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Climatic Influence on the Carotenoids Concentration in a Mediterranean Coastal Lagoon Through Remote Sensing

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Abstract: The Albufera of Valencia, a Mediterranean coastal lagoon, has experienced a shift to hypertrophic conditions over the past 40 years due to agricultural and urban-industrial pollution. From August 2023 to early 2024, the water of the lagoon turned reddish-brown. This change has been observed in the past, but never with this intensity or duration, which typically occurs during periods of drought. In this study, carotenoid concentrations were analyzed in relation to precipitation and temperature using field and remote sensing data from February 2016 to December 2023. In November 2023, samples showed unusually high concentrations of carotenoids. The study confirmed the effectiveness of a new algorithm for estimating carotenoids using Sentinel-2 imagery to complement chlorophyll-a data. Results showed that temperature and precipitation significantly influenced carotenoid/chlorophyll-a ratio, highlighting a climatic control of phytoplankton community structure. These results highlight the importance of long-term monitoring and conservation efforts to address climate change and human impacts. This research is a first step in using optical properties of lakes as an indicator of phytoplankton dynamics under environmental stress and warns of the potential for increased occurrence or persistence of such phenomena with future climate trends.

Keywords: phytoplankton pigments; climate change; ecological monitoring

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Citation: Molner, J.V.; Pérez-González, R.; Sòria-Perpinyà, X.; Soria, J. Climatic Influence on the Carotenoids Concentration in a Mediterranean Coastal Lagoon Through Remote Sensing. *Remote Sens.* **2024**, *16*, 4067. https://doi.org/10.3390/rs16214067

Academic Editors: Michael Nones, Paolo Paron and Maria Nicolina Papa

Received: 20 September 2024
Revised: 28 October 2024
Accepted: 29 October 2024
Published: 31 October 2024

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1. Introduction

Peri-urban wetlands are of critical importance in modern urban environments due to their strategic location at the urban–rural interface. This positioning endows them with substantial ecological, social, and economic value, providing essential ecosystem services such as water purification, flood control, and habitat for biodiversity [1]. However, these wetlands are facing numerous environmental challenges due to anthropogenic pressures, land use changes, and climate change, all of which are being exacerbated by their proximity to expanding urban and agricultural areas [2]. The most notable pressures include uncontrolled urbanization, industrial development, the introduction of invasive species, and agricultural runoff. These factors are causing a significant decline in the ecological quality of these ecosystems [3]. This degradation is a major cause for concern. It diminishes the wetlands' ability to regulate the water cycle and provide habitat for diverse species, which in turn leads to a decline in their overall ecosystem services.

Furthermore, climate change represents an ever-increasing threat to the integrity of these ecosystems. Alterations in precipitation patterns and rising temperatures will severely impact the quantity and quality of water in these wetlands, affecting their hydrology and the availability of habitats for aquatic and terrestrial species [4]. Wetlands require stable water levels to maintain their biological diversity. Fluctuations in hydrology inevitably result in habitat loss and reduced ecosystem resilience.

As mentioned above, wetlands are an important reservoir of diversity, and among this diversity, we find phytoplankton, photosynthetic microorganisms that play a fundamental

role in the ecological dynamics of this type of ecosystem [5]. One of the main characteristics of phytoplankton is the number of pigments they produce, including chlorophyll-a (Chl-a), phycocyanin (PC), and carotenoids (Car). These pigments play specific roles in photosynthesis and are valuable indicators for assessing the ecological status of phytoplankton and the ecosystem [6]. On the one hand, Chl-a is the main pigment present in plants for photosynthesis and light energy capture. The concentration of this pigment is closely linked to the primary production capacity of the ecosystem, as it reflects the ability of autotrophic communities to convert sunlight into organic matter [7]. In the case of PC, it is an accessory pigment that contributes to the absorption of light in the blue and green wavelengths and is a pigment of great interest in low light conditions, in addition to being characteristic of cyanobacteria [8].

In contrast, Car are fat-soluble organic compounds produced by terrestrial plants, algae, and some microorganisms [9]. They serve as accessory pigments, absorbing light and transferring energy to Chl-a during photosynthesis [10]. Additionally, Car act as antioxidants, protecting plant cells from damage caused by ultraviolet light and oxidative stress [11].

The function of Car is based on their optical properties. They absorb mainly in the ultraviolet-blue range, with their maximum absorption occurring between 400 and 500 nm [10]. The non-absorbed light is reflected, giving them an orange-reddish coloration, which is typical of some fruits of terrestrial vegetation that also contain them, such as carrots. The red coloration of these Car is due to their selective absorption of light in the visible spectrum. Astaxanthin and capsanthin, two types of Car found in algae and plants, are responsible for this phenomenon [12].

The relationships among these pigments can provide valuable information about the physiological and ecological status of phytoplankton in water masses and, thus, ecosystem functioning [13]. Regarding the relationship between Chl-a and Car, an increase in Chl-a may indicate adaptations of phytoplankton to low light conditions, leading to a bloom of cyanobacteria. This can result in eutrophic periods, significantly altering the water ecosystem dynamics. Then the water quality worsens significantly, and biodiversity is severely affected [14].

Furthermore, the ratio between Chl-a and Car is affected by climatic conditions because changes in the availability of light and nutrients, as well as fluctuations in water temperature, can cause variations in this ratio [15]. It is important to note that the interaction between climate and wetlands is complex and influenced by other environmental factors, such as nutrient availability and hydrology. This complexity makes it challenging to establish a direct relationship between climate and pigment ratios.

For this reason, accurate and up-to-date data collection is essential for understanding the dynamics of these ecosystems and their response to environmental changes. Traditional in situ sampling methods are valuable for data validation, but they have limitations when covering large areas and monitoring changes over time. Remote sensing is a method that allows us to acquire data from the Earth's surface using sensors carried by satellites [16]. These sensors capture solar radiation reflected or emitted by terrestrial or aquatic surfaces across different spectral bands. The European Space Agency's Sentinel-2 platform is the ideal choice for this task. It offers a valuable combination of advantages that make this satellite highly suitable because it provides global coverage with a revisit frequency of five days, facilitating regular and systematic data acquisition. Its 10 m spatial resolution in some spectral bands allows for detailed analysis of small areas, such as wetlands. The specific spectral bands of Sentinel-2 are ideal for detecting pigments like Car and Chl-a. In particular, the visible spectrum bands (red-green-blue) and near-infrared bands are sensitive to variations in the concentration of these pigments, allowing for precise estimation of the health of aquatic and terrestrial vegetation.

The objective of this study is to investigate the periodicity and conditions that cause the recurrent manifestation of the red-brown water pattern in the Albufera of Valencia. The study aims to determine its relationship with phenomena, such as high temperatures,

summer drought, and climate change. Additionally, we propose the development and calibration of a semi-empirical algorithm for estimating the concentration of Car in the Albufera using Sentinel-2 satellite images. This initiative would contribute to the development of the algorithm and increase the database in relation to the first objective, which is to identify Car abundance patterns in the Albufera. The researchers noted that although similar episodes of color change have occurred in the Albufera in the past decade, none have been as intense or long-lasting as the current phenomenon; nor have they been associated with such high concentrations of Chl-a. There is speculation about the possible role of climate change, particularly high temperatures and drought, in the proliferation of this new phytoplankton community and in the high pigment concentrations. The study of Car increment patterns in the Albufera of Valencia represents a significant advancement in the understanding of aquatic ecosystem biodiversity and dynamics.

2. Materials and Methods

2.1. Study Site

The Albufera of Valencia is an oligohaline, shallow, hypertrophic, Mediterranean coastal lagoon with an average depth of approximately 1 m. Between August 2023 and early 2024, the color of the object underwent a significant change from green to red-brown color. This change was caused by higher concentrations of Car than Chl-a, as shown in Figure 1. The phenomenon has generated significant interest in the local scientific and media communities. It is a lagoon formed for the closure of an original gulf due to the accumulation of fluvial sediments. Together with its surrounding marsh, it constitutes the Albufera Natural Park, a protected wetland spanning 210 km^2. The Albufera is included in the Natura 2000 Network as a Site of Community Importance (SCI) and a Special Protection Area for Birds (SPA).



Figure 1. (**A**) The field photograph depicts the typical green color of the Albufera of Valencia lagoon, which is indicative of the prevalence of blue-green cyanobacteria. Picture dated 9 June 2023; (**B**) The second photograph of the same location shows a change in color to reddish-brown. Picture dated 25 October 2023. Pictures by J.V.M.

