± standard deviation of sea surface temperature (°C) from four studied locations (2002-2022)

Year	**Winter**				**Spring**				**Summer**				**Autumn**			
	EA	**PS**	**IB**	**BB**	**EA**	**PS**	**IB**	**BB**	**EA**	**PS**	**IB**	**BB**	**EA**	**PS**	**IB**	**BB**
2002	17.1±0.78	16.6±0.78	16.6±0.66	16.4±0.9	21.8±2.7	22.4±3.18	22.6±3.17	23.1±3.21	28.4±0.6	28.7±0.71	28.9±0.87	29±0.97	24.4±2.8	24.1±3	23.8±3.11	23.5±3.3
2003	16.8±0.88	16.4±1.12	16.4±1.14	16.1±1.25	21.5±2.46	22.4±2.51	22.5±2.61	23±2.64	27.7±0.62	28.1±0.67	28.5±0.64	28.7±0.67	23.4±2.93	23.2±3.25	23.1±3.45	22.7±3.78
2004	16.9±0.93	16.5±1.34	16.7±1.16	16.3±1.5	21.5±3.1	22.3±2.73	22.8±2.82	22.8±3.03	27.5±0.45	28±0.57	28.3±0.59	28.5±0.73	24.9±3.04	24.8±3.4	24.8±3.42	24.6±3.62
2005	17±0.72	16.7±0.94	16.8±0.92	16.6±1.17	22±2.74	22.4±2.7	22.8±2.87	23.1±3.02	27.4±0.76	27.8±0.85	28.3±0.76	28.5±0.9	23.3±2.59	23.3±2.71	22.6±2.71	22.2±2.75
2006	17±0.57	16.8±0.79	16.9±0.64	16.7±1.01	21.4±2.89	21.7±3.05	22.2±3.08	22.4±3.11	27.7±0.3	28±0.34	28.3±0.28	28.5±0.25	23.6±3.06	23.1±3.18	23.2±3.36	22.3±3.52
2007	17±1.11	16.6±1.43	16.8±1.64	16.4±1.87	22.6±2.17	23.1±2.78	23.5±2.56	23.9±2.79	27.9±0.62	28.4±0.86	28.7±0.62	28.8±0.63	23.6±2.95	23.6±3.25	23.6±3.37	23.3±3.52
2008	17±0.42	16.6±0.59	16.6±0.64	16.3±0.81	21.9±3.09	22.7±3.28	23±3.21	23.3±3.46	28±0.13	28.4±0.27	28.8±0.33	29±0.53	23.2±2.35	23.1±2.46	23.3±2.67	23.3±2.71
2009	17.8±0.49	17.4±0.55	17.8±0.71	17.5±0.95	22.1±2.42	22.6±2.47	23.3±2.44	23.7±2.56	28±0.69	28.4±0.86	28.9±0.88	29.1±0.94	23.7±3.09	23±3.31	23.2±3.28	23.1±3.3
2010	17.7±0.56	17.5±0.72	17.4±0.66	17.2±0.45	21.2±2.96	21.9±3.21	22.6±2.82	23.1±2.79	27.9±0.71	28.2±0.68	28.9±0.64	29.1±0.69	25.3±2.58	24.6±2.75	24.9±2.9	24.6±3.06
2011	16±0.91	15.4±1.2	15.5±1.11	15±0.74	22.1±2.88	22.6±2.89	22.6±2.93	23.1±2.86	27.7±0.3	28±0.28	28.2±0.36	28.3±0.37	24.1±3.3	23.8±3.5	22.9±3.48	22.5±3.52
2012	17.7±0.33	17.4±0.59	17.7±0.88	17.3±1.46	22.5±2.71	22.9±3.01	23.1±2.91	23.6±3.14	28.8±0.61	29.2±0.72	29.6±0.71	29.7±0.75	24.9±3.34	24.9±3.71	24.2±3.66	24±3.79
2013	17.8±0.44	17.6±0.62	17.7±0.69	17.5±0.78	22.4±2.32	23.1±2.38	23.4±2.6	23.8±2.78	27.8±0.65	28.2±0.71	28.6±0.56	28.8±0.58	23.5±2.45	23.2±2.72	23.7±2.65	23.3±2.63
2014	17.5±0.97	17.4±1.19	17.5±1.22	17.2±1.3	22±2.78	22.5±2.91	22.4±2.87	22.9±3.02	27.8±0.4	28.2±0.45	28.7±0.32	28.9±0.39	24.3±2.75	23.6±2.84	23.9±2.9	23.5±3.01
2015	18±0.61	17.7±1.03	18±1.05	17.8±1.27	22.1±2.71	23.3±2.58	22.8±2.57	23±2.8	28.4±0.68	29±0.68	29.2±0.76	29.3±0.79	25.1±3.63	24.8±3.63	25±3.53	24.5±3.8
2016	16.8±0.72	16.5±1.18	16.5±1.26	16.1±1.41	22.1±2.41	22.6±2.65	23.2±2.63	23.5±2.69	28.2±0.29	28.6±0.38	28.9±0.3	29.1±0.38	24.8±3.24	24.3±3.65	24±3.68	24±3.7
2017	18.3±0.87	18±1.23	18.3±1.46	18±1.62	23±2.74	23.4±2.81	23.9±2.63	24.1±2.71	28.5±0.65	28.8±0.74	29.2±0.74	29.4±0.92	23.7±2.21	23.3±2.34	23.7±2.42	23.3±2.44
2018	16.8±0.61	16.5±1.03	16.7±1.05	16.5±1.27	21.5±3.44	22.2±3.53	22.1±3.63	22.4±4.06	28.4±0.33	28.8±0.32	29.1±0.32	29.3±0.34	24.1±2.98	23.5±3.27	23.3±3.25	23±3.35
2019	17.4±0.52	16.9±0.88	16.9±0.94	16.7±1.26	21.4±2.46	22.0±2.23	22.4±2.31	22.6±1.98	28.5±0.54	29±0.68	29.3±0.51	29.5±0.62	24.6±3.51	24.4±3.57	24.5±3.76	24.1±3.67
2020	18.3±0.5	18.2±0.32	18.3±0.27	17.9±0.33	22.4±3.04	23.2±3.32	23.8±3.28	24.2±3.72	27.9±0.38	28.3±0.19	28.7±0.26	29±0.25	25.5±3.08	24.6±3.25	24.4±3.42	23.9±3.65
2021	16.7±0.49	16.2±0.11	16.4±0.2	16.2±0.31	22.9±2.74	23.7±2.65	23.8±2.88	24.2±2.96	28.6±0.73	28.9±0.87	29.3±0.87	29.5±0.96	23.7±2.86	23.4±2.96	23.7±3.03	23.3±3.71
2022	18.1±1.01	17.9±0.93	18.2±0.89	18±0.98	21.8±1.38	22.2±1.3	22.2±1.14	22.5±1.28	28.2±0.47	28.7±0.57	29.1±0.63	29.3±0.78	24±2.43	23.8±2.55	23.9±2.6	23.7±2.62
Total mean	**17.3±0.67**	**17±0.86**	**17.1±0.89**	**16.8±1.06**	**22.0±2.67**	**22.6±2.77**	**22.9±2.76**	**23.3±2.89**	**28.1±0.52**	**28.5±0.59**	**28.8±0.57**	**29±0.64**	**24.2±2.91**	**24±3.11**	**24±3.17**	**23±3.31**

