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Potential for Coastal and Offshore Aquaculture in Portugal: Insights from Physico-Chemical and Oceanographic Conditions

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Abstract: Physico-chemical and biological parameters along the Portuguese coast were analyzed to evaluate the potential to produce aquatic species of economic interest. Water samples were collected in 2018 and 2019 in five different areas of the Portuguese coast. Currents data were collected between 2018 and 2020 and historical waves height data from 1988 to 2019. According to the results, there is a wide variety of species that can be considered for production. The northernmost area presented the lowest temperature, as well as the highest levels of chlorophyll *a*, and nitrate. Under such conditions, the rearing of salmon *Salmo salar*, mussel *Mytilus edulis*, scallop *Pecten maximus*, macroalgae *Porphyra umbilicalis*, and *Undaria pinnatifida* can be considered. Regarding the southernmost area, due to the highest temperature, this area seems appropriate for the production of meager *Argyrosomus regius*, sea bream *Sparus aurata*, sea bass *Dicentrarchus labrax,* and greater amberjack *Seriola dumerili*. This study highlights the challenges in deploying aquaculture structures on the Atlantic coast due to its oceanographic conditions. Site selection for aquaculture is a complex process and pilot studies are essential to analyze the feasibility of developing offshore aquaculture along the coast of Portugal.

Keywords: spatial planning; Portuguese coast; site selection; species selection

1. Introduction

1.1. Aquaculture

The current state of aquaculture plays a critical role in providing food and employment to millions of people, many of whom live and depend on aquaculture for subsistence. For this reason, aquaculture has been identified as the food industry with the highest annual growth rate with 5.3 percent per year in the period 2001–2018 [1]. Aquaculture in Portugal reached 14,336 mts in 2019 corresponding to an increase of 2.5% compared to the previous year [2]. Most of the Portuguese aquaculture is developed in old salt pans in the central and southern areas of Portugal, while freshwater aquaculture is scattered throughout the northern and central regions. In any case, land-based production in aquaculture recirculating systems (RAS) or in natural systems can be an option to increase the aquaculture production and can be appropriate for some species such as flat fishes, e.g., turbot (*Scophthalmus maximus*), Senegalese sole (*Solea senegalensis*), or to produce new species such as the sea urchin *Paracentrotus lividus* [3,4] and the sea cucumber *Holothuria mammata* [5]. However, the limited areas for aquaculture production mean that offshore aquaculture may be seen as a solution for other species rearing. Offshore aquaculture has been accepted as a sustainable, economical, and viable form of food production in many coastal nations [6–8]. This is mainly due to the problems related to coastal pollution, the use of resources [9], and the lack of suitable sites for production. To ensure the correct choice for new aquaculture

facilities offshore, it is necessary to understand all factors that influence the well-being of the organisms [10]. It is required to ensure adequate physico-chemical conditions, such as nitrogenous compounds (ammonia, nitrite, and nitrate), phosphate, silicate, dissolved oxygen, pH, temperature, and chlorophyll *a*. There is a very close relationship between the water quality and the survival and health of organisms, where poor water quality can cause mortality, slow growth, and can induce stress, reducing the farmed animals' health and welfare leading to increased susceptibility to diseases. The effort required by fishes, bivalves, or other aquatic organisms exposed to suboptimal water quality creates impacts and diverts energy from growth. Furthermore, survival declines as the water quality parameters diverge from the optimum for a species. According to Boyd [11], most of the problems with water quality in aquaculture result from the less-than-optimal quality of the water. Some of the major water-quality stressors are inappropriate values of water temperature, salinity, pH, or suboptimal concentrations of dissolved oxygen, ammonia nitrogen, and nitrite among others. From the standpoint of aquaculture implementation, location is the most relevant step as it is the broadest criterium. Knowledge of hydrographic conditions, such as swells and currents, is fundamental to deploying offshore aquaculture cages and other structures. Adverse marine conditions can cause damage to the equipment and lead to stock losses.

1.2. Fish Aquaculture

In Portugal, the production in aquaculture of marine fish represented 27.6% in 2018 and 46.8% in 2019, where 90% and 96% respectively were devoted to turbot, sea bream, and seabass [2,12]. In fact, according to the national statistics, there was a significant increase in the production of turbot (+38.7%) with 3580 mts, sea bream (+117.5%) with 1953 mts, and sea bass (+341.7%) which reached 882 mts in 2019. The increased production in aquaculture facilities of turbot and sea bass was due to more efficient production methods. Although this increase is a positive sign, national production still has a great potential for growth. The expansion of the fish industry may be dependent on the implementation of offshore submersible cages [13]. In this context, oceanographic conditions and temperature are key factors for the selection of species to implement aquaculture facilities in new locations. Temperature strongly influences the metabolism, feeding rate, and growth [14,15] and is also one of the most relevant parameters in fish farms for growing juveniles [16,17].

1.3. Bivalve Aquaculture

Bivalve mollusks rearing reached 15% of the total world catch in 2018, equivalent to 17.7 million mts [1]. In Portugal, bivalve production has the potential to increase due to geographical conditions [18]. The majority of bivalve production is focused on clam and oysters. Unlike what happened with fish, in 2019 the production of bivalves decreased compared to 2018. Clams remained the most affected species (3276 mts) having decreased 17.5%, followed by oysters, which, with 1690 mts, had a reduction of about half (−51.0%) compared to 2018. Mussels, with a production of 1457 mts, also decreased by 16.5%. This decrease in oysters and mussels is due to the fact that some offshore farmers have ceased to operate [2]. It is essential to evaluate the limiting factors for growth such as phytoplankton concentration, which is one of the most influential factors in the development of bivalves. Its availability allows the elimination of feed costs and simplifies farming techniques to produce a high-quality protein and essential fatty acids [19,20], and even a benefit to the environment [21–23].

1.4. Macroalgae Aquaculture

Portugal's maritime area has one of the largest and most diverse macroalgae communities in Europe [24], but its rearing is very scarce and currently concentrated in a single company. In recent decades, the interest in macroalgae has increased in Europe due to their biotechnological potential, bioactivities, and nutritional value for human consumption [25,26]. Nutrient availability, such as nitrogen compounds and phosphates is essential

for its production. Temperature and solar irradiance also must be taken into consideration as these parameters influence the growth and chemical composition of macroalgae [27].

1.5. Objectives

This study is part of the "Aquimar project—General characterization of aquaculture areas for the establishment of marine cultures" which aims to characterize the oceanographic, physico-chemical, geochemical, and biological conditions of the Portuguese coastal waters in order to optimize the selection of sites and species for coastal and offshore aquaculture. Considering that there is an extensive Portuguese coastline that could be used for the development of marine aquaculture, the results of physical, chemical, and biological parameters such as temperature, ocean currents, waves, ammonia, nitrite, nitrate, silicate, phosphate, dissolved oxygen, salinity, pH, and chlorophyll *a* were compared with the ideal growth factors for some fish, bivalves and macroalgae species with economic interest and potential for aquaculture.