Rainfall, together with the management of the Albufera Drainage Board for agricultural use in rice fields, determines the water regime of the lagoon. This affects water availability, salinity, nutrient concentration, and other environmental parameters [17,18]. The rice cycle in the Albufera of Valencia is a key factor that influences the management of the hydrological system and the residence time of water in the lagoon. During the rice sowing and cultivation period, which runs from mid-April to mid-September, water is continuously flowing from the canals into the lagoon to maintain the proper crop level of the rice fields. Throughout this phase, the outlet gates to the sea are partially closed to maintain an intermediate flow and water level in the lagoon, resulting in a low water renewal rate [19].

After the rice harvest, which takes place from mid-September to mid-October, there is a higher rate of water renewal in the lagoon. This change in the rice cycle affects the hydrological dynamics of the Albufera, which in turn influences water quality, as well as the presence of nutrients and suspended matter [19].

Figure 2 shows a Sentinel-2 image of the Albufera, which illustrates the observed reddish hues. These color changes are associated with elevated concentrations of Car, as indicated by the data collected in this study. The Albufera is situated a few kilometers south of Valencia city and is surrounded by a dense urban-industrial belt that contrasts with its natural environment. The map shows the sampling sites where data were collected for the study.

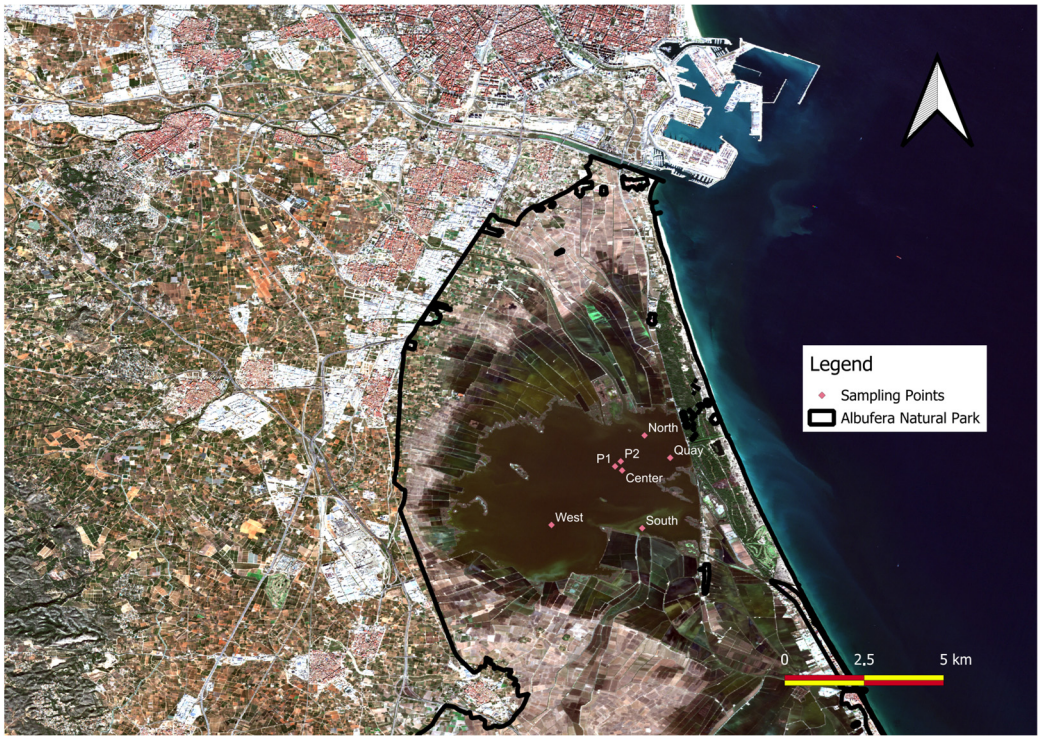


Figure 2. Map of the red-brown Albufera with the sampling points (pink diamonds). The black line represents the boundaries of the Natural Park. Sentinel-2 RGB image of 21 November 2023.

2.2. Sampling Methodology and Analysis

The University of Valencia's Limnology Group has been regularly monitoring the Albufera for decades by carrying out fortnightly samplings at predefined points throughout the year.

The data presented in this study were obtained from a series of field sampling campaigns conducted between February 2016 and December 2023. These field samples were taken on dates that differed by no more than three days from the dates of the corresponding Sentinel-2 satellite images, according to Kutser [20]. In each field trip, the same previously predefined points were sampled (North, Center, P1, P2, Quay, South, and, on occasion, West (see Figure 2)). However, due to logistical or meteorological constraints, not all points were sampled at each sampling event.

During fieldwork, temperature and conductivity are recorded using an EC/TDS/Temperature Tester (Hanna Instruments, Smithfield, RI, USA), and transparency is measured with the Secchi disk. Additionally, water samples are collected for subsequent laboratory analysis of relevant variables in accordance with ongoing research. These samples are maintained at a low temperature and in the absence of light.

Chl-a concentration is determined using the method of Shoaf and Lium [21]. The sample is filtered through Whatman GF/F glass fiber filters with a porosity of 0.47 mm.

The pigments are extracted using a 1:1 solution of 90% acetone and dimethyl sulfoxide, and the absorbance is measured in a spectrophotometer. The calculation equations of Jeffrey and Humphrey [22] are then applied. The Strickland and Parsons [23] formula is used to calculate Car.

2.3. Remote Sensing Data

Since 2015, remote sensing has been integrated into the research group procedures to improve monitoring and fill field data gaps. This is achieved by processing Sentinel-2 satellite images and applying semi-empirical algorithms derived from the correlation between variables measured in situ and captured spectral information.

In this context, the Sentinel-2 mission, launched by the European Space Agency (ESA), represents a fundamental instrument in our research. The Sentinel-2 mission comprises two twin satellites, Sentinel-2A (S2A) and Sentinel-2B (S2B), both equipped with the Multispectral Sensor Instrument (MSI). The sensor measures the irradiance of the Earth's surface in 13 bands, ranging from the visible (VIS) to the shortwave infrared (SWIR). The combined work of both twin satellites enables the acquisition of images with high spatial resolution (up to 10 m) and temporal resolution (revisit time of 5 days) for remote sensing [24].

We downloaded these images from the ESA Copernicus Browser portal. S2A or S2B satellite images that had already been atmospherically corrected with sen2cor (Level 2A) and were from the SYJ quadrant (zone 30), with cloud cover less than 15%. These images were coincident with the dates corresponding to the field data and were used to calibrate the Car algorithm. Additionally, a single image with the best cloud coverage quality was downloaded for each of the remaining months within the study period for which field data were not available, with the intention of using these images to calculate pigment concentration using specific algorithms and to construct a temporal series (see Section 2.5).

The images were processed using SNAP 9.0 software (Brockmann Consult, Hamburg, Germany), which was provided free of charge by ESA. The images were resampled to a 10 m resolution using the interpolation tool integrated in SNAP. The mean remote sensing reflectance of each of the 13 Sentinel-2 spectral bands at the water surface was calculated. This was performed on the 3×3 pixel grids corresponding to each field sampling point and on each of the processed images. The method followed was the one described by Kutser [20].

2.4. Carotenoids Algorithm Retrieval

Once the spectral reflectance of the selected images had been extracted, the dataset was randomly divided into two parts: 70% of the data was reserved for algorithm calibration, while the remaining 30% was used for validation. This approach is fundamental to the development of predictive models, as it allows for the evaluation of the algorithm's capacity to generalize its predictions to data that has not been previously observed.

The calibration phase entails fitting the model to the training data, which in this case constitutes 70% of the dataset. In this phase, statistical techniques, specifically linear regression, are employed to ascertain the correlation between the tested spectral indices and the Car concentrations measured in the field. This process is of great importance, as a well-calibrated model is capable of providing accurate estimates of Car concentrations as a function of spectral reflectance.

Then various spectral indices were evaluated to obtain the best estimation algorithm based on spectral characteristics of Car, which absorbs light on blue, and phytoplankton, which has light scattering in red-edge and near-infrared (Table 1). The models were calibrated using linear regression to relate calculated values to corresponding field values of Car concentration.

Table 1. Models Tested for Algorithm Retrieval.