EA =El Aresh, **PS** = Port Said, **IB** = Izbet el Borg, **BB**= Borg El Burullus.

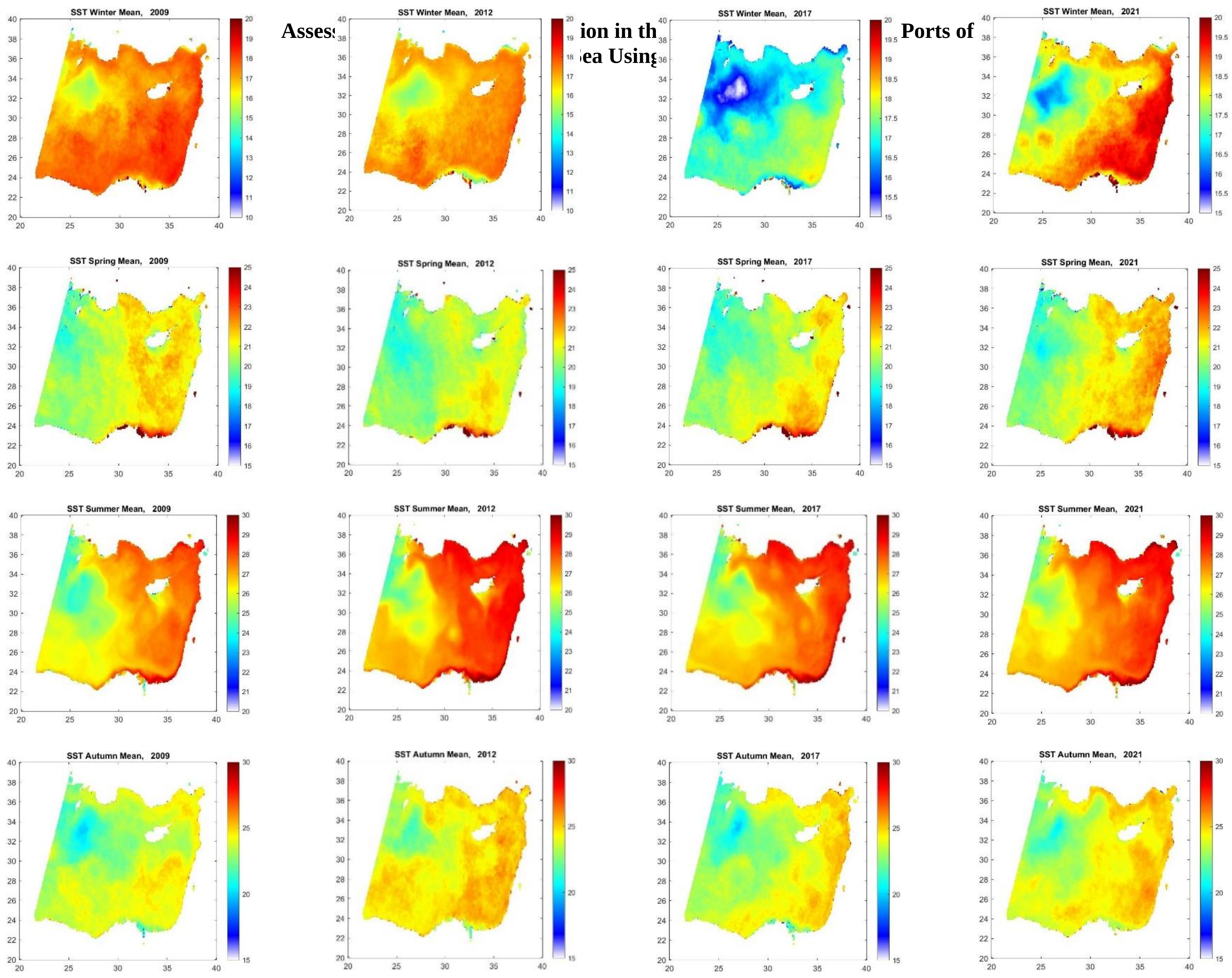


Fig. 2. Maximum and minimum seasonal mean of sea surface temperature (SST)

Table 3. Seasonal means ± standard deviation of chlorophyll-a (Chl-a) concentration (mg/m³) from four studied locations (2002-2022)