2. Materials and Methods

2.1. Field Surveys

This study was conducted alongside the Portuguese Coast in 5 areas (Figure 1) with field surveys in 2 different periods between 5 and 26 October 2018 (2018) and between 13 April and 14 May 2019 (2019).
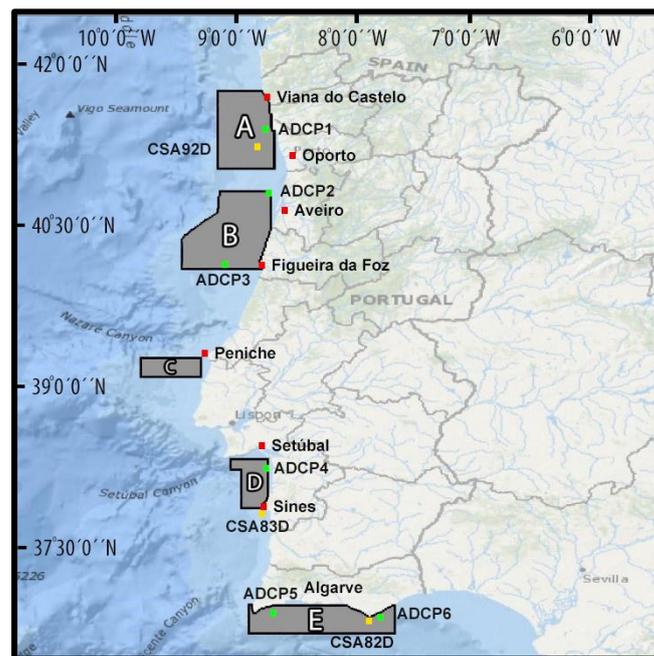

Figure 1. Map of the 5 study areas from the Aquimar project (A—Area A (between Viana do Castelo and Oporto); B—Area B (between Aveiro and Figueira da Foz); C—Area C (Peniche); D—Area D (between Setúbal and Sines); E—Area E (Algarve region); (■ main cities near the surveyed areas); Wave buoys stations ■: CSA92D; CSA83D and CSA82D; Currents stations ■: ADCP1, ADCP2, ADCP3, ADCP4, ADCP5, and ADCP6).

Water samples were collected with CTD (conductivity, temperature, depth) profiles being acquired along the water column. For the purpose of this study, data from the superficial layer (2–7 m depth) was selected. For the nutrients analysis, the water samples were filtered using 0.45 μm pore size polycarbonate filters and preserved at a temperature below −18 °C in high-density polyethylene bottles until subsequent analysis at the Hydrographic Institute (IH) laboratories. Total oxidized nitrogen (also known as nitrate + nitrite, μmol L^{-1}; NO$_x$), nitrites (μmol L^{-1}; NO$_2$), ammonia (μmol L^{-1}; NH$_3$), phosphate

(PO_4; µmol L^{-1}), and silicate (µmol L^{-1}; SiO_2) were analyzed. Nitrates (µmol L^{-1}; NO_3) were estimated by calculating the difference between NO_x^- and NO_2^-. The water samples for chlorophyll *a* (µg L^{-1}) analysis were filtered using 0.45 µm pore size mixed cellulose ester filters and the filters were preserved at a temperature below $-18\,°C$ until subsequent analysis at the IH laboratories. pH and dissolved oxygen (mg-O_2 L^{-1}) measurements were performed at the ship's laboratory, while temperature (°C) and salinity data were extracted from the CTD profiles for the desired depths. Water collection was carried out in 265 stations and 249 stations in 2018 and 2019, respectively (Table 1).

Table 1. Number of stations for water collection per area in the 2018 and 2019 field surveys.

Year \ Areas	A	B	C	D	E	Total
2018	55	65	12	23	110	265
2019	45	59	18	22	105	249

2.2. Biological and Physico-Chemical Analysis

The biological and physico-chemical parameters were determined in the IH laboratories, according to test methods mostly accredited to NP EN ISO/IEC 17025:2005. Quality control was carried out for all tests, including the performance of duplicates (for every batch of 10 samples), blank tests and spiked samples (per day of work), use of certified reference materials CRM), and participation in QUASIMEME (Quality Assurance of Information in Marine Environmental Monitoring) intercalibration exercises. The CRM results were within the uncertainty of the certified materials and the QUASIMEME intercomparison exercises were consistent with satisfactory performance (Z-score < 3). The concentration of nutrients (NO_2, NO_x, NH_3, PO_4, and SiO_2) was determined by segmented flow analysis-molecular absorption spectrometry using a Skalar SANplus Segmented Flow AutoAnalyzer, specifically designed for the analysis of saline samples. NO_2 and NO_x were determined according to Strickland and Parsons [28], PO_4 was determined according to Murphy and Riley [29] and SiO_2 was determined according to Koroleff [30]. Salinity, pH, dissolved oxygen (mg L^{-1}), and temperature (°C) were determined in-situ using the equipment Guideline Autosal8400B, pH Metrohm 744" and "pH Metrohm 827, Thermo Scientific Orion Star 2135 and IDRONAUT General Oceanics, respectively. Chlorophyll *a* concentration was determined by molecular absorption spectrometry using the Jeffrey and Humphrey [31] method using a Thermo Scientific Evolution 201 UV-Vis spectrometer.

The map of surface temperature (up to 7 m) was made using the ArcGIS software for Windows, in the "ArcMap" division, version 10.2.2. This software allows geographic and oceanographic data to be interpolated into high-resolution maps with different interpolation options, where this study used the "Empirical Bayesian Kriging" interpolation method to create the surface temperature maps.

