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REMOTE SENSING ANALYSIS OF PHYTOPLANKTON FOR IDENTIFYING OPTIMAL AREAS FOR BIOFUEL PRODUCTION IN THE NORTH EASTERN ARABIAN SEA

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ABSTRACT

This study aims to find out potential areas for phytoplankton as source of biofuel in oceanic region, Remote sensing technologies have been used to examine phytoplankton areas and their fluctuations over time near the northern Arabian Sea coasts of Pakistan and India. MODIS chlorophyll-a concentrations are used to estimate phytoplankton availability, and cloud computing on Google Earth Engine (GEE) is employed during 2010 and 2022. The findings demonstrate that phytoplankton concentrations change significantly, with larger concentrations observed from December to February, with hotspots around the coastlines. In year-to-year comparisons it becomes evident that chlorophyll-a levels were higher in 2012, 2014, 2015, 2019, and 2020 than in 2010 to 2022. GEE evaluates monthly variation and its dynamics using downloadable images and statistics. These findings provide information on the most optimal areas for phytoplankton production as well as their potential for biodiesel generation.

Keywords: Phytoplankton Biofuel, Remote Sensing of Phytoplankton, Arabian Sea, Google Earth Engine (GEE), JavaScript

INTRODUCTION

Phytoplankton are important components of the aquatic food chain, providing food for marine creatures and creating up to 50% of the world's oxygen through photosynthesis (Reynolds, 2006). The health and quantity of these small photosynthetic creatures have important ramifications for the planet's general health (Tilman *et al.*, 1982; Demarcq *et al*,. 2012). The concentration of Chlorophyll-a (Chl-a), a critical pigment required by phytoplankton for photosynthesis, can be measured for productivity (Liu *et al*, 2020). Monitoring fluctuations in Chl-a levels can provide insights into primary productivity (Schine *et al.*, 2021), while also considering the influence of solar radiation and nutrient availability on phytoplankton growth and water quality (McCarthy and Goldman, 1979; Mattei and Scardi, 2021). Furthermore, changes in phytoplankton populations can impact atmospheric CO_2 levels, emphasizing the need of researching their relationship to climate (Khokhar *et al.*, 2020; Domingues, 2022). The distribution and volume of phytoplankton, according to Barton *et al*. (2010), can give vital information on the biological state and composition of water bodies.

Marine phytoplankton play an important role in ocean ecosystems by promoting matter and energy cycling (Simon *et al.*, 2009; Watanabe *et al.*, 2014; Larsen *et al.*, 2021). Variations in water characteristics, such as nutrient concentrations, can cause changes in the quantity and distribution of these species (Glibert and Mitra, 2022; Pan and Pratolongo, 2022). Large horizontal gradients in water features, such as the border between two water masses, are often associated with greater concentrations of nutrients and phytoplankton biomass, resulting in enhanced primary production (Furnas *et al.*, 2005; Smith, 2006). Additionally, when various water masses collide, ocean fronts have a significant physical role in influencing phytoplankton concentration and variability (Kuhn *et al,* 2019; Glibert, 2019).

Cui *et al*. (2020) demonstrated that satellite remote sensing is an excellent method for monitoring Chlorophyll-a (Chl-a) levels in aquatic environments. This method provides synoptic coverage as well as effective monitoring of phytoplankton dispersion and abundance, all of which are essential in comprehending marine ecosystems and the environment (Gupana *et al.*, 2021). It is possible to measure Chl-a levels using satellite-based spectroscopy in the visible spectrum through evaluating the absorption and scattering characteristics of phytoplankton (Abbas *et al.*, 2019). Algorithms based upon radiation transmission are useful to estimate chlorophyll-a levels in aquatic bodies using methods of remote sensing (Wang *et al.*, 2022). This method has greatly enhanced our understanding of variations in phytoplankton biomass and its biological function. This additionally contributed to our understanding of the role of phytoplankton in climate mechanisms (Papenfus *et al.*, 2020; Seegers *et al.*, 2021).

In recent years, there has been a rise in interest in using phytoplankton as a substitute energy source (Darzins *et al*., 2010; Saad *et al*., 2019; Bhardwaj *et al*., 2020). We can assess the viability of using this source of energy by measuring and monitoring phytoplankton distribution and abundance through remote sensing data (Campbell *et al*., 2011; Morales *et al*., 2021). Researchers could evaluate the ability and potential of phytoplankton as an energy source and estimate their abundance and distribution by using satellite data (Abdelaziz *et al*., 2013; Prabaningtyas *et al*., 2019; Morgado and Vieira, 2021). Remote sensing data sets are valued for evaluating phytoplankton viability as an additional source of energy, since this offers synoptic coverage and efficient surveillance of phytoplankton abundance (Beaugrand and Kirby, 2010; Scaife *et al*, 2015; Pachiappan *et al*, 2019).

This study utilizes satellite remote sensing data and Google Earth Engine (GEE) for the analysis of temporal and spatial variations in Chl-a concentration. The main objective is to improve our understanding of the distribution patterns of phytoplankton in the oceanic ecosystem. Additionally, this research examines the spatial, temporal, and dynamic aspects of phytoplankton availability for biofuel production and evaluates its potential as a sustainable energy source. By consolidating data from satellite observations of chlorophyll-a concentration and dispersion within the study area, this work contributes to the continued viability of phytoplankton as a biofuel resource in the long term.