Year	Winter				Spring				Summer				Autumn			
	EA	**PS**	**IB**	**BB**	**EA**	**PS**	**IB**	**BB**	**EA**	**PS**	**IB**	**BB**	**EA**	**PS**	**IB**	**BB**
2002	3.7±0.28	4.6±0.43	4.0±0.15	4.0±0.1	2.6±0.52	3.8±0.17	3.1±0.34	3.1±0.27	2.9±0.47	4.3±0.9	3.4±0.1	3.4±0.16	3.2±0.21	4.5±0.42	4.0±0.15	3.7±0.4
2003	3.7±0.04	4.8±0.38	3.8±0.08	3.6±0.21	3.0±0.21	4.7±0.82	3.6±0.29	3.7±0.35	2.7±0.27	3.9±0.16	3.2±0.27	3.2±0.24	3.3±0.09	4.9±0.29	4.3±0.43	4.2±0.44
2004	3.3±0.15	4.5±0.99	3.5±0.04	3.4±0.31	3.1±0.7	4.5±0.54	3.4±0.24	3.6±0.31	2.4±0.38	4.1±0.62	3.3±0.28	3.3±0.21	3.0±0.75	4.9±0.62	3.8±0.03	3.3±0.05
2005	3.4±0.25	4.7±0.43	3.6±0.2	3.5±0.3	2.6±0.44	4.0±0.21	3.5±0.21	3.5±0.18	2.2±0.55	4.0±0.24	3.2±0.42	3.2±0.33	3.1±0.2	4.2±0.55	3.9±0.2	3.8±0.28
2006	3.5±0.3	3.9±0.21	3.5±0.25	3.2±0.15	2.7±0.56	4.0±0.1	3.5±0.33	3.6±0.38	2.8±0.06	4.3±0.18	3.5±0.33	3.3±0.41	2.5±0.33	4.5±0.49	4.2±0.4	3.6±0.26
2007	3.7±0.28	4.8±0.64	4.0±0.03	4.1±0.14	2.6±0.8	3.9±0.28	3.3±0.08	3.5±0.27	1.9±0.45	3.9±0.23	3.3±0.14	3.2±0.3	3.9±0.41	5.6±0.82	4.3±0.24	4.1±0.14
2008	3.7±0.31	4.6±0.58	4.4±0.51	4.2±0.49	2.6±0.56	4.3±0.4	3.2±0.36	3.3±0.21	2.4±1.02	4.4±1.57	3.4±0.33	3.2±0.67	4.1±0.5	5.8±0.86	4.6±0.21	4.5±0.35
2009	3.5±0.31	5.1±1.4	4.1±0.18	4.0±0.4	2.7±0.55	3.8±0.54	3.3±0.4	3.4±0.37	2.5±0.32	3.9±0.23	3.5±0.07	3.6±0.13	3.5±0.37	5.2±0.55	4.1±0.17	4.3±0.25
2010	4.2±0.55	7.2±0.94	4.1±0.17	4.2±0.38	3.2±0.57	4.2±0.29	3.4±0.16	3.6±0.2	2.3±0.86	3.5±1.29	3.3±0.27	3.1±0.24	3.9±0.32	6.8±1.52	3.8±0.27	3.6±0.37
2011	3.7±0.17	4.9±0.31	3.8±0.1	3.8±0.29	2.2±0.12	3.8±0.13	3.2±0.45	3.1±0.28	2.3±0.36	3.8±0.27	3.4±0.27	3.1±0.08	3.0±0.1	4.7±0.66	4.1±0.31	3.8±0.14
2012	3.6±0.23	4.2±0.26	4.1±0.38	3.7±0.22	2.7±0.54	4.0±0.44	3.6±0.18	3.5±0.19	2.4±0.64	3.9±0.56	3.3±0.22	3.4±0.2	4.2±1.44	5.4±1.73	3.7±0.54	3.5±0.56
2013	4.2±0.37	8.2±2.41	3.5±0.25	3.5±0.3	2.9±0.46	4.0±0.43	3.4±0.11	3.2±0.13	2.1±0.47	3.4±0.24	3.3±0.21	3.2±0.15	3.1±0.57	4.3±0.31	4.5±0.32	3.8±0.32
2014	3.8±0.17	5.3±0.53	4.1±0.12	3.8±0.41	2.7±0.74	4.3±0.42	3.7±0.41	3.6±0.12	2.5±0.33	3.6±0.37	3.3±0.35	3.2±0.29	3.9±0.43	5.0±0.86	4.1±0.55	3.8±0.39
2015	3.7±0.12	4.9±0.54	4.0±0.21	3.8±0.1	3.0±0.43	4.1±0.24	3.4±0.21	3.3±0.24	2.2±0.63	4.0±0.88	3.4±0.09	3.6±0.31	3.6±0.67	5.5±0.47	4.2±0.91	3.8±1.2
2016	3.4±0.14	4.3±0.52	4.2±0.16	3.8±0.06	3.1±0.55	4.5±0.28	3.7±0.22	3.6±0.28	2.1±0.15	3.4±0.19	3.3±0.24	3.2±0.2	2.2±0.22	3.7±0.28	3.3±0.25	3.3±0.24
2017	3.0±0.24	5.0±1.44	3.7±0.14	3.7±0.06	3.6±0.49	4.5±0.61	3.6±0.18	3.3±0.33	2.6±0.12	3.9±0.19	3.3±0.53	3.3±0.31	1.9±0.59	3.5±1.96	3.1±0.14	3.1±0.16
2018	2.8±0.16	4.1±0.43	3.5±0.08	3.4±0.34	3.4±0.93	4.0±0.46	3.4±0.5	3.4±0.41	2.6±0.1	4.3±0.19	3.6±0.07	3.5±0.1	1.9±0.33	3.3±0.25	3.2±0.11	3.3±0.37
2019	4.3±0.42	5.9±0.06	4.0±0.14	3.7±0.17	3.9±0.46	4.7±0.09	4.6±0.21	4.4±0.39	3.0±0.13	4.1±0.06	3.6±0.43	3.4±0.35	2.3±0.64	3.6±0.96	3.5±0.15	3.6±0.39
2020	3.5±0.45	5.2±0.76	4.3±0.08	5.8±0.11	4.5±1.04	6.5±1.75	3.8±0.47	3.8±0.46	3.4±0.35	4.3±0.92	4.0±0.89	3.8±1.86	2.1±1.22	3.6±1.18	3.5±0.2	3.5±2.2
2021	4.6±0.15	6.8±0.51	5.2±0.09	4.7±0.08	3.8±0.64	5.0±0.48	4.2±0.13	3.9±0.12	2.6±0.65	3.9±0.57	3.4±0.19	3.6±0.5	2.5±1.05	3.9±1.73	3.6±0.89	3.9±0.24
2022	4.0±0.27	5.8±0.41	4.4±0.54	4.8±0.73	3.8±0.45	4.7±1.01	4.1±0.48	3.9±0.62	2.6±0.84	3.7±1.24	3.6±0.18	3.7±0.16	2.0±0.51	3.6±0.61	3.9±0.21	3.6±0.19
Total mean	**3.7±0.25**	**5.2±0.67**	**4.0±0.18**	**3.9±0.25**	**3.1±0.56**	**4.3±0.46**	**3.6±0.28**	**3.5±0.29**	**2.5±0.44**	**3.9±0.53**	**3.4±0.28**	**3.4±0.34**	**3.0±0.52**	**4.6±0.82**	**3.9±0.32**	**3.7±0.43**