2.3. Mean Monthly Temperature

Mean monthly temperature data were collected from the NASA GHRSST (Group for High-Resolution Sea Surface Temperature, Level 4) project platform. This platform collects daily ocean temperature data up to 1 m depth across the globe. It uses AVHRR (Advanced Very High Resolution Radiometer), AMSR-E (Advanced Microwave Scanning Radiometer), GOES (Geostationary Operational Environmental Satellite), and MODIS (Moderate Resolution Imaging Spectroradiometer) systems (Naval Oceanographic Office, GHTSST Level 4, 2008). This platform allows the extraction of oceanographic temperatures every 625 km^2 (25 × 25 km). The daily temperature values were used to collect and calculate the monthly mean temperature values in 2018 (Figure 2a) and 2019 (Figure 2b) within the boundaries of each area studied.
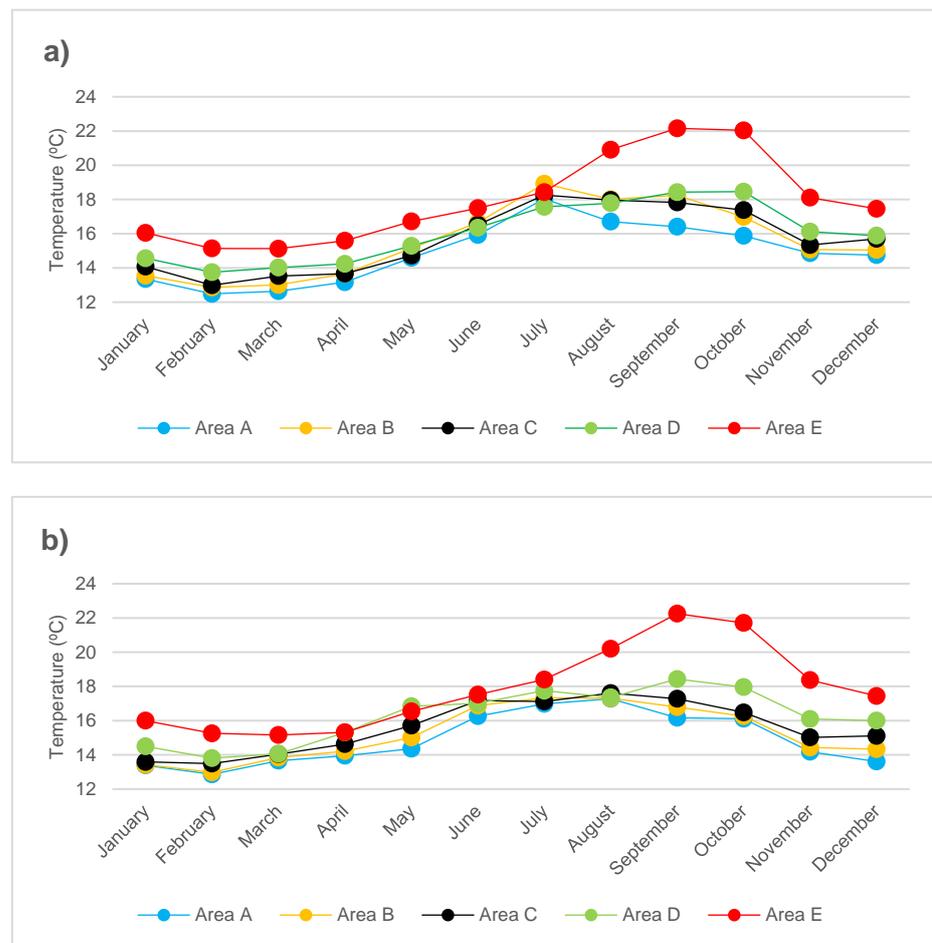
Figure 2. Mean monthly temperature (°C) of the water surface (up to 1 m deep) in the 5 study areas (**a**) 2018 and (**b**) 2019 (water temperature data based on satellite reanalysis data).

2.4. Waves

Wave data was collected from three moored buoys (Figure 1) managed under protocols between the IH and the "Administração do Porto do Douro e de Leixões" (APDL) and "Administração dos Portos de Sines e do Algarve" S. A. (APS) between the time periods of 1996 and 2019 for Leixões; 1988 and 2019 for Sines and 1986 and 2019 for Faro. The analysis of the Leixões buoy is used to characterize the waves in central and north-western Areas A, B, and C, the Sines buoy to characterize the waves in Area D and the Faro buoy to characterize the waves in Area E.

2.5. Currents

In order to study the currents along the water column, several "Acoustic Doppler Current Profiler" (ADCP) of the RD Instruments brand were deployed during the timeframe of the AQUIMAR project, for a minimum period of 3 months at 5–30 m depth between 2018 and 2020. Since Area E covers the entire southern coast of the Algarve, two points were established to cover the area (Figure 1)—one in the western Algarve (Lagos) and one in the eastern Algarve (Olhão). The same method was applied for Area B, where 2 points were defined to collect the data: one point in the north (Aveiro) and the other point in the south (Figueira da Foz). In each of the Areas A and D, one point was set up to represent each location: in Póvoa do Varzim and Comporta, respectively. In Area C it was decided not to place any observation point due to the risk of equipment loss caused by trawling activities.

2.6. Species Selection

A few authors have identified some promising species to be developed in offshore aquaculture as some of them are native and are economically interesting. Among them are fish such as the meagre *Argyrosomus regius* [32], cod *Gadus morhua* [33], salmon *Salmo salar* [34], gilthead sea bream *Sparus aurata* [35], sea bass *Dicentrarchus labrax* [36], sardine *Sardina pilchardus* [37], and greater amberjack *Seriola dumerili* [38]; mollusks bivalves such as mussel *Mytilus edulis* [39], scallop *Pecten maximus* [40], oyster *Magallana gigas* [41], and clam *Ruditapes decussatus* [42]; or even macroalgae as *Gracilaria gracilis* [43], *Porphyra umbilicalis* [44], and *Undaria pinnatifida* [45]. A survey of indexed papers in Scopus (published between 1975 and 2021) was carried out with the aim of compiling the optimal growth parameters for these species that can have the potential to be produced in aquaculture offshore or in coastal areas in Portugal. The maximum, minimum, and optimal data of temperature and limiting compounds for fish, bivalve, and macroalgae species are also analyzed and related to the results of the water quality parameters obtained in the AQUIMAR field surveys and thus, the areas with the greatest potential to implement aquaculture for each species are identified.

2.7. Statistical Analysis and Data Processing

The concentration of nutrients (ammonia, nitrite, nitrate, silicate, phosphate), chlorophyll *a*, dissolved oxygen, temperature, salinity, pH, and chlorophyll *a* data were analyzed by two-way ANOVA using IBM SPSS™ Statistics for Windows, version 23 (IBM Corporation, Armonk, NY, USA). Differences between the means were tested using the Tukey HSD test post hoc. Significant differences were considered when $p < 0.05$. Concentrations of ammonia, nitrite, and phosphate below the respective limits of quantification were signaled. The wave height (Hm0) data were processed and presented in terms of minimum, maximum, and mean values and predominant wave direction found for each site. Sea currents data were analyzed to determine the absolute maximum intensity and the predominant direction for each analyzed location.

3. Results

3.1. Biological and Physico-Chemical Parameters

During the field surveys of 2018 and 2019, ammonia, nitrite, and phosphate systematically revealed concentrations below the respective limits of quantification in all areas (Table 2). In both surveys, Area A presented the highest mean concentrations of nitrate (1.27 and 1.8 µmol L^{-1} respectively), while Areas B (0.55 and 0.75 µmol L^{-1}) and D (0.53 and 0.77 µmol L^{-1}) showed the lowest mean values in both surveys, however, no significant differences were detected ($p > 0.05$). Furthermore, Area A also displayed the highest concentrations of chlorophyll *a* in both surveys (2.03 and 5.12 µg L^{-1}), whereas Areas E (0.30 µg L^{-1}) and C (1.06 µg L^{-1}) presented the lowest mean concentrations in 2018 and 2019, respectively. Although without statistically significant differences ($p > 0.05$), the area that showed the highest silicate concentrations (3.04 and 2.17 µmol L^{-1}) was Area C in both surveys, and Areas D and B indicated the lowest concentrations (1.58 and 1.20 µmol L^{-1}) in 2018 and 2019, respectively. Dissolved oxygen showed statistically significant differences ($p < 0.05$) in area A, with a lower dissolved oxygen value in 2018 (7.66 mg L^{-1}) than in 2019 (9.23 mg L^{-1}). pH showed a very homogeneous behavior between areas and surveys while salinity presented significantly higher values in the south.