MATERIALS AND METHODS

Study Area

The study covers a significant region of the Arabian Sea, mainly the eastern portion across the Pakistani and Indian coastlines, from longitude 61°24'33.446"E to 73°33'39.83"E and latitude 16°41'27.462"N to 25°29'54.651"N, as seen in Fig 1. This region is known for its enormous reserves of natural resources, such as oil routes and seafood, which support millions of people (Al Shehhi *et al*, 2014). The presence of phytoplankton is critical in the Arabian Sea ecology because they form the foundation of the food chain, converting sunlight into energy through the process of photosynthesis to promote the development and survival of other species of aquatic life (Saifullah and Rasool, 2002; Da Silva and Gooday, 2009; Gul and Nawaz, 2014). The Arabian Sea is also an important migration route for many marine species, offering important environments for survival and reproduction. The preservation of this area is of utmost importance due to its role as a habitat for numerous endangered and vulnerable species. Protecting the region is vital for safeguarding biodiversity and ensuring environmental stability (Rasool *et al*., 2002). The Arabian Sea assumes a crucial role in regulating Earth's climate by absorbing carbon dioxide from the atmosphere. Furthermore, it serves as a vital component of the global ecosystem, supporting biodiversity, sustaining human livelihoods, and contributing to climate management (Khokhar *et al*., 2021).

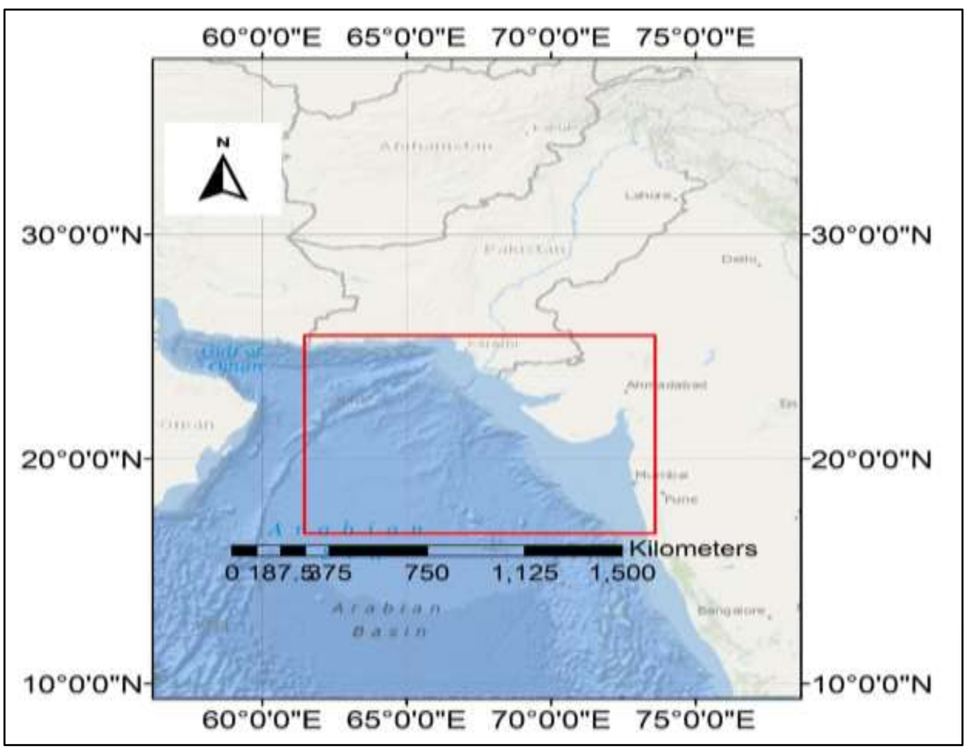

Fig. 1. The North Eastern Arabian Sea.

Phytoplankton Remote sensing data with Google Earth Engine (GEE)

Google Earth Engine (GEE) is a cloud-based platform for geospatial research and visualization. It provides users with access to a large library of satellite images and other geospatial data (Traganos *et al*., 2018; Jia *et al*., 2019). Moreover, the data processing and presentation capabilities of this platform have gained popularity among users for its ability to handle vast quantities of data and perform complex research tasks swiftly and efficiently (Quang *et al*., 2022). GEE has been employed for a variety of applications, including vegetation monitoring and mapping, natural disaster and monitoring variations in land use and land cover (Zhang *et al*, 2021; Feng *et al*., 2022, Li *et al*., 2022). This has also been used for phytoplankton and ocean productivity research, it generates a chlorophyll-a (Chl-a) concentration collection using the MODIS dataset (Abbas *et al*, 2019; Quang *et al*., 2022).

MODIS data and JavaScript codes on Google Earth Engine (GEE):

MODIS (Moderate Resolution Imaging Spectroradiometer) is a remote sensing sensor that provides data on a variety of environmental features. This comprises with land cover, vegetation, ocean color, temperature, and cloud cover. NASA manages this with contains of two satellites, Terra and Aqua, that circle the Earth in polar orbit. The MODIS data is frequently utilized to monitor and comprehend a wide range of natural phenomena and events, this is a set of high-resolution pictures and Level 3 outputs that may be found on GEE. This includes the utilization of ocean color and satellite ocean biology data, which are either produced or collected under the Earth Observing System Data and Information System (EOSDIS) this is NASA program for managing and distributing data from Earth observing satellites. These data can be used to study the biology and hydrology of coastal zones, investigate the impact of climate and environmental variability and change on ocean ecosystems, and monitor the diversity and distribution of coastal marine habitats.

The data sets available on GEE have a resolution of 4616 meters and are a valuable resource with several data bands for researchers studying the Earth's oceans and their ecological processes (Table1). The ocean color data provided by MODIS on GEE enables researchers to study the biological productivity of the oceans and understand the physical and chemical processes that drive ocean productivity and the behavior of marine organisms.

Table 1. MODIS-Aqua/L3SMI Bands.