Model	Reference
SABI	Alawadi [25]
R740/R560 R783/R560 R842/R560 R740/(R490 + R560) R783/(R490 + R560) (R740 + R783)/(R490 + R560)	This study

Validation is conducted using the remaining 30% of the data, which was not utilized during calibration. This is achieved by performing a linear regression between the values predicted by the calibrated algorithm and the field values obtained during measurements. In this context, the estimated values are those predicted by the model based on the spectral reflectance of the images, while the field values are the Car concentrations measured directly at the study site.

The objective of this linear regression is to establish a relationship between the model estimates and the observations. This analysis enables the calculation of performance metrics, such as the coefficient of determination (R^2), which indicates the proportion of the variability in the field data that is explained by the model. An R^2 value approaching 1 indicates that the model has a strong fit and is capable of accurately predicting Car concentrations.

Moreover, additional error indicators can be calculated (Equations (1)–(4)), such as the root mean square error (RMSE), which provides a measure of the average discrepancy between estimated and field values. These results are fundamental to determining the effectiveness of the algorithm and its applicability in the estimation of Car in the ecosystem under study.

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|x_i^{estimated} - x_i^{measured}\right| \quad (1)$$

$$NMAE = \frac{MAE}{\max(x_{measured}) - \min(x_{measured})} \times 100 \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(x_i^{estimated} - x_i^{measured}\right)^2}{N}} \quad (3)$$

$$NRMSE = \frac{RMSE}{\max(x_{measured}) - \min(x_{measured})} \times 100 \quad (4)$$

The practice of dividing the dataset into a calibration set and a validation set is a standard procedure in data analysis and model development. This approach helps to prevent overfitting, which occurs when a model fits too closely to the training data and loses its generalizability. Adherence to this procedure guarantees that the model is not only precise in its representation of the data used to construct it but also retains its efficacy when applied to novel datasets. This is of paramount importance for the interpretation of results in the context of remote sensing of Car in aquatic ecosystems.

2.5. Data Analysis

An initial field database is available from February 2016 to December 2023, with breaks in 2019–2020 and part of 2021. Utilizing this original database, we have calculated the mean Secchi Disk depth and concentrations of Chl-a and Car, in addition to the calculation of the Car/Chl-a ratio for the months during which field sampling was conducted. The objective was to obtain a single numeric value for each variable on a month-by-month basis.

To complete the database with data for months without field data, a Sentinel-2 satellite image was downloaded for each month without field data, and the Chl-a concentration was calculated using the algorithm described by Pereira-Sandoval et al. [26] and Sòria-

Perpinyà et al. [27], and the concentration of Car was calculated using the algorithm developed in the present study. To this end, the mean value of all pixels within the Albufera lake was calculated using a previously defined region of interest (ROI) polygon, excluding the shoreline to circumvent the edge effect.

Meteorological information was obtained from the meteorological station "Tancat de la Pipa", which is managed by the Valencian Association of Meteorology. The station records data in real time and publishes it in a freely accessible virtual database. The data extracted from 2016 to 2023 includes monthly precipitation (mm) and average monthly temperature (°C). The Gaussen xerothermic [28] and Mantorne's [29] aridity indexes were used to classify the months climatically based on the provided information. This method provides a detailed characterization of the climatic conditions during the study period, which is essential for analyzing the relationship between environmental variables and pigment dynamics in the Albufera of Valencia ecosystem.

First, the data was normalized using the Legendre criteria [30]. Subsequently, principal component analysis (PCA) was conducted using the correlation matrix to reduce the dimensionality of field data and facilitate the interpretation of the relationships between pigment concentrations (Car and Chl-a) and environmental variables. The objective of PCA is to identify underlying patterns in the dataset and to determine which climatic and environmental variables exert the greatest influence on the variability of pigment concentrations. Furthermore, PCA enables the identification of instances where Car data exhibit anomalous concentrations, which may be anticipated under specific environmental circumstances. To examine the dynamics of pigments and their correlation with climatic variables, we conducted several methodological procedures. Initially, we performed a trend analysis using the Mann–Kendall test to assess potential temporal trends in pigment concentrations and their ratio to the considered climatic variables. This analysis enabled us to identify significant patterns of change over time. Furthermore, a Pearson correlation analysis was conducted to investigate the connections between pigment concentrations and their ratios with climatic variables for the same month and the previous three months, including aridity indices. The analysis of three months of climatic data is justified by the observation that this coloration has been documented in the context of prolonged droughts, which have been known to last for two to three months. These analyses were performed using the free statistical software PAST 4.05.

3. Results

3.1. Field Data

The field database covers the period from February 2016 to December 2023, with a total of 65 samples. Table 2 presents the descriptive statistics of the variables measured from the water samples collected in the sampling points shown in Figure 2.

Table 2. Summary Statistics of Limnological Variables Recorded at Field Samplings from 2016 to 2023.

	Water Temp (°C)	pH	Conductivity (µS/cm)	Chl-a (mg/m^3)	Secchi (m)	Car (mg/m^3)
N	65	28	65	63	64	60
Min	6.9	7.9	1091	21.1	0.10	10.6
Max	32.0	11.3	2920	376.0	0.65	540.4
Mean	21.7	8.9	2020	135.0	0.30	85.1
Std. error	0.9	0.2	59	10.3	0.01	12.3
Variance	49.2	0.8	229,338	6659.4	0.01	9078.0
Stand. dev	7.0	0.9	479	81.6	0.11	95.3
Median	24.0	8.5	1990	118.9	0.29	61.9
25 percentile	14.8	8.3	1621	76.6	0.25	42.9
75 percentile	28.2	9.6	2400	169.8	0.38	88.9
Skewness	−0.41	1.23	0.02	1.12	0.56	3.64
Kurtosis	−1.25	0.73	−0.85	0.88	0.46	13.97
Geom. mean	20.4	8.9	1962	112.7	0.28	63.1
Coeff. var	32.3	9.8	24	60.4	37.15	111.9

The Chl-a and Car concentration values are normally distributed according to the Shapiro–Wilk test (W = 0.9489, $p = 0.03$, and W = 0.6823, $p < 0.001$ respectively).

Figure 3 displays the PCA results, using one field data for each of the 65 samplings conducted.