Table 2. Mean ± standard deviation values of ammonia, nitrite, nitrate, chlorophyll *a*, silicate, phosphate, pH, dissolved oxygen, and salinity were determined for the 2018 and 2019 surveys for the surface level (2 to 7 m depth). Values below a determined concentration are the limit of quantification for each parameter analyzed are signaled with the symbol <. Note: values sharing a different letter were significantly different ($p < 0.05$) between the area for each year of a field survey; * represents statistically significant differences between the field surveys in the different years ($p < 0.05$).

Area	2018									2019								
	Ammonia NH_3 (μmol L^{-1})	Nitrite NO_2 (μmol L^{-1})	Nitrate NO_3 (μmol L^{-1})	Chlorophyll *a* (μg L^{-1})	Silicate SIO_2 (μmol L^{-1})	Phosphate PO_4 (μmol L^{-1})	pH	Dissolved Oxygen (mg-O_2 L^{-1})	Salinity (PSU)	Ammonia NH_3 (μmol L^{-1})	Nitrite NO_2 (μmol L^{-1})	Nitrate NO_3 (μmol L^{-1})	Chlorophyll *a* (μg L^{-1})	Silicate SIO_2 (μmol L^{-1})	Phosphate PO_4 (μmol L^{-1})	pH	Dissolved Oxygen (mg-O_2 L^{-1})	Salinity (PSU)
A	<1.00	0.19 ± 0.15	1.27 ± 1.31 [a]	2.03 ± 1.05 [a]	2.34 ± 2.35 [a]	0.21 ± 0.14 [a]	8.04 ± 0.06 [a]	7.66 ± 0.68 [a*]	35.52 ± 0.19 [a]	<1.00	0.11 ± 0.13 [a]	1.80 ± 2.30 [a]	5.12 ± 3.64 [a]	1.91 ± 1.49 [a]	<0.20	8.11 ± 0.08 [a]	9.23 ± 0.74 [a*]	35.53 ± 0.25 [a]
B	<1.00	<0.10	0.55 ± 0.57 [a]	0.94 ± 0.66 [a]	2.23 ± 1.64 [a]	<0.20	8.10 ± 0.03 [a]	7.86 ± 0.56 [a]	35.75 ± 0.07 [a]	<1.00	<0.10	0.75 ± 0.92 [a]	1.26 ± 1.23 [b]	1.20 ± 0.64 [a]	<0.20	8.10 ± 0.07 [a]	8.54 ± 0.59 [a]	35.65 ± 0.10 [a]
C	<1.00	<0.10	0.74 ± 1.28 [a]	0.85 ± 0.35 [a]	3.04 ± 1.76 [a]	<0.20	8.08 ± 0.08 [a]	7.82 ± 0.40 [a]	35.95 ± 0.04 [a]	<1.00	<0.10	1.18 ± 0.60 [a]	1.06 ± 0.70 [b]	2.17 ± 1.45 [a]	<0.20	8.12 ± 0.05 [a]	8.59 ± 0.69 [a]	35.80 ± 0.06 [a]
D	<1.00	<0.10	0.53 ± 0.51 [a]	0.62 ± 0.49 [a]	1.58 ± 0.32 [a]	0.21 ± 0.14 [a]	8.10 ± 0.07 [a]	7.85 ± 0.39 [a]	36.11 ± 0.06 [ab]	<1.00	<0.10	0.77 ± 0.55 [a]	1.35 ± 1.08 [b]	1.50 ± 0.55 [a]	<0.20	8.14 ± 0.04 [a]	8.76 ± 0.45 [a]	35.94 ± 0.03 [ab]
E	<1.00	<0.10	0.90 ± 1.31 [a]	0.30 ± 0.21 [b]	2.35 ± 1.64 [a]	0.24 ± 0.29 [a]	8.12 ± 0.05 [a]	7.29 ± 0.83 [a]	36.48 ± 0.16 [b]	<1.00	0.15 ± 0.12 [a]	1.80 ± 0.13 [a]	2.34 ± 1.99 [ab]	1.24 ± 0.65 [a]	<0.20	8.07 ± 0.07 [a]	8.58 ± 0.49 [a]	36.09 ± 0.06 [b]

As previously stated, the temperature can be the most important factor to decide the location of offshore and coastal aquaculture implementation and species selection. It can be noticed that the highest temperatures were measured during the 2018 survey (Figure 3). Area E presented the highest surface temperatures and Area A the lowest surface temperatures in both surveys.
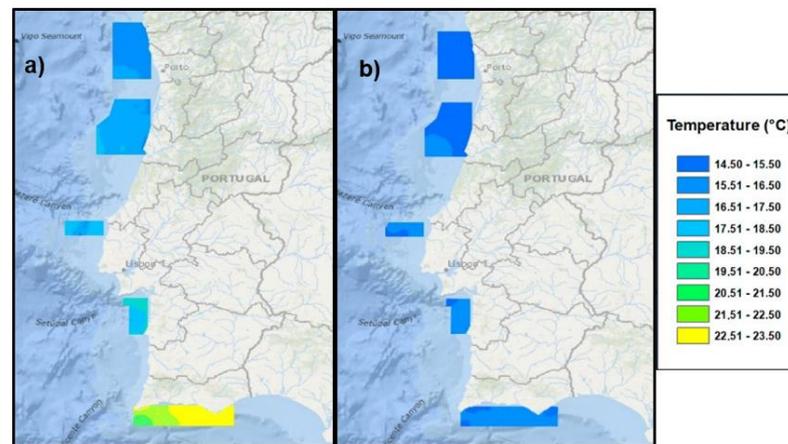

Figure 3. Map of surface temperature (°C) in the 5 study areas of the Portuguese coast in (**a**) October 2018 and (**b**) April 2019 surveys.

3.2. Limit and Optimal Parameters for Production

The compilation of minimum, maximum, and optimal temperatures to grow the selected species with potential for offshore and coastal aquaculture in Portugal are presented in Tables 3–5. Nutrient levels (ammonia and nitrite) that can compromise the survival and growth performance of fish and bivalves are also presented in Tables 3 and 4. The most important and common parameter for all groups of species is temperature, although, for bivalves, it is also fundamental to assess the food availability in the terms of phytoplankton, for which chlorophyll *a* was used as a phytoplankton biomass indicator (Table 4). For macroalgae, the nutrient availability in the form of nitrogen and phosphate was described in Table 5. The pH, dissolved oxygen, and salinity values observed in Table 2 are within the requirements of the species studied and were not considered limiting factors.

Table 3. Minimum, maximum, and optimal temperature (°C) and limits of ammonia (μmol L^{-1}) and nitrite (μmol L^{-1}) tolerated by the selected fish.