Name	**Units**	**Min**	**Max**	**Wave length**	**Description**
chlor_a	mg/m^3	0*	99.99*		Chlorophyll a concentration
nflh	m W cm-2 & mu;m-1 sr-1	-0.5*	5.03*		Normalized fluorescence line height
poc	mg/m^3	-2147.48*	12953.4 *		Particulate organic carbon
Rrs_412	sr-1	0*	0.11*	412nm	Remote sensing reflectance at band 412nm
Rrs_443	sr-1	0*	0.08*	443nm	Remote sensing reflectance at band 443nm
Rrs_469	sr-1	0*	0.08*	469nm	Remote sensing reflectance at band 469nm
Rrs_488	sr-1	0*	0.08*	488nm	Remote sensing reflectance at band 488nm
Rrs_531	sr-1	0*	0.07*	531nm	Remote sensing reflectance at band 531nm
Rrs_547	sr-1	0*	0.07*	547nm	Remote sensing reflectance at band 547nm
Rrs_555	sr-1	0*	0.07*	555nm	Remote sensing reflectance at band 555nm
Rrs_645	sr-1	0*	0.05*	645nm	Remote sensing reflectance at band 645nm
Rrs_667	sr-1	0*	0.04*	667nm	Remote sensing reflectance at band 667nm
Rrs_678	sr-1	0*	0.04*	678nm	Remote sensing reflectance at band 678nm
sst	and degree C	-2*	40*		Sea surface temperature

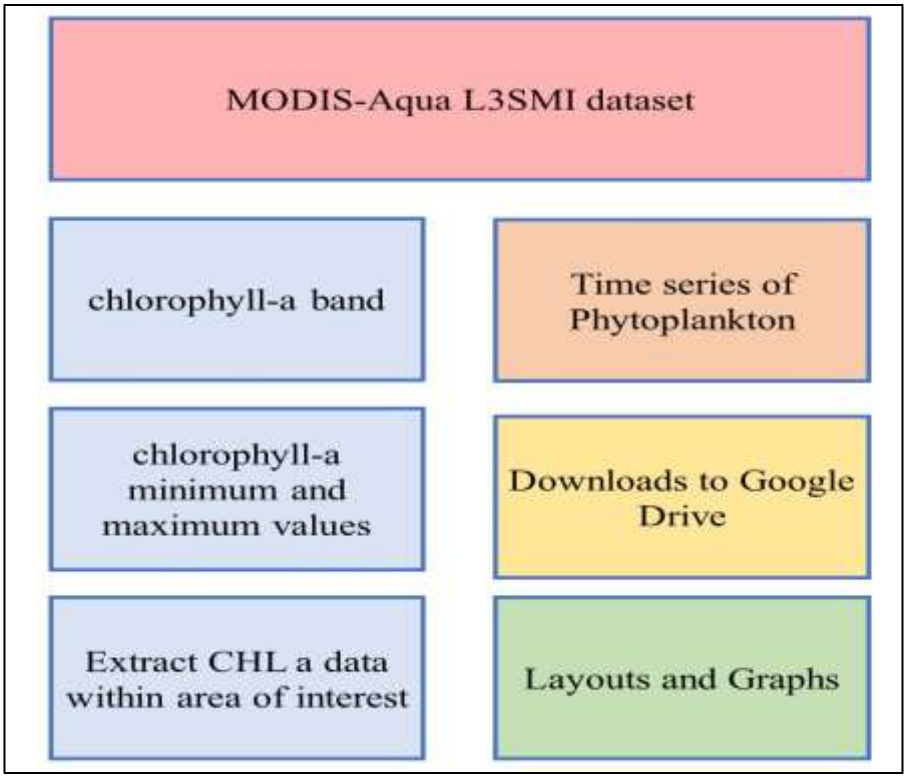

Fig. 2. Flowchart of the methodology.

Google Earth Engine uses the following approaches to import and analyze chlorophyll-a data from the MODIS-Aqua L3SMI dataset. Using JavaScript codes for MODIS data within dates 2010 to 2022 has been done, when retrieved, chlorophyll-a band has selected for display, and a color palette is utilized to visualize the chlorophyll-a data, highlighting its minimum and maximum values. Finally to make a graph of chlorophyll-a concentration vs time and to upload the chlorophyll-a standard image to Google Drive many codes have been used as Fig. 2.