EA =El Aresh, **PS** = Port Said, **IB** = Izbet el Borg, **BB**= Borg El Burullus

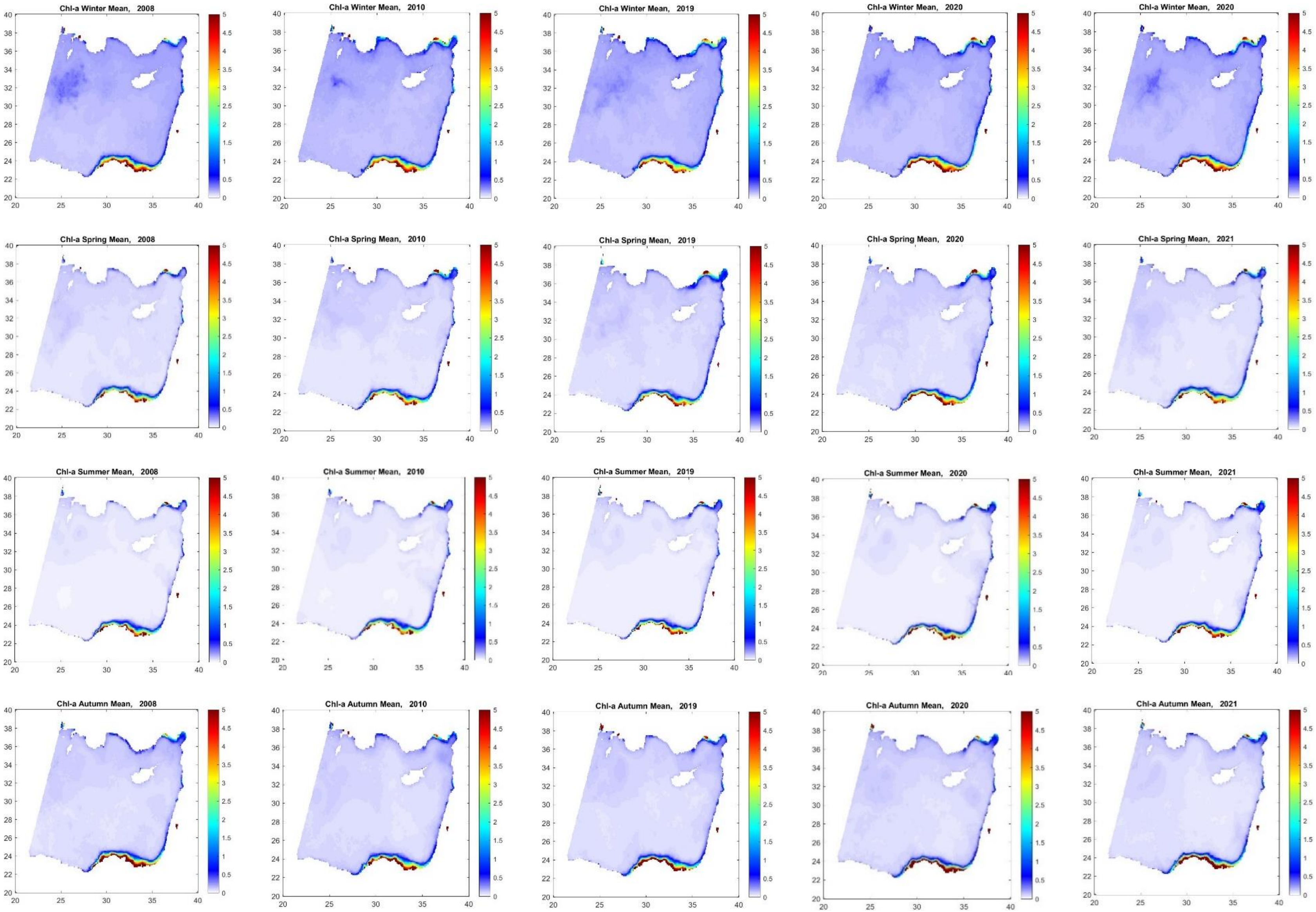
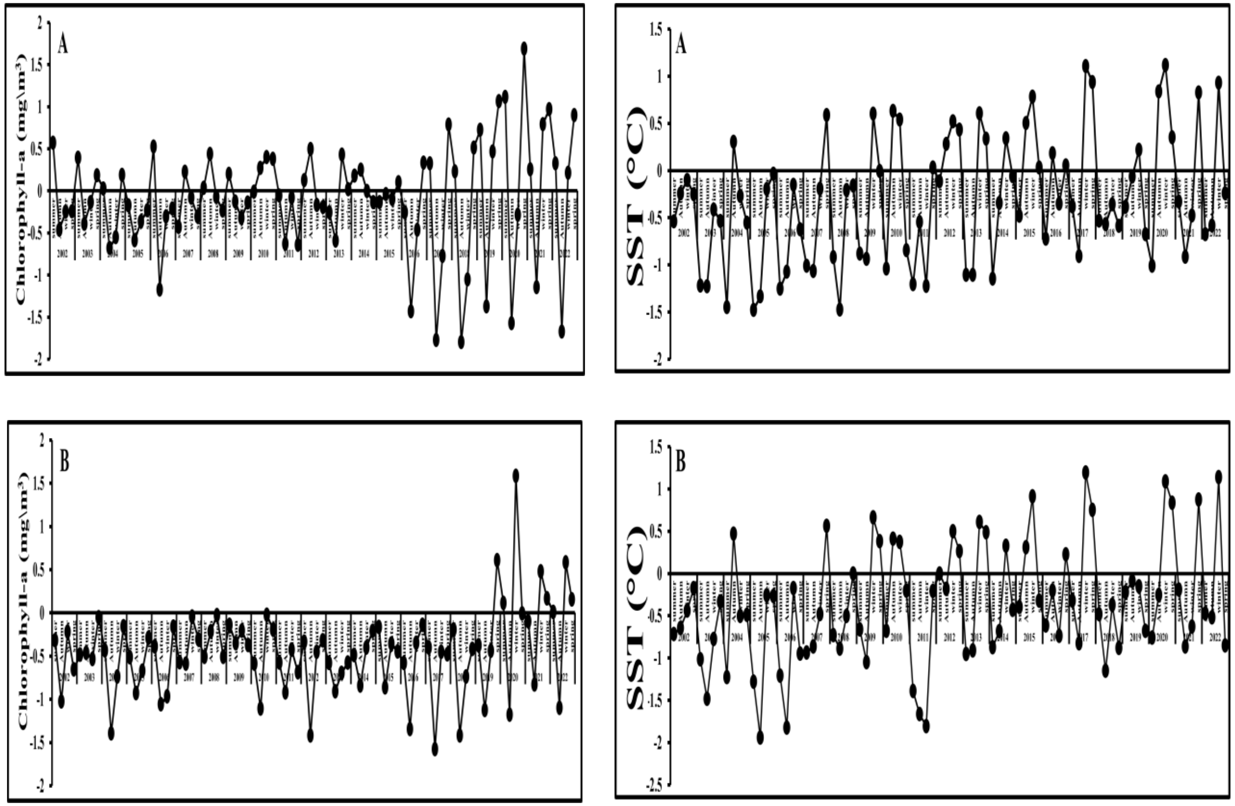