Fish	Temperature (°C)			Ammonia (NH$_3$)	Nitrite (NO$_2$)
	Minimum	Maximum	Ideal		
Meagre (*Argyrosomus regius*)	13.0 °C [29] 14.0 °C [46]	28.0 °C [29] 26.0 °C [46]	20.0–21.0 °C (Larvae) [29] 26 °C [47]	Lc 50 * —41.1 μmol L^{-1} (3.0 ± 0.9 g; 96 h; 30 PSU; 22 °C; pH: 8.2) [48]	Lc 50 * —849.6 μmol L^{-1} (3.2 ± 0.6 g; 96 h; 30 PSU; 22 °C; pH: 8.0) [49]
Atlantic Cod (*Gadus morhua*)	−1.5 °C [50]	17.0 °C (Juvenile) [51]	7.0 °C [51] 15.4 ± 1.1 °C [52] 8.2 ± 1.5 °C [52] 9.0 °C [53]	>5.9 μmol L^{-1} - Slow growth of juveniles, [54]	>20 μmol L^{-1} - Slow growth (7.0 ± 1.9 g; 96 days; 33 PSU; pH: 8.0) [55]
Atlantic Salmon (*Salmo salar*)	0.0–7.0 °C (Parr + smolt) [56,57] 14.0 °C [58–60] 8.0 °C (Post-smolt) [61,62]	22.0–28.0 °C (Parr + smolt) [56,57] 18.0 °C [58–60] 12.0 °C (Post-smolt) [61,62]	13.0 °C [63–65] 12.0–18.0 °C [66]	Lc 50 * —5.34 μmol L^{-1} (4.8–9.2 cm; 96 h; 12.5 °C; pH: 6.05; [67]) >2.06 μmol L^{-1}— Slow growth (17.4 ± 0.1 g; 35 PSU; pH: 7.2) [68]	>74 μmol L^{-1} - Slow growth (Smolt) [69]

Table 3. *Cont.*

Fish	Temperature (°C)			Ammonia (NH$_3$)	Nitrite (NO$_2$)
	Minimum	Maximum	Ideal		
Gilthead bream (*Sparus aurata*)	11.0 °C [70] 11.0–12.0 °C [71] 13.0 °C [72] >12.0 °C [73] >12.0 °C [74]	32.9 °C [70] 30.0 °C [75] 30.0 °C [74]	24.0–26.0 °C [76,77] 24.0 °C (Larvae) [78] 22.0 °C [75] 23.0 °C [73] 25.0 °C [74]	Lc 50 * —146.8 µmol L^{-1} (160 g; 96 h; 34 PSU; 18 °C; pH 8,1) [79] Lc 50—44.7 µmol L^{-1} (1.1 ± 0.1 g; 96 h; 30 PSU; 20 °C) [80]	-
Sea bass (*Dicentrarchus labrax*)	5.0 °C [81] 2.0–3.0 °C [77] 5.0 °C [82] 11.0–15.0 °C (Larvae) [77]	28.0 °C [81] 30.0–32.0 °C [77] 26.0 °C (Larvae) [83] 28.0 °C [82] 30.0–32.0 °C (Larvae) [77]	22.0–24.0 °C [81] 22.0–25.0 °C [77] 25.0 °C [84] 20.0–22.0 °C (Larvae) [77] 20.0 °C [85]	Lc 50 * —99.8 µmol L^{-1} (11 g; 96 h; 37 PSU; 21.8 °C; pH 8.0) [79]	Lc 50 * —1035 µmol L^{-1} (15 cm; 96 h; 36 PSU; 23 °C; pH 8.1–8.4) [86]
Sardine (*Sardina pilchardus*)	13.0 °C (Larvae) [37]	22.0 °C (Larvae) [37]	15.5–17.5 °C [87]	Lc 50 * —43.45 µmol L^{-1} (*Sardinella brasiliensis*; 1.04 ± 0.20 g; 96 h; 33.2 PSU; 19.2 °C) [88]	-
Greater amberjack (*Seriola dumerili*)	17.0 °C (Juvenile) [89]	-	26.5 °C (*Seriola lalandi*) [90] 26.0 °C (Juvenile) [89]	-	-

- Data not found. * Lc 50—Lethal concentration required to cause mortality in 50% of the individuals in a test.

Table 4. Minimum, maximum, and optimal temperature (°C) and limits of ammonia (µmol L^{-1}) and nitrite (µmol L^{-1}) tolerated by the bivalves to be produced in aquaculture and data of chlorophyll a (µg L^{-1}) or amount of microalgae needed for growth.

Bivalves	Temperature (°C)			Ammonia (NH$_3$)	Nitrite (NO$_2$)	Phytoplankton (Chlorophyll *a* or Concentration)
	Minimum	Maximum	Ideal			
Blue mussel (*Mytilus edulis*)	5.0 °C [91]	28.2 °C [91]	13.0–22.0 °C (*Mytilus californianus*) [92] 15.0–20.0 °C [93] 11.0–18.0 °C [94]	Lc 50 * —1.47 µmol L^{-1} (22 ± 2.5 mm; 21 days; 15.9 ± 0.5 °C; pH: 7.94 ± 0.07; 29.7± 0.03 PSU) [94]	-	Min: 0.5 µg L^{-1}– 0.9 µg L^{-1} Ideal: 6.3 µg L^{-1}– 10 µg L^{-1} (Chlorophyll *a*) [95,96]
Scallop (*Pecten maximus*)	4.0 °C [97] 6.5 °C [98] 5.0–8.0 °C [99]	22.9 °C [98]	16.0–17.0 °C [98] 10.0–14.0 °C [100]	-	-	Fast growth: 300 µg L^{-1} (*Rhodomonas baltica*) [101]
Osyter (*Magallana gigas*)	8.0–10.0 °C [102]	32.0 °C [103]	18.0–20.0 °C (*Magallana angulata*) [104]	-	-	Fast growth: 25 cells/hour/larvae (*Magallana angulata*) [105]
Razor clam (*Ruditapes decussatus*)	10.0 °C [106]	28.0 °C (Larvae D) [106]	20.0 ± 1.0 °C (Nothern region of the Iberian peninsula) [107] 22.0 ± 1.0 °C (Southern region of the Iberian peninsula) [107]	Slow growth: 99.8 µmol L^{-1} [108]		Fast growth: 70.000 cells mL^{-1} (*Isochrysis galbana*, *Pavlova lutheri* and *Chaetoceros muelleri* (1:1:2)) [109]

- Data not found. * Lc 50—Lethal concentration required to cause mortality in 50% of the individuals in a test.

Table 5. Minimum, maximum, and optimal temperature (°C), phosphate (μmol L^{-1}) and nitrogen (μmol L^{-1}) for the production of the selected potential macroalgae species to be produced in aquaculture in Portugal.

Macroalgae	Temperature (°C)			Phosphate (P)	Nitrogen Compounds (N)
	Minimum)	Maximum	Ideal		
Gracilaria (*Gracilaria gracilis*)	10.0 °C [110]	28.0 °C [110]	18.0–23.0 °C [110] 20–25 °C (*Gracilaria* sp.) [111] 25 °C (*Gracilaria verrucos*) [112]	-	-
Nori (*Porphyra umbilicalis*)	3 °C (Porphyra yezoensi) [113] 8 °C (*Porphyra haitanensi*) [113]	20.0 °C [114]	10.0–15.0 °C [113] 10.0 °C [115]	Fast growth: 19.50 μmol L^{-1} [116]	Fast growth: 35 μmol L^{-1} (Ammonia) [115]
Wakame (*Undaria pinnatifida*)	5 °C [117]	25.0 °C [117]	12.0–13.0 °C [118] 15.0 °C [117]	-	-

- Data not found.