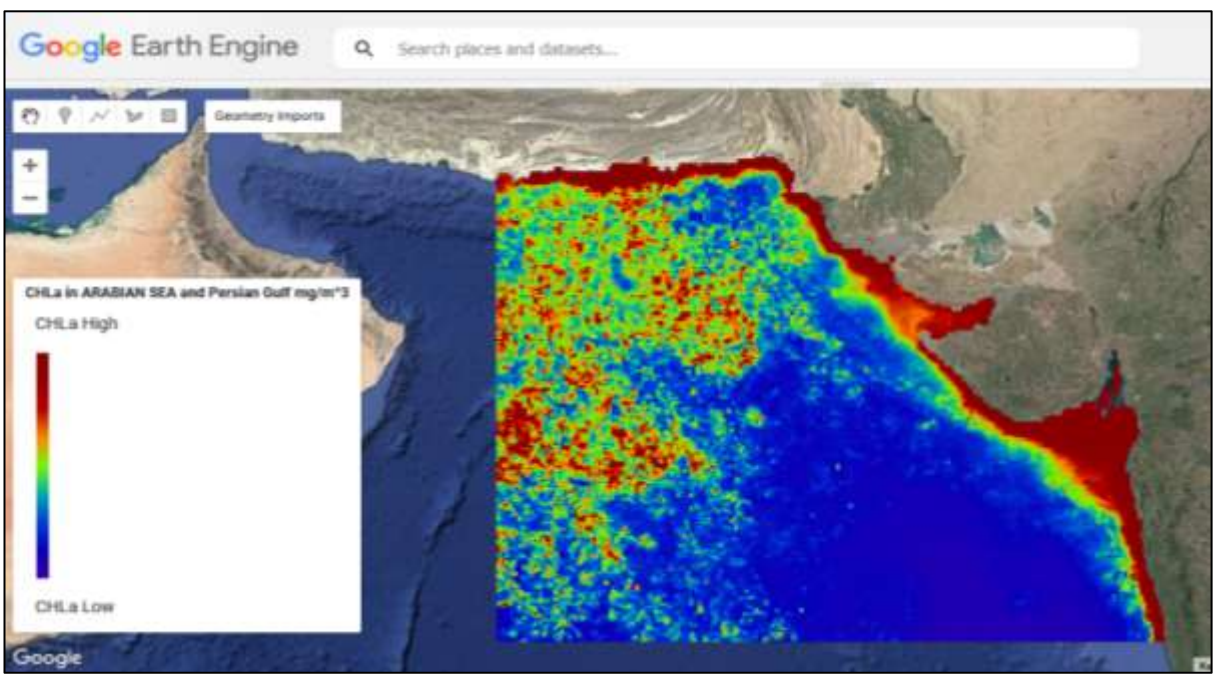

Fig. 3. Spatial distribution of Chlorophyll a (Chl-a) concentration proxy to phytoplankton.

RESULTS

This study conducted to assess the time series of chlorophyll-a data and study the spatial patterns of phytoplankton using monthly data to assess the dynamics of phytoplankton biomass. The study results show that chlorophyll-a concentrations exhibit fluctuations, corresponding to changes in phytoplankton biomass. The distinct pattern in chlorophyll-a levels over the years suggests with literature review that factors like changes in temperature, nutrient availability, or light availability influence the growth of phytoplankton in the study area. The study provided an analysis of the geographic distribution of chlorophyll-a concentrations, revealing the highest values in the northern and western regions of the study area, with a notable concentration in the coastal creeks of Pakistan and India (Fig. 3).

Fig 4 shows time series graphs of phytoplankton concentrations, with greater concentrations seen in 2012, 2014, 2015, 2019, and 2020, indicating good conditions for phytoplankton development. These findings contribute to the study and maintenance of marine ecosystem by providing essential knowledge into concentration of phytoplankton trends and its distribution.

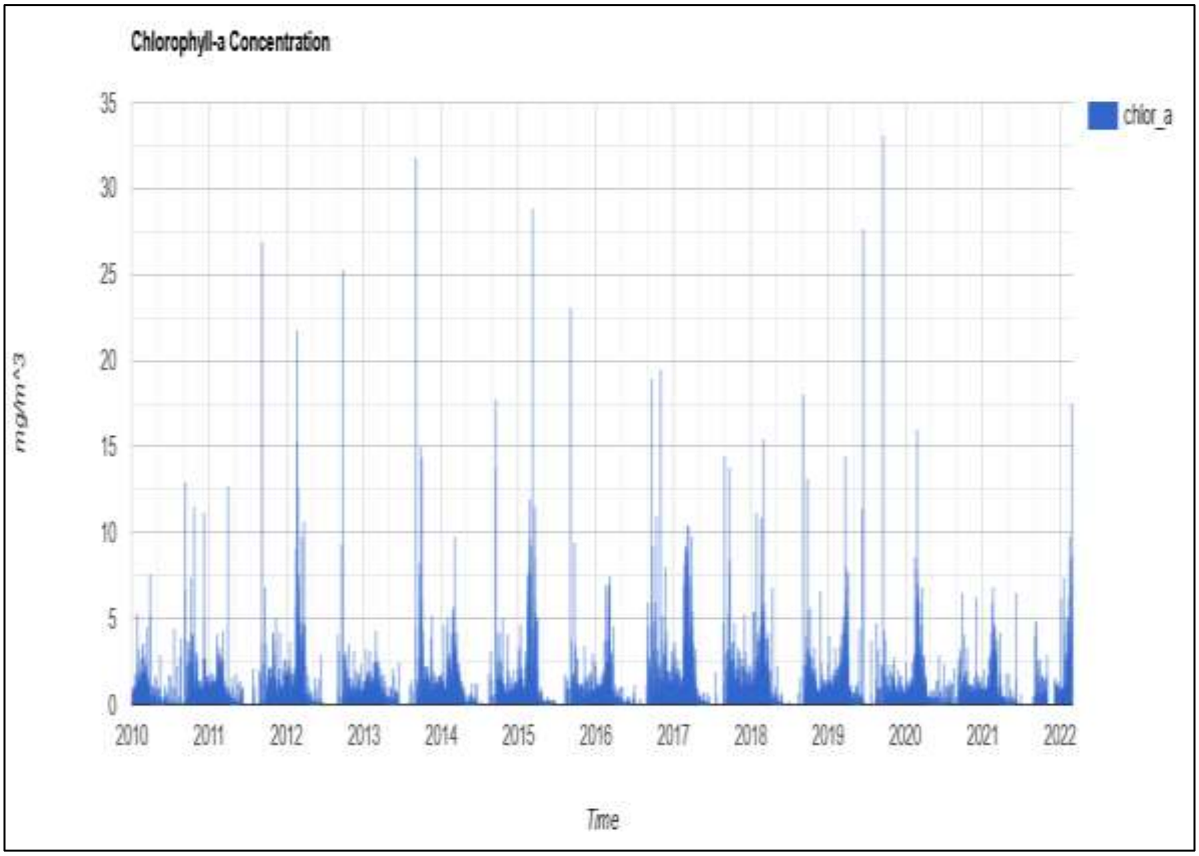

Fig. 4. Time series data illustrating the average concentration of MODIS Chl-a from 2010 to 2022.