Fig. 3. Maximum and minimum seasonal mean of chlorophyll-a (Chl-a) concentration (mg/m³)

Table 4. Seasonal means of fish production (tons) from four studied locations (2002-2022)

Year	Spring				Autumn				Winter				summer			
	EA	PS	IB	BB	EA	PS	IB	BB	EA	PS	IB	BB	EA	PS	IB	BB
2002	103	2935	4162	196	178	3241	5094	256	549	2480	5832	115	670	2744	6112	239
2003	97	2020	3313	222	804	3381	2599	250	330	1864	2063	178	169	3935	3925	243
2004	87	2618	2318	288	695	4200	4473	333	287	1979	1987	213	148	3508	3610	335
2005	80	3414	2724	430	611	3440	3414	581	248	3461	4122	242	130	4196	4251	431
2006	124	2762	2348	1448	858	3722	3506	1609	152	2807	5064	814	2324	3502	4242	1429
2007	63	2347	1697	1703	833	6304	7614	3008	431	2124	6249	2764	1011	7351	5709	2764
2008	153	2101	2774	1763	883	5926	6835	1803	286	4920	7588	3086	2274	5035	9224	2330
2009	171	2341	3578	1763	473	3725	8135	3090	558	4272	4820	3086	463	4230	9417	2904
2010	199	2215	2989	1626	294	3368	6661	2873	274	3217	6587	2860	357	4210	9340	2757
2011	290	3086	4624	1984	437	2986	4535	3355	106	2932	4791	3084	463	2933	9747	3209
2012	575	2756	4348	2991	535	3296	3895	2972	196	2611	2359	2958	819	2964	6212	3059
2013	565	2808	2560	2904	672	2842	3977	3096	209	2380	885	2698	438	3080	6904	3009
2014	327	2961	5326	2908	282	3204	3269	3143	279	3269	1517	2772	799	3102	6835	3026
2015	151	3440	3952	3031	604	3734	2706	2808	148	2876	1243	2776	474	3527	6573	3282
2016	239	3665	2169	3090	336	3480	2475	2646	282	3257	528	2797	615	4024	5687	3350
2017	246	3225	2549	3131	367	3442	7360	2676	244	3017	594	2763	509	3405	6900	3363
2018	0	4115	2502	3114	80	2828	6304	2299	90	3383	507	2007	16	3421	7336	3168
2019	81	2589	2659	3417	32	2606	4250	2283	86	1298	667	1633	16	3260	5680	3440
2020	47	2859	2871	3390	33	2487	4679	2201	34	1535	810	1238	0	2949	7543	3649
2021	157	1394	3142	2810	162	3277	5161	1968	7	1893	917	1711	86	3441	8401	3791

EA =El Aresh, PS = Port Said, IB = Izbet el Borg, BB= Borg El Burullus.


A
Chlorophyll-a (mg\m³)
A
SST (°C)
B
Chlorophyll-a (mg\m³)
B
SST (°C)