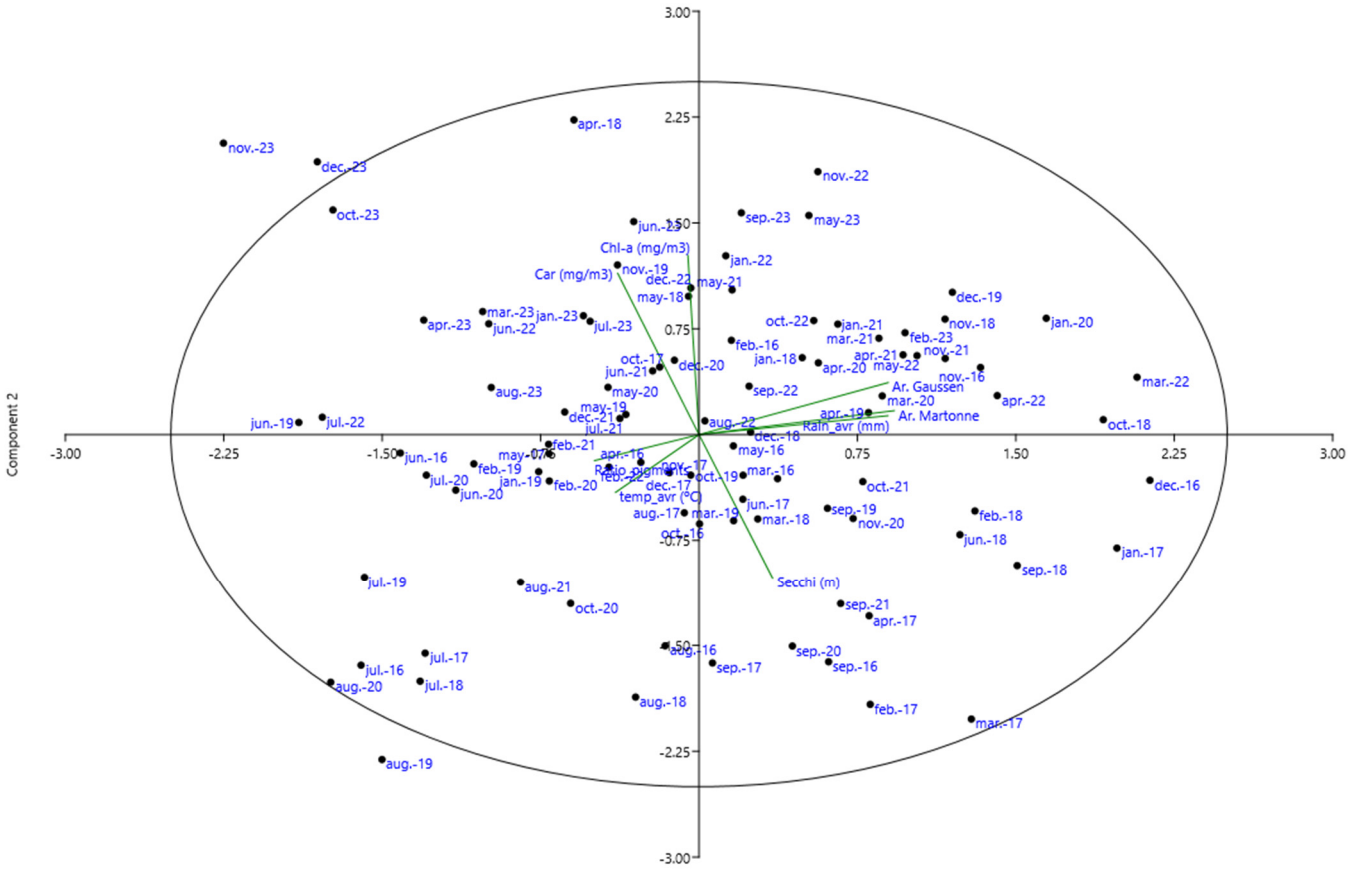


Figure 3. PCA plot performed on field data from 2016 to 2023. The circle corresponds to the 95% confidence interval.

Tables 3 and 4 present the results of the PCA in matrix form.

Table 3. Percentage of Variance Explained by Each Principal Component in the PCA Analysis.

PC	Eigenvalue	% Variance
1	3.223	40.29
2	2.326	29.07
3	1.168	14.60
4	0.788	9.85
5	0.413	5.17
6	0.070	0.87
7	0.007	0.09
8	0.004	0.05

PC1 is positively correlated with climatic variables (precipitation and aridity indexes), while PC2 is positively correlated with phytoplankton pigments. Figure 3 illustrates that the data for aug-19, nov-23 and dec-23 are anomalous in comparison to the remainder of the dataset, indicating that the concentration of pigments was particularly elevated during this period.

Table 4. Correlation Matrix Obtained Throughout the PCA Analysis.

	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8
Car/Chl	−0.2798	−0.0883	0.6156	−0.5989	0.0758	−0.0674	0.4042	−0.0494
Chl-a (mg·m^{-3})	−0.0298	0.6101	−0.1713	0.2357	0.3483	−0.0294	0.6440	−0.0709
Car (mg·m^{-3})	−0.2175	0.5487	0.2252	−0.1325	0.4145	0.0104	−0.6374	0.0708
Secchi (m)	0.1966	−0.4880	−0.1658	−0.0826	0.8288	0.0426	0.0103	−0.0083
temp_mean (°C)	−0.2234	−0.1964	0.5523	0.6958	0.1006	0.3263	0.0359	0.0667
Prec_mean (mm)	0.5055	0.0644	0.3456	0.1425	0.0141	−0.3588	−0.0967	−0.6799
Aridity Gaussen	0.5063	0.1771	0.1001	−0.2325	−0.0609	0.8014	0.0332	−0.0335
Aridity Martonne	0.5225	0.0816	0.2809	0.0534	0.0095	−0.3393	0.0608	0.7209

3.2. Algorithm Retrieval

The calibration and validation results of the algorithms used to estimate Car in the Albufera of Valencia are presented in Table 5. After analyzing the data, we have identified an algorithm that demonstrates higher accuracy in estimating Car in this ecosystem.

Table 5. Results of Calibration and Validation of Algorithms for the Estimation of Car in the Albufera of Valencia.

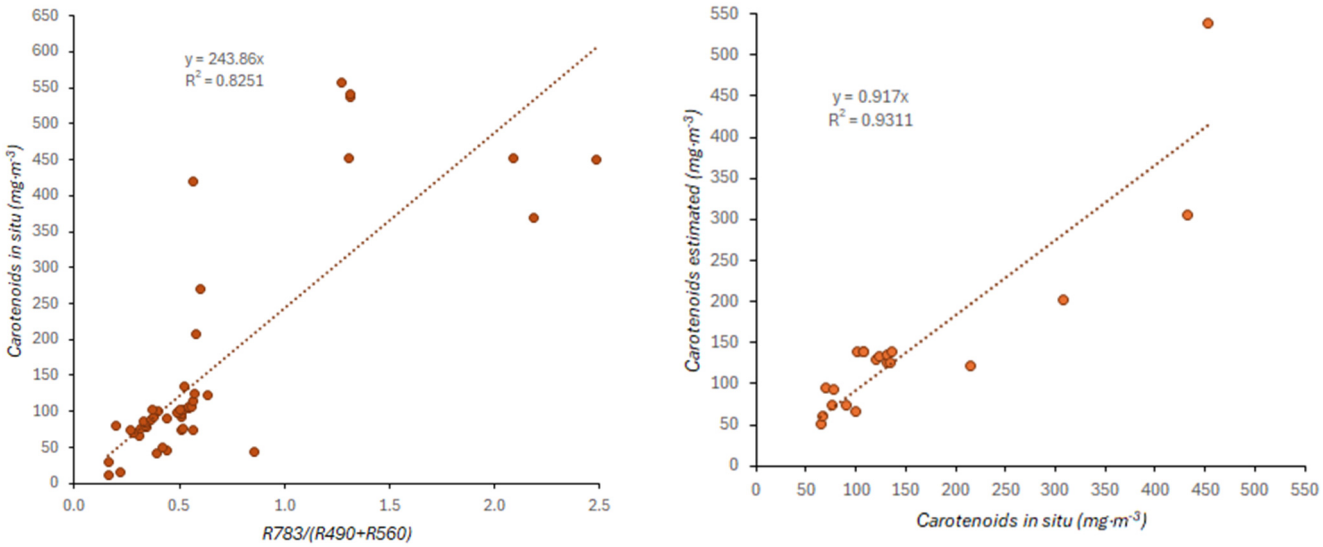
Algorithm	R^2	RMSE (mg·m^{-3})	nRMSE	MAE (mg·m^{-3})	nMAE
395.96 × SABI^2 + 500.176 × SABI + 114.4164	0.72	66.32	17.08%	46.19	11.90%
178.5 × R740/R560	0.83	59.76	15.39%	45.86	11.81%
184.71 × R783/R560	0.83	58.08	14.96%	45.20	11.64%
213.59 × R842/R560	0.82	65.14	16.78%	50.12	12.91%
232.16 × R740/(R490 + R560)	0.81	55.01	14.17%	34.29	8.83%
243.86 × R783/(R490 + R560)	0.83	49.52	12.76%	33.12	8.53%
118.97 × (R740 + R783)/(R490 + R560)	0.82	52.23	13.46%	33.52	8.63%

The algorithm that demonstrated the best performance in estimating Car concentrations for the Albufera of Valencia is the one that achieved the highest coefficient of determination (R^2) and the lowest values for mean absolute error (MAE), normalized mean absolute error (NMAE), root mean square error (RMSE), and normalized root mean square error (NRMSE). These metrics collectively indicate that this algorithm not only provides a strong correlation between the estimated and observed values but also minimizes the discrepancies in predictions, thereby making it the most reliable choice for our analysis. Therefore, this algorithm was selected for its superior accuracy and consistency in estimating carotenoid concentrations, which is crucial for understanding the dynamics of the aquatic ecosystem in the Albufera lagoon:

$$[\text{Car}] = 243.86 \times \frac{\text{R783}}{\text{R490} + \text{R560}} \quad (5)$$

For a better understanding of its performance, refer to the calibration and validation plots presented in Figure 4.

The results indicate that the selected algorithm is effective in accurately estimating Car in the Albufera of Valencia. Its application has complemented the existing algorithm for Chl-a, as documented in the literature. This was essential in completing the field database, which had gaps where no sampling had been carried out.