DISCUSSION

Phytoplankton represents a promising resource for biofuel production (Morales *et al*., 2021). These microscopic marine organisms, found abundantly in water bodies, utilize sunlight, carbon dioxide, and nutrients through photosynthesis to produce organic matter. Some phytoplankton species, like diatoms and cyanobacteria, naturally accumulate lipids or oils that can be harvested and converted into biofuels, such as biodiesel and bioethanol (Smith *et al*., 2010). This feature offers several advantages, including renewability, rapid growth, and carbon neutrality. Moreover, their high lipid content makes them an attractive source of oil for biofuel production. Nonetheless, challenges related to cultivation, harvest, processing, and potential environmental impacts persist. Overcoming these hurdles would require continued research and development efforts, but the potential benefits of harnessing phytoplankton for biofuel production make it a compelling area of exploration (Rogers *et al*., 2014; Suganya *et al*., 2016). Remote sensing is crucial in discovering optimal sites for phytoplankton growth in biofuel production since the development and dispersal of these tiny plants are ruled by environmental variables (Nezlin, 2005). Remote sensing equipment, such as satellites, aircraft, or drones, can provide valuable information for this purpose, researchers can use remote sensing tools such as satellite images to study the environmental and physical aspects of several places in order to identify the best locations for phytoplankton development (Zhang and Kovacs, 2012). For example, satellite data can be used to monitor ocean temperature and identify upwelling, which is an important source of nutrients for phytoplankton.

Satellite imaging may also be used to route the movement of ocean currents, which might affect phytoplankton dispersion (Johns *et al*, 2020). Researchers can assist maximize the efficiency of biofuel production by employing remote sensing technologies to find suitable places for phytoplankton development. This can have major environmental and economic benefits, as phytoplankton-derived biofuels are considered a more sustainable and environmentally friendly alternative to traditional fossil fuels (Lee *et al*, 2013). This information may subsequently be used to improve the management and placement of phytoplankton biofuel farms. Remote sensing can also help determine the optimal water temperature, nutrient levels, and light exposure for phytoplankton development. Monitoring phytoplankton health and growth over time via remote sensing is also critical to maintaining the sustainability as well as effectiveness of phytoplankton biofuel generation.

Remote sensing technology is essential for locating and improving phytoplankton biofuel sites, it enables the most efficient use of phytoplankton as a renewable energy source while ensuring long-term resource management. Since, it gives crucial information on a range of parameters, remote sensing is especially valuable for observing and analyzing the phytoplankton biofuel production process. One of the most significant advantages of remote sensing is the ability to monitor phytoplankton development and health (Sayers *et al*, 2021). The approach provides information on the geographical distribution and density of phytoplankton across large areas, allowing for the identification of optimum growth circumstances as well as the detection of environmental stressors that may hamper growth. This information might be utilized to optimize growth conditions and ensure long-term biofuel production.

In light of the findings from this study, it's crucial to delve deeper into the implications of the spatial and temporal patterns observed in the northern Arabian Sea, where phytoplankton can play a vital role in biofuel production. The spatial distribution of chlorophyll-a (Chl-a) as a proxy for phytoplankton, as illustrated in Fig 3, reveals specific areas with higher concentrations. These regions, often clustered around coastlines, present attractive targets for phytoplankton production. The proximity to coastlines could facilitate easier access for harvesting and processing operations.

The temporal dynamics of phytoplankton concentrations, exemplified in Fig 4, show notable peaks during the winter months, from December to February. This seasonality in phytoplankton growth is influenced by various environmental factors, including temperature, nutrient availability, and sunlight. The higher concentrations during these months signify optimal periods for harvesting, ensuring maximum biofuel yield. Furthermore, the year-to-year comparisons highlight significant variations in chlorophyll-a levels. Notably, years 2012, 2014, 2015, 2019, and 2020 exhibited higher phytoplankton concentrations than in the years from 2010 to 2022. This inter-annual variability highlights the importance of flexibility in biofuel production strategies. Adaptability in response to changing conditions is essential to capitalize on peak phytoplankton growth years, potentially leading to increased biofuel output.

The study is used Google Earth Engine (GEE) for monthly variation analysis and dynamic assessments, incorporating downloadable images and statistics, offers a robust toolset for monitoring and managing phytoplankton production (Traganos *et al*., 2018; Jia *et al*., 2019). The ability to track changes in real-time and over extended periods is invaluable for optimizing biofuel production efforts. The findings presented in this study not only identify prime regions for phytoplankton cultivation but also underscore their potential as a sustainable source of biofuel. By capitalizing on the spatial and temporal patterns in phytoplankton distribution, future initiatives can develop targeted and adaptable strategies for biofuel production, addressing both environmental concerns and the growing demand for renewable energy sources in the region (Li *et al*., 2022).

Remote sensing may also be used to monitor environmental factors that influence phytoplankton development, such as sea surface temperature, salinity, and nutrient concentrations (Liu *et al*, 2016). Remote sensing detects changes in ambient conditions and modifies the farming system accordingly by tracking important environmental factors (Vostokova *et al*, 2022). Remote sensing identifies the existence of dangerous algal blooms and forecasts their migration in addition to monitoring growth conditions. This capability facilitates the implementation of early warning and management protocols, ensuring the safety of both the phytoplankton culture and the surrounding environment. It allows for a rapid response to any detected abnormalities in the data, thus minimizing potential risks. Google Earth Engine empowers global researchers by providing cloud-based access to extensive ocean data, allowing real-time monitoring and fostering collaboration for environmental conservation. It revolutionizes remote sensing analysis and advances the understanding of our dynamic oceans.

The Arabian Sea is increasingly recognized as a potential goldmine for phytoplankton biofuel production due to its unique environmental characteristics and abundant phytoplankton populations. The identification of suitable areas within the Arabian Sea for optimizing phytoplankton biofuel production represents a critical step toward harnessing this sustainable energy source. In this research paper, we delve into the multifaceted aspects of this endeavor, from the initial identification of promising sites to the subsequent development of strategies for enhanced biofuel production. This study encompasses a comprehensive analysis of the Arabian Sea's environmental variables and the utilization of remote sensing technologies to pinpoint ideal locations for phytoplankton growth. These findings hold potential significance for both alternative energy generation and policy development.