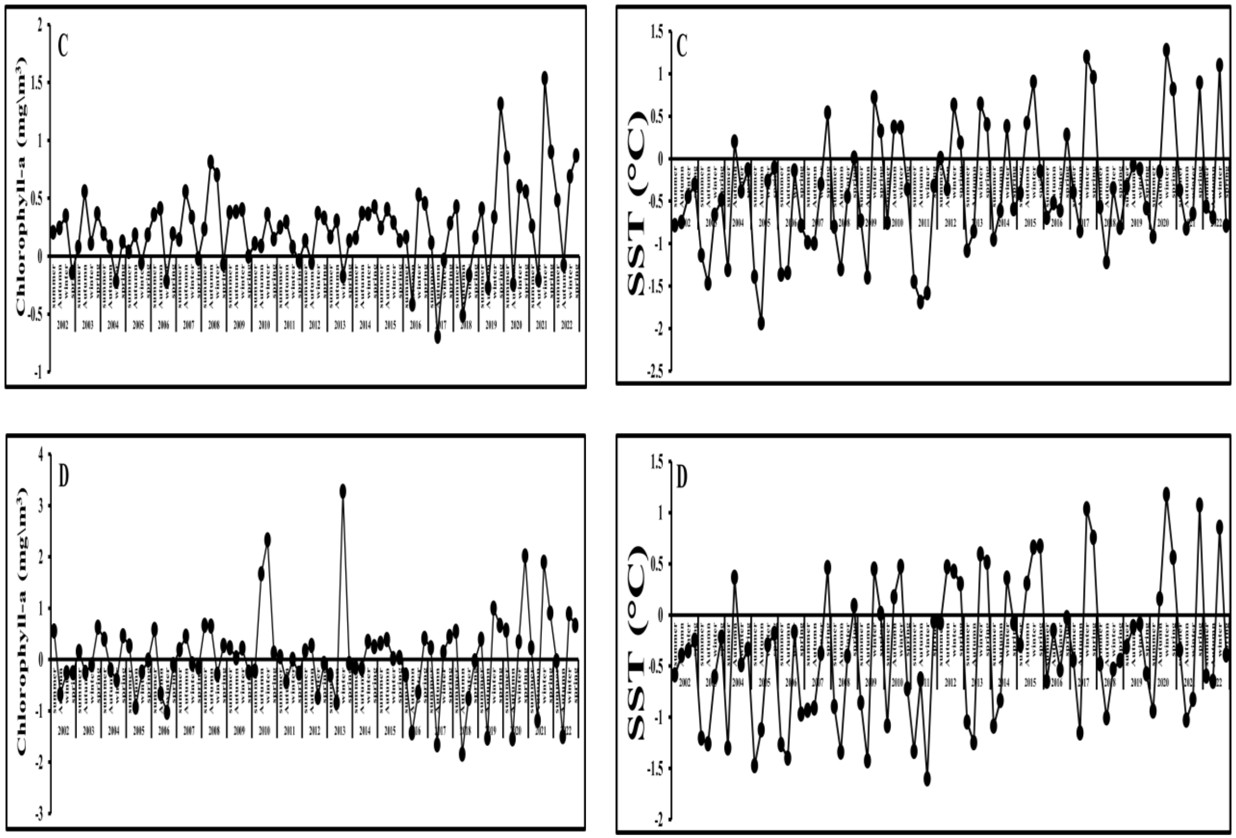


Fig. 4. Seasonal mean anomalies of SST and Chl a; A= Al Aresh B= Borg El Burullus C= Izbet El Borg D= Port said

4. Relationship between environmental variables and fish production

The correlation analysis revealed a strong positive relationship between chlorophyll-a concentrations and fish catch rates, particularly for pelagic species like sardines and mackerel. Fish catches were highest during spring and autumn, coinciding with periods of high phytoplankton productivity. SST also influenced fish distribution, with certain species preferring cooler waters during the winter and spring months.

The relationship between sea surface temperature and chlorophyll a concentration during the seasonal period from 2002 to 2021 in fishing areas is shown in Figs. (5, 6). Predictions of temperature change and chlorophyll a concentration response showed that correlation analysis followed by regression analysis indicated a negative relationship between sea surface temperature increase and chlorophyll a concentration, especially in the Arish and Port Said areas. Statistical analyses also revealed statistically significant differences in the sea surface temperature trend when compared between seasons. On the other hand, there was a noticeable variation in chlorophyll a concentration.

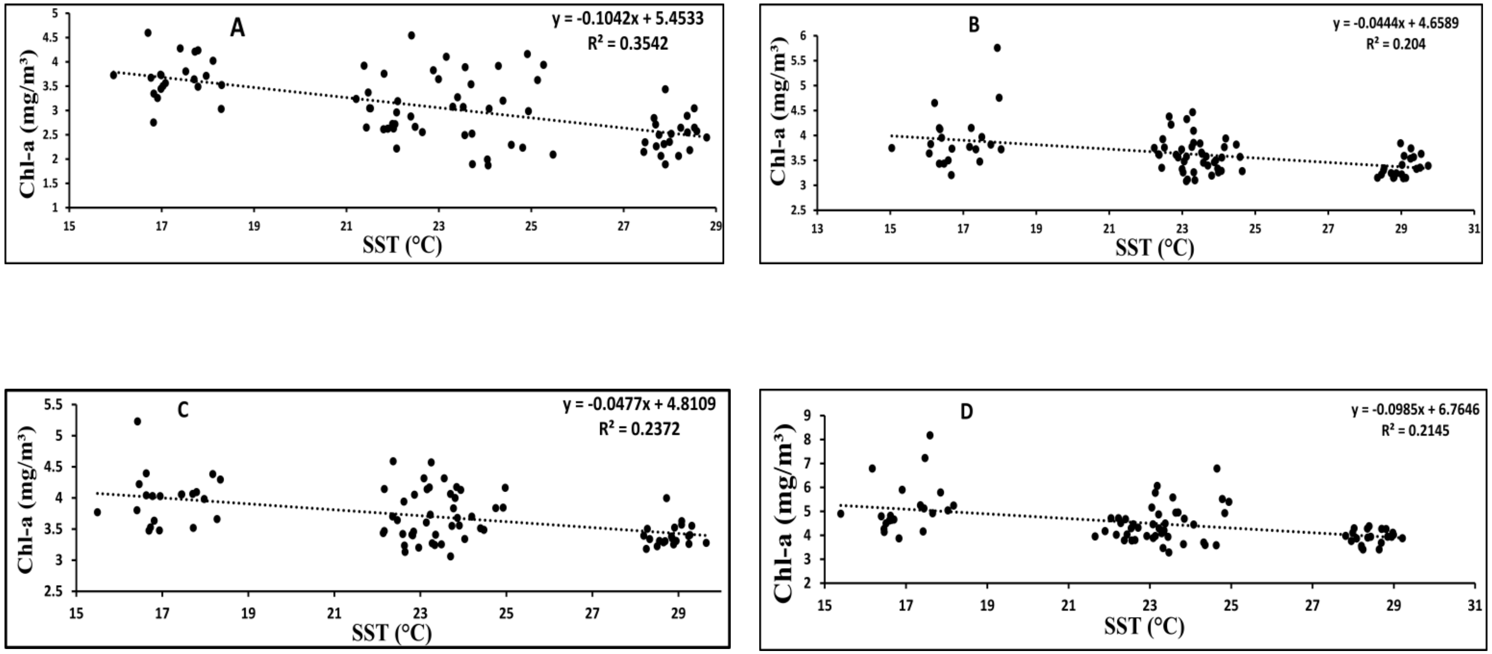


Fig. 5. Relationship between Chl a and SST in A= Al Aresh B= Borg El Burullus C= Izbet El Borg D= Port said