(**a**) (**b**)

Figure 4. (**a**) Calibration plot of the R783/(R490 + R560) index for the estimation of Car in Albufera of Valencia; (**b**) Validation plot with field data.

3.3. Temporal Series

The monthly time series was generated from the original field database. In order to obtain data for the months without field data for Chl-a and Car, the values estimated by remote sensing algorithms applied to Sentinel-2 imagery were used. This methodology is described in Section 2.5. The temporal tracking of the pigment ratio alongside means monthly precipitation and aridity is shown in Figures 5 and 6, respectively. This representation allows for a preliminary observation of the hypothesized relationship between these variables, which has been suggested from the observation of the phenomenon over the years. The abnormal accentuation in the autumn of 2023 is particularly noteworthy, as shown in the figure.

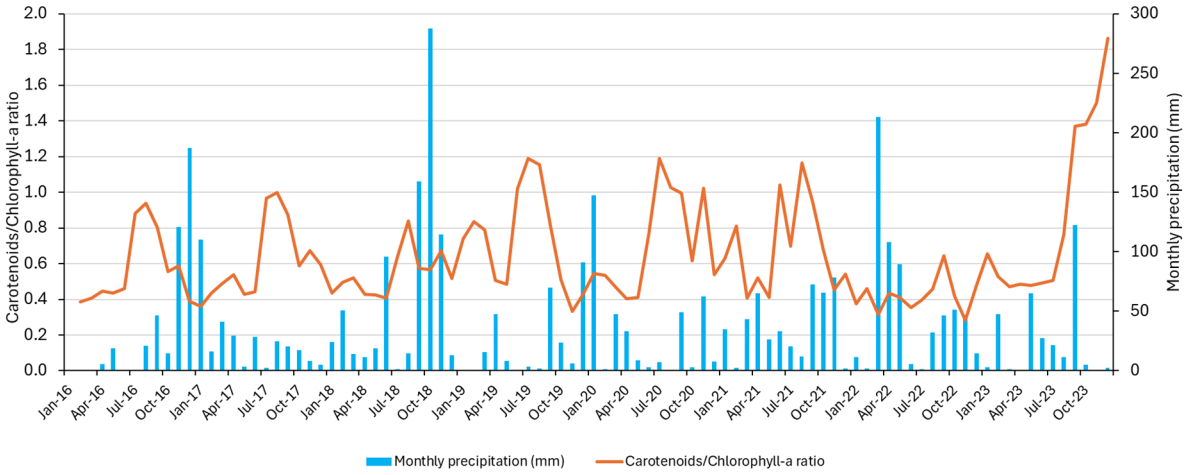


Figure 5. Graph showing the monthly Car/Chl-a ratio (orange) and monthly precipitation (mm) during the study period.

The graph shows that the water has turned golden-brown (0.6 < [Car]/[Chl-a] < 1) or red-brown (1 < [Car]/[Chl-a]) during periods of scarce precipitation. This index reflects the relative abundance of Car compared to Chl-a, which can be indicative of shifts in phytoplankton community composition under varying environmental conditions. While this classification is based on our expert judgment and extensive field observations, further

studies could provide a more robust framework for understanding these color changes in the context of the Albufera lagoon. This coloration has been observed after prolonged droughts, lasting two to three months. The fall of 2023 was notable for an unprecedented magnitude and duration, as observed both visually and statistically in historical records.

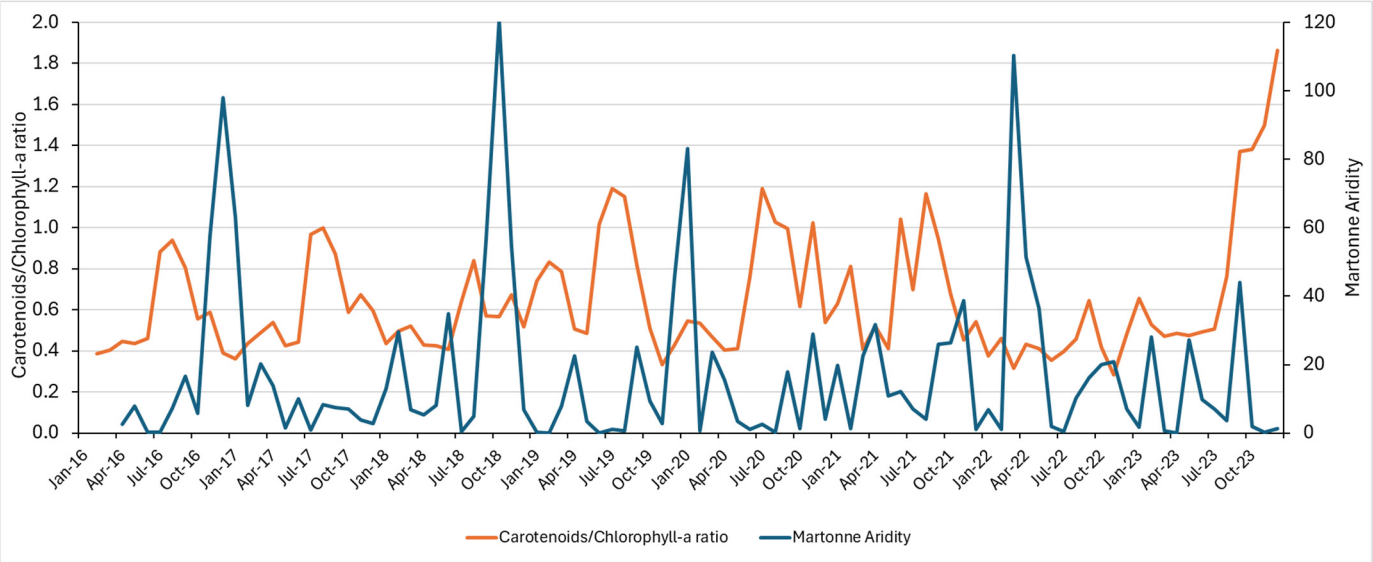


Figure 6. Graph showing the monthly Car/Chl-a ratio (orange) and Martonne aridity index during the study period.

3.4. Data Analysis

An exhaustive analysis of trends in climatic variables and pigment concentration in the Albufera has been conducted. In terms of climatic variables, there is no significant trend in monthly average temperature ($p = 0.3771$) or monthly precipitation ($p = 0.824$) recorded between 2016 and 2023 in the Albufera of Valencia. However, when analyzing only the months corresponding to the meteorological summer (June to August), slightly different trends become apparent. No significant trend was observed in monthly precipitation ($p = 0.2749$). However, there was a gradual increase in monthly average temperatures during the summer months ($p = 0.0441$). This finding is particularly relevant when considering mean maximum temperature ($p = 0.0158$), absolute maximum ($p = 0.074$), and mean minimum temperature ($p = 0.039$).

Regarding biological variables, there is a significantly increasing trend in Chl-a ($p < 0.0001$) and Car ($p < 0.0001$), while the ratio between the two shows no significant trend ($p = 0.4536$). Additionally, the Secchi disk depth of vision shows a decreasing trend ($p < 0.0001$), which is consistent with the increasing pigment concentration.

Significant correlations were found after performing a correlation analysis between pigments and the considered climatic variables. The correlations were more remarkable in the case of the variables at three months (refer to Table 6).

Specifically, the Car/Chl-a ratio showed a significant correlation with the meteorological variables of the previous three months, including accumulated rainfall, average temperature, and aridity indices. The ratio is positively correlated with the average temperature over a period of three months and negatively correlated with precipitation and aridity over the same period. Observations indicate that when the rainfall in the previous three months is less than 50 mm, there is a high probability that the ratio will exceed the 0.6 threshold. This can result in values of 1.2 during very arid summer periods, which can cause the visual effect of "red-brown water", as evidenced in autumn 2023. Under normal conditions, the Car/Chl-a ratio ranges between 0.35 and 0.55 when the water appears green.

Table 6. Results for r of Pearson's Correlation Between Pigments and Meteorological Data.