Finally, remote sensing technology offers data on phytoplankton growth, environmental conditions, and biofuel production efficiency, allowing educated judgments on phytoplankton management. These data points allow for the development of new technologies or the modification of growing conditions in order to optimize the potential of the phytoplankton biofuel technology. This research tells that there is need of collaboration of a plant scientist, a chemist or chemical engineer, and a geographer to produce biofuel from phytoplankton.

This research highlights the importance of continuous monitoring and evaluation of phytoplankton health and growth over time. It emphasizes the need for sustainable practices in phytoplankton biofuel production to ensure its long-term effectiveness and environmental viability. The knowledge and insights presented in this paper pave the way for a more sustainable and eco-friendly energy future, where phytoplankton biofuels can play a vital role in reducing our reliance on traditional fossil fuels.

CONCLUSION

This research shows that remote sensing technologies may be used to monitor phytoplankton concentration fluctuations and identify ideal coastal sites for biodiesel production. It gives critical information on growing conditions, environmental considerations, and biofuel efficiency, allowing for sustainable resource management and the use of renewable energy. Identifying places with high chlorophyll-a concentrations assists in the selection of suitable sites for biofuel production while taking into account other factors such as nutrition, temperature, and salinity. These discoveries are critical for managing marine ecosystems and reducing the effects of climate change. The lipid concentration of phytoplankton makes it a prospective biofuel source, and understanding biomass dynamics helps optimize production conditions, lowering greenhouse gas emissions and environmental damage caused by fossil fuels.

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Data and Codes

Data and codes are accessible upon reasonable request.

REFERENCES

Abbas, M.M., A.M. Melesse, L.J. Scinto, and J.S. Rehage (2019). Satellite estimation of chlorophyll-a using moderate resolution imaging spectroradiometer (MODIS) sensor in shallow coastal water bodies: Validation and improvement. *Water*, 11(8): 1621.

Abdelaziz, A.E., G.B. Leite, and P.C. Hallenbeck (2013). Addressing the challenges for sustainable production of algal biofuels: I. Algal strains and nutrient supply. *Environmental Technology*, 34: 1783-1805. https://doi.org/10.1080/09593330.2013.827748.

Al Shehhi, M.R., I Gherboudj, and H. Ghedira (2014). An overview of historical harmful algae blooms outbreaks in the Arabian Seas. *Marine Pollution Bulletin*, 86: 314-324. DOI: 10.1016/j.marpolbul.2014.06.048.

Barton, A.D., S. Dutkiewicz, G. Flierl, J. Bragg, and M.J. Follows (2010). Patterns of diversity in marine phytoplankton. *Science*, 327: 1509-1511. DOI: 10.1126/science.1184961.

Beaugrand, G., and R.R. Kirby (2010). Climate, plankton and cod. *Global Change Biology*, 16: 1268-1280. https://doi.org/10.1111/j.1365-2486.2009.02063.x.

Bhardwaj, N., K. Agrawal, and P. Verma (2020). Algal biofuels: an economic and effective alternative of fossil fuels. In: *Microbial strategies for techno-economic biofuel production*, 207-227. DOI: 10.1007/978-981-15-7190-9_7.

Campbell, P.K., T. Beer, and D. Batten (2011). Life cycle assessment of biodiesel production from microalgae in ponds. *Bioresource technology*, 102: 50-56. https://doi.org/10.1016/j.biortech.2010.06.048.

Cui, T.W., J. Zhang, K. Wang, J.W. Wei, B. Mu, Y. Ma, X.Y. Chen, and X.Y. Chen (2020). Remote sensing of chlorophyll a concentration in turbid coastal waters based on a global optical water classification system. ISPRS *Journal of Photogrammetry and Remote Sensing*, 163: 187-201. https://doi.org/10.1016/j.isprsjprs.2020.02.017.

Da Silva, A.A., and A.J. Gooday (2009). Large organic-walled Protista (Gromia) in the Arabian Sea: density, diversity, distribution and ecology. *Deep Sea Research Part II: Topical Studies in Oceanography*, 56: 422-433. https://doi.org/10.1016/j.dsr2.2008.12.027.

Darzins, A., Pienkos, P., and L. Edye (2010). Current status and potential for algal biofuels production. *A report to IEA Bioenergy Task*, 39: 403-412.

Demarcq, H., G.Reygondeau, , S. Alvain, and V. Vantrepotte (2012). Monitoring marine phytoplankton seasonality from space. *Remote Sensing of Environment*, 117: 211-222. https://doi.org/10.1016/j.rse.2011.09.019.

Domingues, R. B. (2022). Seasonal and Spatial Variability of Phytoplankton Primary Production in a Shallow Temperate Coastal Lagoon (Ria Formosa, Portugal). *Plants*, 11: 3511. https://doi.org/10.3390/plants11243511.

Feng, S., W. Li, J. Xu, T. Liang, X. Ma, W. Wang, and H. Yu (2022). Land use/land cover mapping based on GEE for the monitoring of changes in ecosystem types in the upper Yellow River basin over the Tibetan Plateau. *Remote Sensing*, 14(21): 5361.

Furnas, M., A. Mitchell, M. Skuza, and J. Brodie (2005). In the other 90%: phytoplankton responses to enhanced nutrient availability in the Great Barrier Reef Lagoon. *Marine Pollution Bulletin*, 51: 253-265. DOI: 10.1016/j.marpolbul.2004.11.010.

Glibert, P. M. (2019). Phytoplankton in the aqueous ecological theater: Changing conditions, biodiversity, and evolving ecological concepts. *Journal of Marine Research*, 77: 83-137. DOI: 10.1357/002224019828474304.

Glibert, P. M., and A. Mitra (2022). From webs, loops, shunts, and pumps to microbial multitasking: Evolving concepts of marine microbial ecology, the mixoplankton paradigm, and implications for a future ocean. *Limnology and Oceanography*, 67: 585-597. https://doi.org/10.1002/lno.12018.