3.3. Sea State

The sea state is characterized in Table 6, which shows the minimum, maximum, and mean of the wave height (Hm0) and predominant wave direction along the years mentioned in chapter 2.4 in the 5 study areas. It is possible to observe that Hm0 was lower in the south area (Area E) and higher in the north area (Areas A, B, and C). The predominant wave direction on the west coast of Portugal was Northwest and on the south coast of Portugal, the predominant wave direction was West-Southwest.

Table 6. Minimum, maximum, and mean of the significant wave height (Hm0) (m) and predominant wave direction in the areas studied.

	Sea State			
Areas	Hm0 (m) Minimum	Hm0 (m) Maximum	Hm0 (m) Mean	Predominant Wave Direction
A, B and C	0.30	9.70	2.10	NW
D	0.28	9.79	1.72	NW
E	0.14	6.97	0.96	WSW

3.4. Sea Currents

Taking into consideration the proximity of Areas A and B and the observation points, both these areas were considered as a single area for the purpose of sea currents analysis (Table 7). For this period, the predominant current was South-Southwest with a current intensity reaching 0.50 m per second. Area D showed great variability in the current direction along the observation period, going from North-Northwest to South-Southwest, with a current intensity reaching 0.36 m per second. Area E displayed great variability in the current direction as well, ranging from East-Northeast to West-Southwest with a current intensity reaching 0.75 m per second. The current maximum intensity was observed in depths ranging from 5 to 15 m and decreased gradually with increasing depth.

Table 7. Current predominant direction and maximum intensity (m s^{-1}) in the studied areas.

	Sea Currents	
Areas	**Intensity (m s^{-1}) Maximum**	**Current Direction**
A and B	0.40–0.50 (5–15 m depth)	SSW
C	No data	No data
D	0.36 (5 m depth)	NNW—SSE
E	0.75 (5 m depth)	ENE—WSW

4. Discussion

The choice of locations of national maritime areas destined for aquaculture (aquaculture production areas—APA) in Portugal is questionable and was not always correctly selected from a technical point of view [28]. This helps to explain why aquaculture production in Portugal has not increased significantly in recent years as observed in the statistical data published by INE [2]. The Portuguese Maritime Spatial Plan considers several maritime spaces for aquaculture, however, several areas included in this study were not considered (Areas A, C, and D) and this may be due to the fact that offshore aquaculture requires heavy investment and entails increased risks. In the following sections, we focus on the discussion of the water quality parameters for each of the species selected as potential species for increased seafood production. Then, the oceanographic parameters such as waves, currents, and structures or equipment that can be used are analyzed in an integrated way.

4.1. Fish

The growth performance and welfare of farmed fish are highly dependent on water quality parameters and the knowledge of the variable physical-chemical environment is limited in the Portuguese coastal area. In this study, data from October 2018 and April 2019 field surveys showed, as expected, that ammonia and nitrite concentrations are well below the toxic limit for any selected fish species that can be farmed in these marine areas. Similarly, dissolved oxygen, salinity, and pH levels are within the optimal range for developing marine fish farming [30,119–123]. In general, the data from the field surveys highlight the good quality of the water and its potential for the implementation of new productions. However, the essential parameter that changes the most throughout the five areas studied and that strongly influences the survival, health, welfare, feed intake, food conversion ratio, and growth performance is the temperature [36,124–126]. Since the previously mentioned parameters do not present limiting values for the culture of the selected species, the discussion is mainly focused on temperature values.

4.1.1. Meagre *Argyrosomus regius*

The meagre *Argyrosomus regius* has a high tolerance to various temperature and salinity values. This characteristic allows the meagre to develop in various habitats, including the Mediterranean, Black Sea, and on the west coast of Europe and Africa [127]. Such versatility allows the meagre to grow in all areas of the Portuguese coast since no temperature value reached the minimum values of 13.0 °C and the maximum values of 28.0 °C [32]. However, the area that presents better conditions to produce the meagre is Area E, where temperatures above 20 °C were observed since the optimal temperature of this species is between 20.0–26.0 °C [32,47]. The mean monthly temperature data displayed temperature values above 20.0 °C in Area E in August, September, and October and the minimum temperatures values reached 15.0 °C in February, in both years. Although 15.0 °C is not the ideal temperature to produce the meagre, this species can withstand these decreases in temperature [128]. In Areas A, B, and C, where the temperature can reach values

below 13.0 °C, the implementation of offshore or land-based fish farms of the meagre is discouraged, as the growth of this species will be reduced.

4.1.2. Atlantic Cod *Gadus morhua*

Although in this study we have not analyzed temperatures at depths below 7 m, it is expected that the installation of an offshore fish farm of Atlantic cod, *Gadus morhua*, can only be implemented in the northern region of the country and using submersible cages, which can lead to problems related to feeding and cage maintenance. In October 2018, no area presented the optimal temperatures of 7.0–15.4 °C, pointed out for this species by several authors [50–53]. Although the April 2019 field survey showed optimal temperature values in all areas, the mean monthly temperature data demonstrates that throughout the year, it would not be possible to farm cod. In Area A, temperatures higher than 15.4 °C were observed during 5 months (June, July, August, September, and October). The other areas also presented temperatures above 15.4 °C causing constraints related to the cod's welfare, growth performance, and potentially high mortality rates.

4.1.3. Atlantic Salmon *Salmo salar*

Atlantic salmon requires low temperature for optimal growth, and these conditions are only found in the coastal regions of the north and center of Portugal. The field surveys data highlight that only in Areas A, B, and C, the production of this species might be possible. In Areas D and E, the maximum temperature limits (18.0 °C) are exceeded according to the tolerated temperature values for this species [58,60,63–66]. In the year 2018, the area that stands out for salmon growth was Area A, where, only in July, temperatures reached 18.0 °C according to the mean monthly temperature data. The remaining 11 months were in the range of 12.0–18.0 °C. In the following year, Areas A, B, and C never exceeded the minimum and maximum limits of temperatures supported by Atlantic salmon.

4.1.4. Gilthead Sea Bream *Sparus aurata*

During the two surveys performed, none of the areas studied presented temperatures lower than 13.0 °C for surface waters. This is the temperature at which several authors suggest that *Sparus aurata* stops feeding [69,129]. Some authors refer that the optimal temperature for gilthead sea bream is between 22.0–26.0 °C [74,75,77,130]. Area E, in October 2018, showed optimal mean temperature values for this species growth (22.5 °C). However, in the April 2019 field survey, a decrease of nearly 7.0 °C, to 15.8 °C, was observed. The mean monthly temperature from the GHRSST project data indicates that Areas A, B, and C showed temperatures below 13.0 °C in February 2018, pointing out the difficulties for the gilthead sea bream fish farms in these areas. Areas D (where gilthead sea bream is already produced in cages in Sines) and E did not show temperatures below 13.0 °C in 2018, nor in 2019. However, the area that presented temperatures closer to the optimal values for the production was Area E, where this species is already produced in extensive or semi-intensive systems on old salt ponds and in land-based tanks. Nevertheless, it should be noted that in 2019, the highest volume of sea bream produced comes from new production establishments located offshore in this area and in Madeira Island [2].