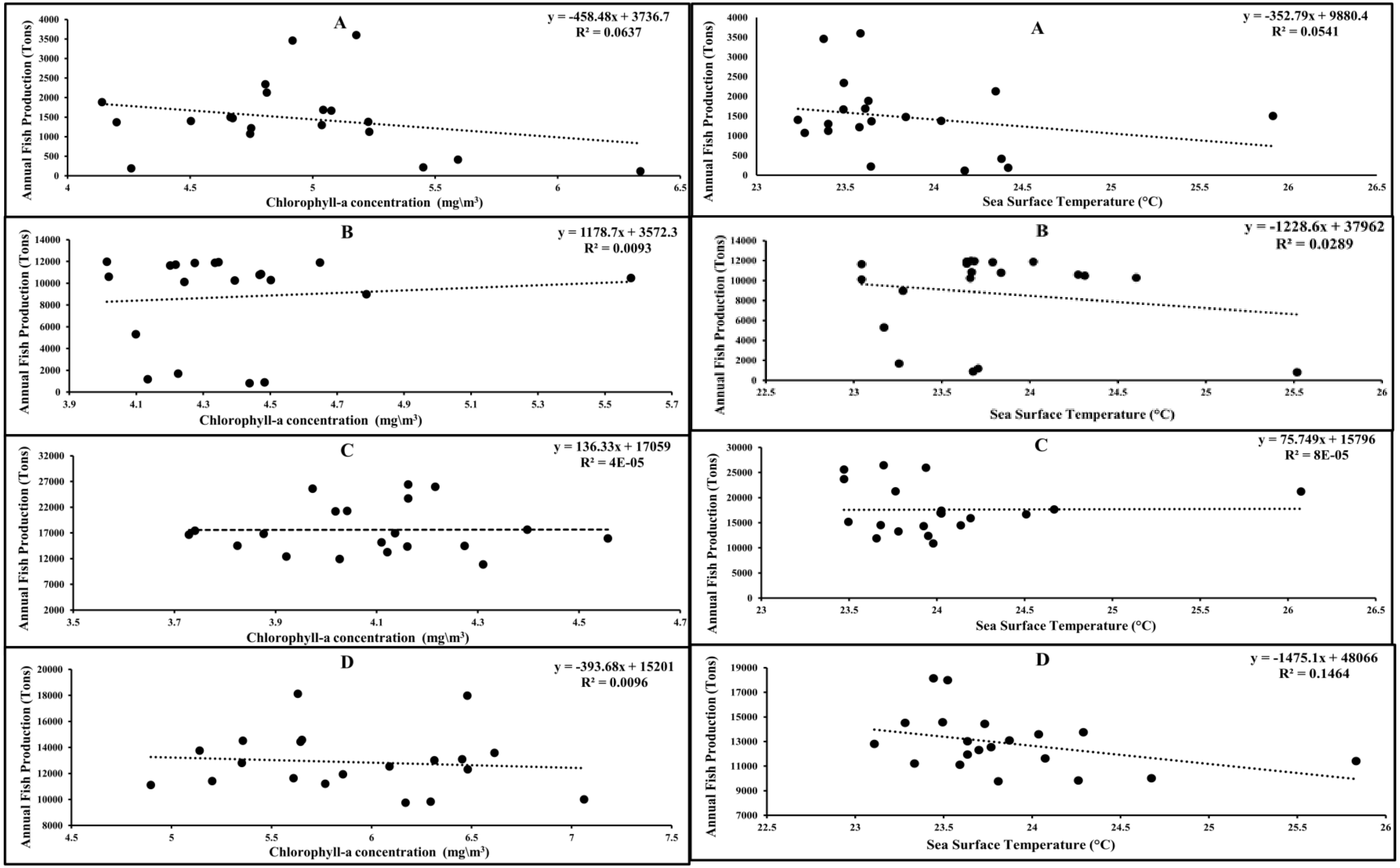


Fig. 6. Relationship between Chl a, SST and Fish Production in A= Al Aresh B= Borg El Burullus C= Izbet El Borg D= Port said