Gul, S., and M. F. Nawaz (2014). The Dinoflagellate Genera Protoperidinium and Podolampas from Pakistan's Shelf and Deep Sea Vicinity (North Arabian Sea). *Turkish Journal of Fisheries and Aquatic Sciences*, 14: DOI: 10.4194/1303-2712-v14_1_11.

Gupana, R. S., D. Odermatt, I. Cesana, C. Giardino, L. Nedbal, and A. Damm (2021). Remote sensing of sun-induced chlorophyll-a fluorescence in inland and coastal waters: Current state and future prospects. *Remote Sensing of Environment*, 262: 112482. https://doi.org/10.1016/j.rse.2021.112482.

Jia, T., X. Zhang, and R. Dong (2019). Long-term spatial and temporal monitoring of cyanobacteria blooms using MODIS on Google Earth Engine: A case study in Taihu Lake. *Remote Sensing*, 11: 2269. https://doi.org/10.3390/rs11192269.

Johns, E. M., R. Lumpkin, N. F. Putman, R. H. Smith, F. E. Muller-Karger, D. T. Rueda-Roa, *et al*. (2020). The establishment of a pelagic Sargassum population in the tropical Atlantic: Biological consequences of a basin-scale long distance dispersal event. *Progress in Oceanography*, 182: 102269.

Khokhar, F. N., Z. Burhan, T. Naz, J. Abbasi, N. Ahmad, A. Ali, *et al*. (2020). Phytoplankton community dynamics during Asian monsoon system preponderate in the coastal waters of northern region of Arabian Sea boarding Pakistan. *Pakistan Journal of Botany*, 52: 703-709. DOI: http://dx.doi.org/10.30848/PJB2020-2(28).

Khokhar, F. N., N. Ahmed, A. Ali, K. Gabol, A. R. Khooharo, M. Faheem, *et al*. (2021). Distribution and abundance of dinoflagellates from the coastal waters of Karachi, Pakistan, northern part of the Arabian Sea. Brazilian *Journal of Biology*, 82: https://doi.org/10.1590/1519-6984.245124.

Kuhn, A. M., S. Dutkiewicz, O. Jahn, S. Clayton, T. A. Rynearson, M. R. Mazloff, and A. D. Barton (2019). Temporal and spatial scales of correlation in marine phytoplankton communities. *Journal of Geophysical Research: Oceans*, 124: 9417-9438. https://doi.org/10.1029/2019JC015331.

Larsen, S., L. Comte, A. Filipe, M. Fortin, C. Jacquet, R. Ryser, *et al*. (2021). The geography of metapopulation synchrony in dendritic river networks. *Ecology Letters*, 24: 791-801. https://doi.org/10.1111/ele.13699.

Lee, E., R. L. Heng, and L. Pilon (2013). Spectral optical properties of selected photosynthetic microalgae producing biofuels. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 114: 122-135.

Li, D., Z. Gao, and Y. Wang (2022). Research on the long-term relationship between green tide and chlorophyll-a concentration in the Yellow Sea based on Google Earth Engine. *Marine Pollution Bulletin*, 177: 113574. https://doi.org/10.1016/j.marpolbul.2022.113574.

Liu, X., W. Xiao, M. R. Landry, K. P. Chiang, L. Wang, and B. Huang (2016). Responses of phytoplankton communities to environmental variability in the East China Sea. *Ecosystems*, 19: 832-849.

Liu, Z., M. Iqbal, Z. Zeng, Y. Lian, A. Zheng, M. Zhao, *et al*. (2020). Comparative analysis of microbial community structure in the ponds with different aquaculture model and fish by high-throughput sequencing. *Microbial pathogenesis*, 142: 104101. https://doi.org/10.1016/j.micpath.2020.104101.

Mattei, F., and M. Scardi (2021). Collection and analysis of a global marine phytoplankton primary-production dataset. *Earth System Science Data*, 13: 4967-4985. https://essd.copernicus.org/articles/13/4967/2021/.

McCarthy, J. J., and J. C. Goldman (1979). Nitrogenous nutrition of marine phytoplankton in nutrient-depleted waters. *Science*, 203: 670-672. DOI: 10.1126/science.203.4381.670.

Morales, M., C. Aflalo, and O. Bernard (2021). Microalgal lipids: A review of lipids potential and quantification for 95 phytoplankton species. *Biomass and Bioenergy*, 150: 106108. https://doi.org/10.1016/j.biombioe.2021.106108.

Morgado, F., and L. R. Vieira (2021). Phytoplankton: Biodiesel Production and Other Applications for Marine Biotechnology. In: *Affordable and Clean Energy*, pp.982-992. Cham: Springer International Publishing. DOI: 10.1007/978-3-319-71057-0_118-1.

Nezlin, N. P. (2005). Patterns of seasonal and interannual variability of remotely sensed chlorophyll. *The Caspian Sea Environment*, 143-157.

Pachiappan, P., P. Santhanam, A. Begum, and B. Balaji Prasath (2019). An introduction to plankton. *Basic and applied phytoplankton biology*, 1-24. DOI: 10.1007/978-981-10-7938-2_1.

Pan, J., and P. D. Pratolongo (Eds.) (2022). *Marine Biology: A Functional Approach to the Oceans and Their Organisms*. CRC Press. https://doi.org/10.1201/9780429399244.

Papenfus, M., B. Schaeffer, A. I. Pollard, and K. Loftin (2020). Exploring the potential value of satellite remote sensing to monitor chlorophyll-a for US lakes and reservoirs. *Environmental Monitoring and Assessment*, 192: 808. https://doi.org/10.1007/s10661-020-08631-5.

Prabaningtyas, S., T. Ardyati, and C. Retnaningdyah (2019, December). The Community Structure of Microalgae and Exploring its Potential to Biofuel Producing in Ranu Grati, East Java Indonesia. In: *IOP Conference Series: Earth and Environmental Science*, 391(1): 012029. IOP Publishing. DOI: 10.1088/1755-1315/391/1/012029.