4.1.5. Sea Bass *Dicentrarchus labrax*

In the two field surveys, no temperature value exceeds the limits tolerable to the rearing of the sea bass *Dicentrarchus labrax*. These results indicate that it is possible to install sea bass fish farms offshore throughout the Portuguese coast. In fact, sea bass is produced in Portugal mainly in semi-intensive systems, however, production is still very low (882 mts in 2019) [2]. Several authors [36,77,81,82] indicate that the minimum and maximum temperature limits for sea bass are between 2 and 8 °C and between 28.0 and 32.0 °C, respectively. However, for optimal growth, only Area E in October 2018, shows the optimal temperatures (20.0–25.0 °C) referred by other authors [77,81,84,85]. Looking at the mean monthly temperature data, no month in 2018 and 2019 reached the maximum or

minimum temperature limits for this species production in the areas studied. However, the growth performance is possibly optimized in Area E where closer to the optimum temperature was observed.

4.1.6. Sardine *Sardinia pilchardus*

The temperature data obtained in the field surveys indicate that it is possible to farm sardine along the Portuguese coast. The minimum and maximum temperatures tolerable by sardine larvae are 13.0 °C and 22.0 °C, respectively, but larval growth rate was higher for larvae reared at 17 °C [37]. These temperatures are within the range of temperatures registered in all areas, although another study [84] specified that the optimal temperature is between 15.5 °C and 17.5 °C. As such, the areas that are outside this limit are Areas D and E, where temperatures were above 17.5 °C in the 2018 survey. The mean monthly temperature data validates that Area E has 5 months in 2018 and 2019 (July, August, September, October, and November) where temperatures were above the optimal value. The mean monthly temperature data indicates that the other areas had temperatures close to 13 °C (which will probably affect growth) [37]. However, it should be noted that juvenile sardine maintained in captivity with water circulation in open systems for 1 year at 19.0 ± 1.0 °C grew substantially and showed adequate levels of essential fatty acids EPA and DHA for human consumption [131]. It should also be noted that this species is not produced on a commercial scale and its production is still a challenge due to low larval survival rates. Wild sardines were kept in captivity with temperatures between 18.2 °C and 21.6 °C and survival rates varied between less than 20 to more than 80% after four weeks, with most of the mortality occurring in the first days after transport [132]. Further research and development of the rearing technology for this species will be needed before commercial production can be implemented.

4.1.7. Greater Amberjack *Seriola dumerili*

The greater amberjack requires high temperature to grow, and these conditions can only be observed in the Algarve coast (Area E) or in the Portuguese islands such as São Miguel Island in the Azores archipelago, where cage production already exists. Fish meal substitution in the diet was possible for this species for long periods without affecting growth with water temperature maintained at 21.5 ± 2.4 °C [133]. The greater amberjack needs an increase of temperature from 19.0 °C to 24.0 °C to spawn [134] so, for hatchery implementation, Area E is the best choice. Areas A, B, and C are not recommended for greater amberjack production. Area D comes close to 19.0 °C during the summer months but temperatures can reach 14.0 °C during the winter months. Although Area E is the most suitable area to introduce fish farms for this species, the maximum temperature registered in the field surveys was 22.0 °C, nevertheless, this area displays the highest temperatures from all areas studied.

4.2. Bivalves

The field surveys highlighted the most promising sites to produce bivalves on the Portuguese coast, where the key parameters like temperature, chlorophyll *a,* and silicate are discussed. This last parameter is not directly related to the concentration of diatoms (they have a silicate frustule and are filtered by bivalves) in the water, however, it indicates the areas that have the highest concentrations of silicate (and possibly diatoms) [135] that could be beneficial for shellfish farms [136]. Dissolved oxygen, salinity, and pH are in the optimal ranges for the studied species and the concentration of toxic parameters such as ammonia and nitrite were below toxic limits.

4.2.1. Mussel *Mytilus edulis*

Focusing on field surveys data, blue mussel growth can be compromised in Area E, as this mussel has an optimal temperature range of 10.0–20.0 °C [92–94], and this area showed a mean temperature of 22.5 °C in October 2018. However, currently, it is in this

area where most of the mussel farms in extensive offshore systems take place [2]. The mean monthly temperature data highlights that beneficial conditions exist in all studied areas except for 3 months (August, September, and October) in Area E in both years, 2018 and 2019, where temperatures recorded were above 20 °C. Observing the chlorophyll *a* data and considering that the site selection should match, as much as possible, with the physiological needs of mussels to reach a commercial size in the shortest possible period, the area approaching the ideal concentration of 6.3 µg L^{-1} referenced by [95] was Area A, with mean concentrations of 2.03 µg L^{-1} in October 2018 and 5.12 µg L^{-1} in April 2019. However, it should be considered that the oceanographic conditions in this area are not the most suitable for the implementation of offshore longlines. Regarding silicate data, the observed values are relatively low in all areas. The area that showed the highest mean silicate concentrations was Area C with 3.04 µmol L^{-1} and 2.17 µmol L^{-1} in the October 2018 and April 2019 field surveys, respectively, but once again it should be noted that sea agitation can compromise offshore cultivation.

4.2.2. Scallop *Pecten maximus*

All areas in the April 2019 field survey present ideal conditions to implement scallop production. However, only Area A shows optimal temperature values (10–17 °C) in the October 2018 field survey, according to the reference temperature [97,98] and with minimum temperature limits of 4 °C [97] and maximum temperature of 22.9 °C [98]. The mean monthly temperature data indicates that only in July 2018 and August 2019, the temperature exceeded 17.0 °C in Area A. Area E showed 7 months with a temperature above 17.0 °C in 2018 and 2019 (from June to December), where growth will certainly be reduced although it may not cause mortality. Scallop achieved faster growth with a microalgae concentration of 300 µg L^{-1} (*Rhodomonas baltica*) in experimental trials [101]. It is worth mentioning that Area A showed a higher chlorophyll *a* mean concentration but was still far below the values described in the trials. In terms of silicate concentration, Area A exhibits a mean concentration of 3.04 µmol L^{-1} in October 2018 and 2.17 µmol L^{-1} in April 2019 field surveys, which corresponds to the second area with the highest silicate concentrations behind Area C which may indicate that the water from these locations could be the most suitable for the production of this species.