	[Car]/[Chl-a]	[Chl-a] (mg/m^3)	[Car] (mg/m^3)
[Car]/[Chl-a]			
[Chl-a] (mg/m^3)	−0.320 **		
[Car] (mg/m^3)	0.319 **	0.787 ***	
Secchi disk (m)	−0.166 ns.	−0.834 ***	−0.760 ***
Monthly temperature (°C)	0.315 **	−0.225 *	−0.004 ns.
3 months average temperature (°C)	0.417 ***	−0.203 *	0.085 ns.
Monthly rainfall (mm)	−0.288 ns.	0.003 ns.	−0.195 ns.
3 months accumulated rainfall (mm)	−0.437 ***	0.251 *	−0.031 ns.
Gaussen aridity (monthly)	−0.319 **	0.129 ns.	−0.089 ns.
Gaussen aridity (3 months average)	−0.482 ***	0.352 ***	0.034 ns.
Mantorne aridity (monthly)	−0.312 **	0.022 ns.	−0.193 ns.

Signification level: "*" means $p < 0.05$, "**" means $p < 0.01$, "***" $p < 0.001$, ns. is nonsignificant.

4. Discussion

4.1. Climatic Control on Pigments Dynamics

The increased climatic variability and land use change to which ecosystems such as peri-urban wetlands are exposed represent a determining factor that implies numerous changes. The concentration of Chl-a and Car in an organism is highly responsive to changes in the surrounding environment. These changes may be due to alterations in temperature, sunlight, wind, or nutrient availability [31].

The rise in temperature associated with climate change results in the stratification of water masses and a reduction in vertical mixing, which ultimately leads to a decline in the availability of nutrients in the surface layers of the water. This, in turn, frequently results in an increase in the proliferation of cyanobacteria, which leads to a notable rise in the concentration of Chl-a and Car in water bodies [31]. Nevertheless, stratification in the limnological sense has never been observed in the Albufera lagoon. According to the methodology of Hutchinson [32], later described by Wetzel [33], a thermocline is considered to be present when there is a drop of more than 1 °C per meter of depth, maintained for at least three continuous meters. This is not possible in the Albufera, a shallow lake with an average depth of 1 m, where the action of the wind generates daily vertical mixing, preventing the formation of a thermal gradient of 3°. For this reason, there are no published studies on this phenomenon in the lagoon.

In any case, a reduction in water availability, whether due to a lack of precipitation or the occurrence of sudden meteorological events such as storms or intense rainfall within a short timeframe, also impacts water quality. In periods of drought, water levels decline, which can concentrate nutrients and create favorable conditions for the proliferation of algae or cyanobacteria. Conversely, heavy rainfall can increase water turbidity and cause nutrients to leach from the surrounding land, which can also alter pigment concentrations [31].

Recent studies, such as that conducted by Ding et al. [34], have demonstrated that climatic changes, particularly increased temperatures and alterations in the rainfall regime, are modifying the phenology of phytoplankton in inland water bodies. Such alterations consequently influence pigment concentration, which has direct ramifications for water quality and biodiversity.

The analyses show a consistent pattern of increasing concentrations of Chl-a and Car since 2016. However, the ratio between the two pigments does not exhibit a clear trend. Our analysis indicates that climatic factors, particularly the cumulative effect during the previous three months, control the ratio between pigments. Other notable events have been observed in the summers of 2010, 2015, 2016, 2017, and 2018, in addition to the most significant event in summer–autumn 2023 in terms of extent and magnitude. During these years, Car equaled or exceeded Chl-a, resulting in a higher ratio between them and a more

golden-brown appearance of the water. However, attention to this discrepancy was limited at that time because the watercolor was less pronounced than in 2023.

The absence of this phenomenon in 2022 is likely due to the abundant rainfall recorded in the spring of that year (1164.6 mm between March and June 2022). Although analytical data is not available for the years 2019, 2020, and 2021, remote sensing from the Sentinel-2 satellite reveals that the Car/Chl-a ratio was above 0.8 in all summers of these years, always coinciding with high temperatures and very low precipitation. A comparable circumstance was mentioned in 1995, which was also a year of severe drought. However, complete analytical data from that time is not available. These results emphasize the intricate interplay between biotic and abiotic components in aquatic ecosystems, highlighting the significance of considering multiple factors in water quality studies.

The analysis of the algorithm's effectiveness in this study highlights several important considerations. It is crucial to consider the algorithm's limitations, particularly in relation to Car concentration. The study found that errors in estimation increase above 200 mg/m^3, which may impact the accuracy of results at higher concentrations. The limitation of this study is compounded by the scarcity of data in this range compared to lower concentrations. This is due to the uniqueness of these events, which may introduce biases in the analysis. However, a high correlation between pigment ratio and climatic variables has been observed, suggesting a significant influence of the environment on pigment dynamics in the Albufera of Valencia ecosystem. Additionally, the relationship between pigments appears to be influenced by other factors that should be considered for long-term management, such as water availability, pollution, and eutrophication.

Our analysis indicates that climatic factors, particularly the cumulative effect during the previous three months, control the ratio between pigments. Therefore, the climate significantly influences the composition of phytoplankton communities. The data indicates that climatic conditions, such as temperature and precipitation, actively shape pigment dynamics in the Albufera. These findings emphasize the urgent necessity to gain a deeper understanding of these climatic mechanisms and their effects on ecosystem health, particularly in the context of climate change and other human pressures. This knowledge is crucial for developing adaptive management strategies that safeguard the long-term integrity and resilience of this valuable aquatic ecosystem.

In their study, Hintz et al. [35] anticipated that phytoplankton communities could adapt to alterations in light availability. They postulated that these changes would manifest in two distinct ways: firstly through the acclimation of the species themselves and, secondly, through the emergence of new species. Furthermore, the emergence of new species was observed, yet there was minimal adaptation among existing species. Instead, there was a notable shift in the emergence of new species, indicating a significant transformation in the community and structure of phytoplankton. This study corroborates the findings of previous research, demonstrating that in response to substantial environmental fluctuations, a species that had previously been present in smaller quantities was able to take over the lagoon.

A variety of environmental stressors can exert a deleterious impact on phytoplankton communities. One such stressor, and one that is particularly prevalent in the Mediterranean, is the warming of the water. In the study by Häder et al. [36], it was observed that the different species of phytoplankton in their study area exhibited modified behaviors when exposed to conditions of oxygen deficiency and water warming. This resulted in the loss of photosynthetic capacity in some species and facilitated bacterial growth, which increased oxygen consumption and contributed to the expansion of hypoxic zones.

4.2. Comparison with Other Remote Sensing Studies on Color Changes in Aquatic Environments

Satellite-borne sensors are employed in inland water studies for a variety of purposes, with the choice of sensor type dependent on the specific requirements of the study in question. These sensors may be classified as either hyperspectral or multispectral. In this study, the analogous satellite is Sentinel 2, which has a lower spatial resolution and

longer revisit time than Landsat-8. However, it includes thermal bands that allow for the monitoring of water temperature, which is useful for analyzing how temperature influences phytoplankton proliferation and pigment concentration. An additional example of a sensor is the MODIS (Moderate Resolution Imaging Spectroradiometer), which exhibits a lower spatial resolution than the aforementioned sensors but boasts a higher revisit frequency (1–2 days). This makes it more suitable for monitoring extensive areas and providing data on water temperature.

Upon comparison with other similar studies, it becomes apparent that there is a lack of solid baselines in previous literature. While some studies, such as Bhattacharjee et al. [37] and El-Alfy et al. [38], have explored Car detection by remote sensing in aquatic environments, most of the literature concentrates on terrestrial plants. The absence of comparative studies makes it challenging to compare our findings and emphasizes the necessity for further research in this field of remote sensing applied to phytoplankton.

In terms of optical differences, our study found that the inverse indices, with red edge and infrared positively correlated with pigments and blue and green negatively, were more effective. This contrasts with the study by El-Alfy et al. [38], which observed a correlation between Car, obtained also with Strickland and Parsons [23] method, and the B3/B8 band ratio. The difference in results can be attributed to the optically turbid nature of the hypertrophic Albufera lagoon, which is dominated by cyanobacteria [39]. Additionally, Bhattacharjee et al. [37] developed the Normalized Difference Haloarchaea Index (NDHI) in a hypersaline lake and applied existing indices such as the salinity index (SI) and the surface algal bloom index (SABI) [25]. Although the mathematical similarity between the methods used in our study and those mentioned by Alawadi [25] is evident, our research did not yield satisfactory results when using the former. It is worth noting that SABI, as stated by Alawadi [25], is a robust method for detecting algal blooms in nature.