DISCUSSION

The findings of this study highlight the critical role of environmental variables in influencing fish distribution and productivity along the Egyptian Mediterranean coast. SST and chlorophyll-a concentrations emerged as key drivers of fish population dynamics, with seasonal variations in these parameters closely linked to fish catch rates. The use of remote sensing data provides a valuable tool for fisheries management, enabling the identification of suitable fishing zones and the optimization of fishing efforts. Temperature anomalies and global warming, especially in recent years, have significantly reduced the health of coral reefs, reduced the numbers of associated fish, and changed the catch per unit effort **(D'Agostino *et al*., 2020; Eddy *et al*., 2021)** (Fig. 4). The present work illustrates the relationship between sea temperature, chlorophyll concentration, and shared fishing areas (Southern Mediterranean) between El Arish Port, Port Said Port, Ezbet El Borg Port, and Burj El Burullus Port. The Mediterranean Sea has witnessed a series of heat stresses and chlorophyll levels between 2002 and 2021, which had an impact on the ecosystem. The fluctuations in sea surface temperature (SST) and chlorophyll concentration in the southern Egyptian Mediterranean between 2007 and 2013, with correlations to fish harvests in different ports. From 2007 to 2011, fish harvests increased, followed by a sharp decline in 2013, which coincided with a decrease in chlorophyll concentration. The variability in fish production is explored through data from four major ports: El Arish, Port Said, Ezbet El-Burg, and Burj Burullus. The fish harvest at El Arish Port in 2006, reached 2,324 tons with a low chlorophyll concentration of 0.0637. By 2008, fish harvest slightly decreased to 2,274 tons, but chlorophyll peaked at 1.01766, while SST remained constant at 27°C. while at Port Said in 2007, fish production was highest (7,351 tons) with low chlorophyll (0.2301). In 2008, fish harvest dropped to 5,926 tons, but chlorophyll increased to 0.8602, while SST dropped from 27.90°C to 23.15°C. Fish production at Ezbet El-Burg peaked in 2011 (9,747 tons) and 2009 (9,417 tons), though chlorophyll remained low (0.2711 in 2011, 0.0696 in 2009), with SST at 29.90°C. On the other hand, fish productivity at Burj Burullus increased in 2020 (3,649 tons) and 2021 (3,791 tons), with chlorophyll unusually high in 2020 (1.861) but lower in 2021 (0.5028), while SST rose from 28.97 to 29.544°C. The results reveal complex interactions between SST, chlorophyll concentration, and fish harvests, varying by location and year. Generally, higher chlorophyll concentrations, which are indicators of phytoplankton abundance, tend to correlate with increased fish productivity, as phytoplankton form the base of the marine food web **(Behrenfeld & Falkowski, 1997)**. However, the data show exceptions to this pattern, particularly in regions like Ezbet El-Burg and Port Said, where fish production remained high despite low chlorophyll concentrations. The sea surface temperature also plays a critical role in influencing marine ecosystems. Warmer SSTs, as seen in Ezbet El-Burg and Burj Burullus, may support greater metabolic activity and growth rates in fish **(Pörtner *et al*. 2014)**, but there is a threshold beyond which high SSTs could become detrimental. The lower temperatures recorded in Port Said in the autumn of 2008 suggest that fish stocks in this area may be more productive in cooler conditions, as the temperature dropped to 23.15°C. These findings are consistent with other research on the match/mismatch hypothesis, which suggests that the timing of phytoplankton blooms and the availability of fish larvae must align to maximize fish recruitment **(Cushing, 1990)**. In this study, the temporal variability in chlorophyll concentration and SST reflects the delicate balance of these ecological interactions.

SST and fish production

The study revealed a strong correlation between SST and fish production, suggesting that temperature plays a critical role in influencing fish abundance and distribution. Warmer SSTs can have various biological and ecological impacts on marine species, including changes in metabolic rates, spawning periods, and migratory patterns. For example, shifts in SST may cause some species to move to cooler areas or alter their reproduction cycles, directly affecting the availability of fish stock in certain regions **(Cheung *et al*. 2010)**. This is consistent with other research which has found that variations in SST, driven by climate change, can significantly impact the distribution and productivity of marine species **(Pörtner *et al*. 2014)**. In the context of the Egyptian Mediterranean waters, the increasing trend in SST observed in this study aligns with broader global patterns of ocean warming, which have been widely documented **(IPCC, 2019)**. Such changes could have profound implications for the local fisheries, as some species may become less abundant or migrate, leading to reduced catches **(Xènia *et al*., 2022; Khaled *et al*., 2023a; Dell'Apa *et al*., 2023)**. These findings highlight the necessity for adaptive management strategies in fisheries to mitigate the adverse impacts of warming season fish production.

Chl-a concentration and primary productivity

Chlorophyll-a concentration is a well-established proxy for phytoplankton biomass and primary productivity, which form the foundation of the marine food web. The positive correlation between Chl-a and fish production observed in this study suggests that primary productivity is a key determinant of fish stock abundance in the Egyptian Mediterranean Sea. This finding is supported by previous studies that have demonstrated the importance of primary productivity in supporting higher trophic levels, including fish populations **(Behrenfeld & Falkowski, 1997; Irwin *et al*., 2006; Khaled *et al*., 2023b; Said *et al*., 2024)**. The temporal variability in Chl-a concentration, as detected from satellite data, reflects seasonal fluctuations in phytoplankton blooms, which are often driven by nutrient availability and oceanographic conditions such as upwelling and water mixing **(Bosc *et al*., 2004; Mahdy *et al*., 2022; Li *et al.*, 2024; Zhou *et al.*, 2024)**. The observed peaks in Chl-a during specific seasons could explain the corresponding increases in fish production, as these periods likely provide optimal feeding conditions for fish larvae and juveniles, supporting their growth and survival **(Cushing, 1990)**.

Implications for fisheries management

The significant regional differences in environmental conditions and fish production suggest that fisheries management in the Egyptian Mediterranean must be tailored to local conditions. The relationship between SST, chlorophyll concentration, and fish production underscores the need for adaptive management strategies that account for environmental variability **(Platt & Sathyendranath, 2008)**. The use of remote sensing tools, as demonstrated in this study, can aid in monitoring these changes and providing early warnings for shifts in fish stocks, enabling more informed decision-making. In this study, the use of MODIS-Aqua satellite data enabled the detection of key environmental variables, SST and Chl-a, which are crucial for understanding the dynamics of fish populations. Given the projected impacts of climate change on marine environments, incorporating remote sensing technologies into fisheries management is essential for enhancing the resilience of fish stocks and sustaining fish production. Adaptive management strategies should consider the environmental thresholds identified in this study, such as critical SST levels that may trigger declines in fish populations. Furthermore, the establishment of marine protected areas (MPAs) or seasonal fishing restrictions during periods of low productivity could help preserve fish stocks in the face of environmental variability **(Katsanevakis *et al*., 2011)**.

Challenges and future research

Despite the clear benefits of remote sensing, there are limitations to its application in fisheries management. The spatial and temporal resolution of satellite data may not always capture fine-scale variability, especially in coastal and nearshore areas where many artisanal fisheries operate **(Gohin *et al*., 2008)**. Additionally, while SST and Chl-a provide useful indicators, other environmental factors such as salinity, ocean currents, and dissolved oxygen should be considered in future studies to gain a more comprehensive understanding of fish habitat suitability.

CONCLUSION

This study demonstrates the importance of understanding the dynamic interactions between SST, chlorophyll concentration, and fish production in the Mediterranean Sea. The use of satellite data to monitor these variables provides valuable insights for fisheries management, particularly in light of ongoing environmental changes. Tailoring management practices to the specific environmental conditions of each region will be key to ensuring the sustainability of fish stocks in the face of future climate variability. Regional management strategies should take into account both factors to optimize fish harvests while maintaining ecological balance

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