Quang, N. H., M. N. Nguyen, M. Paget, J. Anstee, N. D. Viet, M. Nones, and V. A. Tuan (2022). Assessment of Human-Induced Effects on Sea/Brackish Water Chlorophyll-a Concentration in Ha Long Bay of Vietnam with Google Earth Engine. *Remote Sensing*, 14: 4822. https://doi.org/10.3390/rs14194822.

Rasool, F., S. Tunio, S. Hasnain, and E. Ahmad (2002). Mangrove conservation along the coast of Sonmiani, Balochistan, Pakistan. *Trees*, 16: 213-217. https://doi.org/10.1007/s00468-001-0151-5.

Reynolds, C. S. (2006). *The ecology of phytoplankton*. Cambridge University Press. https://doi.org/10.1017/CBO9780511542145.

Rogers, J. N., J. N. Rosenberg, B. J. Guzman, V. H. Oh, L. E. Mimbela, A. Ghassemi, *et al*. (2014). A critical analysis of paddlewheel-driven raceway ponds for algal biofuel production at commercial scales. *Algal research*, 4: 76-88.

Saad, M. G., N. S. Dosoky, M. S. Zoromba, and H. M. Shafik (2019). Algal biofuels: current status and key challenges. *Energies*, 12: 1920. https://doi.org/10.3390/en12101920.

Saifullah, S. M., and F. A. Y. Y. A. Z. Rasool (2002). Mangroves of Miani Hor lagoon on the north Arabian Sea coast of Pakistan. *Pak. J. Bot*., 34: 303-310.

Sayers, M. J., G. L. Fahnenstiel, R. A. Shuchman, and K. R. Bosse (2021). A new method to estimate global freshwater phytoplankton carbon fixation using satellite remote sensing: initial results. *International Journal of Remote Sensing*, 42(10): 3708-3730.

Scaife, M. A., A. Merkx-Jacques, D. L. Woodhall, and R. E. Armenta (2015). Algal biofuels in Canada: Status and potential. *Renewable and Sustainable Energy Reviews*, 44: 620-642. https://doi.org/10.1016/j.rser.2014.12.024.

Schine, C. M., A. C. Alderkamp, G. van Dijken, L. J. Gerringa, S. Sergi, P. Laan, *et al*. (2021). Massive Southern Ocean phytoplankton bloom fed by iron of possible hydrothermal origin. *Nature Communications*, 12: 1211. https://doi.org/10.1038/s41467-021-21339-5.

Seegers, B. N., P. J. Werdell, R. A. Vandermeulen, W. Salls, R. P. Stumpf, B. A. Schaeffer, *et al*. (2021). Satellites for long-term monitoring of inland US lakes: The MERIS time series and application for chlorophyll-a. *Remote Sensing of Environment*, 266: 112685. https://doi.org/10.1016/j.rse.2021.112685.

Simon, N., A. L. Cras, E. Foulon, and R. Lemée (2009). Diversity and evolution of marine phytoplankton. *Comptes rendus biologies*, 332: 159-170. https://doi.org/10.1016/j.crvi.2008.09.009.

Smith, V. H. (2006). Responses of estuarine and coastal marine phytoplankton to nitrogen and phosphorus enrichment. *Limnology and oceanography*, 51: 377-384.

Smith, V. H., B. S. Sturm, F. J. Denoyelles, and S. A. Billings (2010). The ecology of algal biodiesel production. *Trends in Ecology and Evolution*, 25(5): 301-309.

Suganya, T., M. Varman, H. H. Masjuki, and S. Renganathan (2016). Macroalgae and microalgae as a potential source for commercial applications along with biofuels production: A biorefinery approach. *Renewable and Sustainable Energy Reviews*, 55: 909-941.

Tilman, D., S. S. Kilham, and P. Kilham (1982). Phytoplankton community ecology: the role of limiting nutrients. *Annual Review of Ecology and Systematics*, 13: 349-372. https://doi.org/10.1146/annurev.es.13.110182.002025.

Traganos, D., B. Aggarwal, D. Poursanidis, K. Topouzelis, N. Chrysoulakis, and P. Reinartz (2018). Towards global-scale seagrass mapping and monitoring using Sentinel-2 on Google Earth Engine: The case study of the Aegean and Ionian seas. *Remote Sensing*, 10: 1227. https://doi.org/10.3390/rs10081227.

Vostokova, A. S., S. V. Vostokov, and I. V. Saling (2022, December). Regional features of seasonal variability of phytoplankton in the Black Sea studied by remote sensing data. In: *28th International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics* (Vol. 12341, pp. 1010-1013). SPIE.

Wang, T., Y. Sun, H. Su, and W. Lu (2022). Declined trends of chlorophyll-a in the South China Sea over 2005-2019 from remote sensing reconstruction. *Acta Oceanologica Sinica*, 42: 1-14. DOI: 10.1007/s13131-022-2097-y.

Watanabe, K., A. Kasai, E. S. Antonio, K. Suzuki, M. Ueno, and Y. Yamashita (2014). Influence of salt-wedge intrusion on ecological processes at lower trophic levels in the Yura Estuary, Japan. *Estuarine, Coastal and Shelf Science*, 139: 67-77. https://doi.org/10.1016/j.ecss.2013.12.018.

Zhang, C., and J. M. Kovacs (2012). The application of small unmanned aerial systems for precision agriculture: a review. *Precision Agriculture*, 13: 693-712.

Zhang, G., M. Wu, J. Wei, Y. He, L. Niu, H. Li, and G. Xu (2021). Adaptive threshold model in Google Earth Engine: A case study of Ulva prolifera extraction in the South Yellow Sea, China. Remote Sensing, 13: 3240. https://doi.org/10.3390/rs13163240.

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