The best features of Sentinel 2 are that it has an advantage in imaging frequency and the ability to provide large area images with good resolution, and for these two reasons, it was chosen for this study. The study by Li et al. [40] showed that the combination of different satellites in studies provides better accuracy in estimating water quality and phytoplankton pigments.

The algorithm calibration has shown a direct correlation between the recent trends in phytoplankton pigments and a higher reflectivity of the water body in the near-infrared range, specifically between 740 and 783 nm. This range exhibits optical properties that differ from those expected for phytoplankton, which would be anticipated to have higher backscattering of light at 705 nm [41]. However, this finding may be partially due to light scattering caused by high concentrations of suspended particles [42]. This change in light scattering patterns could have significant implications for the spectral composition of water and the processes of photobiology and photochemistry in the aquatic environment [43].

4.3. Implications of This Study

The optical behavior of the Albufera lagoon is thought to vary due to the presence of one or more species of cyanobacteria or chlorophyceae, which may explain the elevated Car concentrations observed in autumn 2023. However, it is unclear whether these species have been present in the Albufera lagoon or in other environments previously. Additional research utilizing both microscopic and molecular approaches is necessary to further validate the results of this study.

To date, there have been few studies specifically addressing the concentration and ratio of Car to Chl-a in this type of ecosystem. This study has allowed us to evaluate the relationship between these patterns and climatic variables.

A clear trend in the color changes observed in the lagoon has not been discernible, as this phenomenon has occurred more noticeably for the first time. Despite this, the study reveals evidence of climatic control on the pigment ratio and, consequently, on the composition of the phytoplankton community over the last eight years. This raises the possibility of medium- to long-term persistence of this phenomenon in the lagoon, provided

that the appropriate aridity conditions are present. Therefore, it is crucial to consider the potential implications of climate change on the occurrence of such episodes.

The identified trend toward an increase in temperature during the summers of 2016 to 2023 generates concern due to the likelihood of greater summer aridity in the area. This climate change aligns with projections of increasing temperature and decreasing precipitation for the Mediterranean region in the coming years, resulting in increased aridity in the basin [44,45]. The frequency and intensity of drought events in the region may disrupt algal bloom patterns and modify the composition and structure of phytoplankton communities. It is possible that this phenomenon may recur in the future and persist due to evolving climatic conditions.

4.4. Future Research

To improve the results of this work, future research should focus on identifying the microorganism responsible for Car production in the Albufera. It is important to note that the remote sensing approach used in this study can complement and enrich microscopic and molecular investigations of phytoplankton in the Albufera of Valencia. This information is essential for a comprehensive understanding of the biological processes involved in the synthesis and cycling of Car in the aquatic ecosystem. Additionally, it is possible to expand the study period by utilizing Landsat-5 and Landsat-8 satellite data to analyze phenomena that occurred prior to 2016. This text provides a historical perspective on the dynamics of Car in the Albufera, which contextualizes the trends observed in our current analysis. Future research aims to investigate the relationship between the inputs of different forms of nitrogen and phosphorus through the irrigation ditches into the lagoon and their influence on the trends detected in individual pigments. This detailed analysis could provide a better understanding of the factors that drive the observed changes in pigment composition and concentration in the Albufera of Valencia.

5. Conclusions

The algorithm developed for the estimation of Car concentration in the Albufera of Valencia has been validated using field data, yielding statistically satisfactory results. The algorithm permitted the estimation of pigments over an eight-year period (2016–2023), demonstrating its utility as a continuous monitoring tool for water quality in this aquatic system. During the aforementioned period, a statistically significant trend of increasing Chl-a and Car concentrations was observed, concomitant with a decrease in water transparency. This suggests a progressive deterioration of the trophic status of the lagoon.

Furthermore, climatic variables, including temperature, precipitation, and aridity indices, have been identified as having a notable correlation with the Car/Chl-a ratio. However, these climatic factors do not exert a significant influence on the individual concentrations of these pigments. This suggests that climatic conditions exert a greater influence on the composition of the phytoplankton community than on the total algal biomass. However, no statistically significant periodicity could be established in the occurrence of the red-brown water phenomenon in the Albufera, although these episodes coincide with periods of prolonged drought.

A trend of increasing temperatures has been identified during the study period, indicating the potential for these episodes to persist in the future. In this context, it is crucial to continue monitoring the pigment ratio as an indicator of changes in phytoplankton communities in response to climatic conditions. This approach provides a valuable complement to other methodologies, offering a comprehensive understanding of the ecological processes that affect water quality in aquatic systems, such as the Albufera de Valencia.

Author Contributions: Conceptualization, J.V.M. and J.S.; methodology, J.V.M.; investigation, J.V.M. and R.P.-G.; data curation, J.V.M. and J.S.; writing—original draft preparation, J.V.M. and R.P.-G.; writing—review and editing, X.S.-P. and J.S.; supervision, X.S.-P. and J.S.; funding acquisition, X.S.-P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Conselleria d'Educació, Universitats i Ocupació of the Generalitat Valenciana, grant number CIPROM/2021/049.

Data Availability Statement: Images are available through the ESA Copernicus Hub, and the data presented is available from the corresponding author upon request because the project is still in progress and the data is being utilized for the development of other works.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Alikhani, S.; Nummi, P.; Ojala, A. Urban Wetlands: A Review on Ecological and Cultural Values. *Water* **2021**, *13*, 3301. [CrossRef]
2. Hettiarachchi, M.; Morrison, T.H.; McAlpine, C. Forty-three years of Ramsar and urban wetlands. *Glob. Environ. Change* **2015**, *32*, 57–66. [CrossRef]
3. Azous, A.L.; Horner, R.R. *Wetlands and Urbanization: Implications for the Future*; Lewis Publishers: Boca Raton, FL, USA, 2001.
4. Burley, J.G.; McAllister, R.R.J.; Collins, K.A.; Lovelock, C.E. Integration, synthesis and climate change adaptation: A narrative based on coastal wetlands at the regional scale. *Reg. Environ. Change* **2012**, *12*, 581–593. [CrossRef]
5. Cardoso, S.J.; Roland, F.; Loverde-Oliveira, S.M.; Huszar, V.L. Phytoplankton abundance, biomass and diversity within and between Pantanal wetland habitats. *Limnologica* **2012**, *42*, 235–241. [CrossRef]
6. Sebastia, M.-T.; Rodilla, M.; Sanchis, J.-A.; Altur, V.; Gadea, I.; Falco, S. Influence of nutrient inputs from a wetland dominated by agriculture on the phytoplankton community in a shallow harbour at the Spanish Mediterranean coast. *Agric. Ecosyst. Environ.* **2012**, *152*, 10–20. [CrossRef]
7. Marra, J.; Bidigare, R.R.; Dickey, T.D. Nutrients and mixing, chlorophyll and phytoplankton growth. *Deep-Sea Res.* **1990**, *37*, 127–143. [CrossRef]
8. Rousso, B.Z.; Bertone, E.; Stewart, R.A.; Rinke, K.; Hamilton, D.P. Light-induced fluorescence quenching leads to errors in sensor measurements of phytoplankton chlorophyll and phycocyanin. *Water Res.* **2021**, *198*, 117133. [CrossRef]
9. Britton, G.; Liaaen-Jensen, S.; Pfander, H. *Carotenoids Hand Book*; Birkhäuser: Basel, Switzerland, 2004.
10. Féret, J.B.; Gitelson, A.A.; Noble, S.D.; Jacquemoud, S. PROSPECT-D: Towards modeling leaf optical properties through a complete lifecycle. *Remote Sens. Environ.* **2017**, *193*, 204–215. [CrossRef]
11. Huang, J.J.; Lin, S.; Xu, W.; Cheung, P.C.K. Occurrence and Biosynthesis of Carotenoids in Phytoplankton. *Biotechnol. Adv.* **2017**, *35*, 597–618. [CrossRef]
12. Rosas-Saavedra, C.; Stange, C. Biosynthesis of Carotenoids in Plants: Enzymes and Color. *Subcell. Biochem.* **2016**, *79*, 35–69.
13. Margalef, R. *Ecologia*; Ediciones Omega. SA: Barcelona, Spain, 1974.
14. Brient, L.; Lengronne, M.; Bertrand, E.; Rolland, D.C.; Sipel, A.; Steinmann, D.; Baudin, I.; Legeas, M.; Rouzic, B.L.; Bormans, M. A phycocyanin probe as a tool for monitoring cyanobacteria in freshwater bodies. *J. Environ. Monit. JEM* **2008**, *10*, 248–255. [CrossRef] [PubMed]
15. Lehman, P.W. Comparison of chlorophyll a and carotenoid pigments as predictors of phytoplankton biomass. *Mar. Biol.* **1981**, *65*, 237–244. [CrossRef]
16. Glasgow, H.B.; Burkholder, J.M.; Reed, R.E.; Lewitus, A.J.; Kleinman, J.E. Real-time remote monitoring of water quality: A review of current applications, and advancements in sensor, telemetry, and computing technologies. *J. Exp. Mar. Biol. Ecol.* **2004**, *300*, 409–448. [CrossRef]
17. Soria, J.M. Past, present and future of la Albufera of Valencia Natural Park. *Limnetica* **2006**, *25*, 135–142. [CrossRef]
18. Jégou, A.; Sanchis-Ibor, C. The Opaque Lagoon. Water Management and Governance in l'Albufera de València Wetland (Spain). *Limnetica* **2019**, *38*, 503–515. [CrossRef]
19. Soria, J.; Vera-Herrera, L.; Calvo, S.; Romo, S.; Vicente, E.; Sahuquillo, M.; Sòria-Perpinyà, X. Residence Time Analysis in the Albufera of Valencia, a Mediterranean Coastal Lagoon, Spain. *Hydrology* **2021**, *8*, 37. [CrossRef]
20. Kutser, T. The possibility of using the Landsat image archive for monitoring long time trends in coloured dissolved organic matter concentration in lake waters. *Remote Sens. Environ.* **2012**, *123*, 334–338. [CrossRef]
21. Shoaf, W.; Lium, B. Improved extraction of chlorophyll a and b from algae using dimethyl sulfoxide. *Limnol. Oeanogr.* **1976**, *21*, 926–928. [CrossRef]
22. Jeffrey, S.T.; Humphrey, G.F. New spectrophotometric equations for deter-mining chlorophylls a, b, c1 and c2 in higher plants, algae and natural phytoplankton. *Biochem. Physiol. Pflanz.* **1975**, *167*, 191–194. [CrossRef]
23. Strickland, J.D.H.; Parsons, T.R. *A Practical Handbook of Seawater Analysis*; Fisheries Research Board of Canada: Ottawa, ON, Canada, 1972.
24. Fletcher, K. (Ed.) *ESA's Optical High-Resolution Mission for GMES Operational Services*; ESA Communications: Noordwijk, The Netherlands, 2012; ISBN 978-92-9221-419-7.
25. Alawadi, F. Detection of surface algal blooms using the newly developed algorithm surface algal bloom index (SABI). In *Remote Sensing of the Ocean, Sea Ice, and Large Water Regions 2010*; International Society for Optics and Photonics: Bellingham, WA, USA, 2010; p. 782506.

26. Pereira-Sandoval, M.; Urrego, E.P.; Ruiz-Verdú, A.; Tenjo, C.; Delegido, J.; Soria-Perpinyà, X.; Vicente, E.; Soria, J.; Moreno, J. Calibration and validation of algorithms for the estimation of chlorophyll-a concentration and Secchi depth in inland waters with Sentinel-2. *Limnetica* **2019**, *38*, 471–487. [CrossRef]
27. Soria-Perpinya, X.; Urrego, P.; Pereira-Sandoval, M.; Ruíz-Verdú, A.; Peña, R.; Soria, J.; Delegido, J.; Vicente, E.; Moreno, J. Monitoring the ecological state of a hypertrophic lake (Albufera of València, Spain) using multitemporal Sentinel-2 images. *Limnetica* **2019**, *38*, 457–469. [CrossRef]
28. Gaussen, H.; Bagnouls, F. L'indice xérothermique. *Bull. Assoc. Geogr. Fr.* **1952**, *29*, 10–16. [CrossRef]
29. De Martonne, E. *Les Régions Géographiques de la France*; Flammarion: Paris, France, 1921.
30. Legendre, P.; Legendre, L. *Numerical Ecology*, 3rd ed.; Elsevier: Amsterdam, The Netherlands, 2012.
31. Hintz, N.H.; Schulze, B.; Wacker, A.; Striebel, M. Ecological impacts of photosynthetic light harvesting in changing aquatic environments: A systematic literature map. *Ecol. Evol.* **2022**, *12*, e8753. [CrossRef]
32. Hutchinson, G.E. *A Treatise on Limnology*; Wiley: New York, NY, USA, 1957.
33. Wetzel, R.G. *Limnology*; Saunders: Philadelphia, PA, USA, 1975.
34. Ding, Y.; Pan, B.; Zhao, G.; Sun, C.; Han, X.; Li, M. Geo-climatic factors weaken the effectiveness of phytoplankton diversity as a water quality indicator in a large sediment-laden river. *Sci. Total Environ.* **2021**, *792*, 148346. [CrossRef]
35. Hintz, N.H.; Zeising, M.; Striebel, M. Changes in spectral quality of underwater light alter phytoplankton community composition. *Limnol. Oeanogr.* **2021**, *66*, 3327–3337. [CrossRef]
36. Häder, D.-P.; Gao, K. Aquatic Productivity under Multiple Stressors. *Water* **2023**, *15*, 817. [CrossRef]
37. Bhattacharjee, R.; Choubey, A.; Das, N.; Ohri, A.; Gaur, S. Detecting the carotenoid pigmentation due to haloarchaea microbes in the Lonar lake, Maharashtra, India using Sentinel-2 images. *J. Indian Soc. Remote Sens.* **2021**, *49*, 305–316. [CrossRef]
38. El-Alfy, M.A.; Alzeny, A.M.; El-Tohamy, W.S.; Qayoom, I.; Abd El-Hamid, H.T. Integrating Sentinel 2A data for selecting the best methods in observation of biological pigments in coastal water. *Ecol. Front.* **2024**, *44*, 538–546. [CrossRef]
39. Romo, S.; García-Murcia, A.; Villena, M.J.; Sánchez, V.; Ballester, A. Tendencias del fitoplancton en el lago de la Albufera de Valencia e implicaciones para su ecología, gestión y recuperación. *Limnetica* **2008**, *27*, 11–28. [CrossRef]
40. Li, J.; Hong, D.; Gao, L.; Yao, J.; Zheng, K.; Zhang, B.; Chanussot, J. Deep learning in multimodal remote sensing data fusion: A comprehensive review. *Int. J. Appl. Earth Obs. Geoinf.* **2022**, *112*, 102926. [CrossRef]
41. Ogashawara, I.; Kiel, C.; Jechow, A.; Kohnert, K.; Ruhtz, T.; Grossart, H.-P.; Hölker, F.; Nejstgaard, J.C.; Berger, S.A.; Wollrab, S. The use of Sentinel-2 for chlorophyll-a spatial dynamics assessment: A comparative study on different lakes in northern Germany. *Remote Sens.* **2021**, *13*, 1542. [CrossRef]
42. Zhan, Y.; Delegido, J.; Erena, M.; Soria, J.; Ruiz-Verdú, A.; Urrego, P.; Sòria-Perpinyà, X.; Vicente, E.; Moreno, J. Mar Menor lagoon (SE Spain) chlorophyll-a and turbidity estimation with Sentinel-2. *Limnetica* **2022**, *41*, 305–323. [CrossRef]
43. Gilerson, A.; Zhou, J.; Hlaing, S.; Ioannou, I.; Schalles, J.; Gross, B.; Moshary, F.; Ahmed, S. Fluorescence component in the reflectance spectra from coastal waters. Dependence on water composition. *Opt. Express* **2007**, *15*, 15702–15721. [CrossRef] [PubMed]
44. Noto, L.V.; Cipolla, G.; Pumo, D.; Francipane, A. Climate change in the Mediterranean Basin (Part II): A review of challenges and uncertainties in climate change modeling and impact analyses. *Water Resour. Manag.* **2023**, *37*, 2307–2323. [CrossRef]
45. Gomez-Gomez, J.D.; Pulido-Velazquez, D.; Collados-Lara, A.J.; Fernandez-Chacon, F. The Impact of Climate Change Scenarios on Droughts and Their Propagation in an Arid Mediterranean Basin. A Useful Approach for Planning Adaptation Strategies. *Sci. Total Environ.* **2022**, *820*, 153128. [CrossRef]

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