4.2.3. Oyster *Magallana gigas*

Wild stocks of *Magallana gigas* already exist from Norway to southern Portugal [137]. Currently, oyster production is performed mainly in Portuguese estuaries and basins such as the Ria de Aveiro and the Ria Formosa. *Magallana gigas* is also already produced, together with *Magallana angulata,* in the Sado estuary [103]. An older study [138] suggests that under ideal conditions and with high food availability, maximum growth for *Magallana gigas* might be achieved at temperatures approaching 20.0 °C. The field survey of 2018 showed one area where this temperature range is noticeable, namely Area D (18.6 °C; mean). In the 2019 field survey, there is no area that presents the optimal temperature for this species farm, however, with minimum limits of 8.0–10.0 °C [102] and maximum limits of 28.0 °C [103], it is possible to implement oyster farms throughout the Portuguese coast, offshore or land-based. Analysing the chlorophyll *a* concentration data, the three Areas B, D, and E present beneficial conditions to develop the production of *Magallana gigas*. This species is already produced offshore in Area E, but the installation of oyster farms in new sites should always be carried out after pilot studies to ensure that the chosen site provides adequate conditions for survival and growth.

4.2.4. Razor Clam *Ruditapes decussatus*

The razor clam has a range of optimal temperatures depending on its geographical origin [107]. The populations of this species exhibit optimal spawning temperatures of 20.0 ± 1.0 °C in the north of the Iberian Peninsula and 22.0 ± 1.0 °C in the south of the Iberian Peninsula [107]. Usually, clams are produced in onshore nurseries and buried in

the sediment, however, its offshore production has been studied and recently a hatchery that intends to perform the growth of this species offshore was established and in the growing phase on the southern coast (Area E). The 2018 field survey indicates that the ideal temperature to produce razor clam is only verified in Area E, where the temperature reached 22.5 °C (mean). In the 2019 field survey, no area presented optimal conditions to implement an offshore clam farm. However, with minimum temperature limits of 8.0 °C and maximum limits of 28.0 °C [106], all areas are within these values. The chlorophyll *a* concentration in Area E was low when compared to the other areas in the 2018 field survey. However, in the 2019 field survey, Area E was the second area with the highest chlorophyll *a* concentration (2.34 µg L^{-1}; mean).

4.3. Macroalgae

In Portugal, the production of macroalgae is almost non-existent, with only a land-based company producing it, but several studies carried out in the Aveiro area, point out the potential of seaweeds to remove nitrogen from the water of a fish farm and to contribute to the creation of new jobs [139]. Essential parameters for macroalgae growth, such as nitrate and phosphate concentration presented stable values with no significant differences in the Portuguese coast. The concentration of ammonia and nitrite were below the limit of quantification. Dissolved oxygen and pH parameters are not considered to be limiting factors, are within the limits for the studied macroalgae implementation, and, therefore, only phosphate, nitrate, and temperature values are discussed.

4.3.1. Gracilaria gracilis

Areas D and E presented the optimal temperatures (18.0–23.0 °C) for *Gracilaria* sp. rearing [107–109,140]. However, with a maximum temperature limit of 28.0 °C and a minimum temperature of 10.0 °C [110], this species can be found along the Portuguese coast. In the field surveys, no area exceeded the temperature limits tolerable by this species. Along with temperature, growth needs to be enhanced with a high concentration of nutrients, where Areas A and E stand out in the concentrations of nitrate and phosphate. The highest nitrate concentrations were observed in Area A and E in the April 2019 survey with 1.80 µmol L^{-1} (mean) and the areas with the highest mean phosphate concentration were Area A and D with 0.21 µmol L^{-1} and Area E with 0.24 µmol L^{-1}. In addition to Area E having the highest nitrate concentrations, the mean monthly temperature data reinforces that this area has 5 months of the year (July and November in 2018 and 2019) with optimal temperatures (18.0–23.0 °C) to farm these macroalgae.

4.3.2. Porphyra umbilicalis

Nori is one of the most cost-effective and advantageous macroalgae to produce. This species can reach the commercial size in 45 days [113]. With optimal temperatures of 10.0–15.0 °C [113,115,141], the most adequate sites for the implementation of this species production are located in the north and center of the country. In the field surveys, the only area that approaches the optimal temperature values for this species farm was Area A with 14.6 °C (mean) in April 2019 but with 16.1 °C (mean) in October 2018. The remaining areas exceed 15.0 °C in both field surveys, however, with a minimum limit of 8.0 °C [113] and a maximum limit of 20.0 °C [114], only Areas D and E are not adequate for production. Mean monthly temperature data indicates that Area A has the highest number of months with optimal temperatures of 10.0–15.0 °C, where only in the summer months (June, July, and August) and autumn (September and October), temperatures exceeded 15.0 °C in both 2018 and 2019. In terms of nutrients, Area A showed the highest nitrate concentration and the second-highest phosphate concentration in the October 2018 survey. In the April 2019 survey, Area A and E were the areas with the highest nitrate concentration as previously mentioned, but the mean phosphate concentration was below the limit of quantification (<0.20 µmol L^{-1}). It should be highlighted that the potential of this species to be farmed in integrated multitrophic aquaculture (IMTA) was observed [142].

4.3.3. *Undaria pinnatifida*

Literature references indicate that the optimum temperature of wakame *Undaria pinnatifida* is between 12.0–15.0 °C [117,118]. The only area that shows values within this range is Area A in the April 2019 field survey with temperatures of 14.6 °C (mean). However, this macroalga can be found throughout the Portuguese coast, since it presents temperature limits above 5.0 °C and below 25.0 °C [117]. This macroalga has a high capacity to adapt to temperature, depending on its geographical origin, but some authors [143,144] point out that this species tolerates temperature variations but in the long term, natural selection reduces the population. The mean monthly temperature data indicates that the area that has more months with optimal temperatures is Area A between the months of November to May in both studied years. There is no comparable data for nitrogen and phosphate requirements for this macroalgae.

4.4. Waves, Currents, and Equipment

Offshore aquaculture presents significant technical challenges in the design, testing, and construction of systems, such as cages and longlines, and there are also many biological, regulatory, social, and economic problems to be solved [145]. The net cages have innumerable factors that require deep analysis to ensure the safety of production. These factors range from the cage structure itself and deployment depth; the location and weight of the anchors; the ropes attached to the cage; the drag forces applied on the structure by currents and waves; backup plans if the anchors get dragged on the sea floor; ropes entanglement; uncommon sea conditions that may damage the materials, such as storms [146–148]. Light intensity, the availability of dissolved oxygen, rearing density and food supply capacity should also be considered for the survival and welfare of the species produced in submerged cages [59,149,150]. Nevertheless, aquaculture cages had rapidly developed in the last decades [148] and can cope with these factors to a certain degree. For instance, the authors [146–148] studied the impact of currents and waves in aquacultures cages. It was observed by [146] that drag forces are dependent on the cage size and system used, where sea currents from 0.2 m s^{-1} to 0.5 m s^{-1} had a proportional increase on the lift force. Compared to the results of this study, Area E had currents velocities that reached 0.75 m s^{-1}, indicating that production in cages in this location has to be equipped and prepared to withstand greater lift forces. The results of [147] were inconclusive regarding the waves and currents on the aquaculture cage system used. Although, some results had significant differences, such as the mooring from the cage system not being affected by waves, neither the currents nor the fine numerical mesh from the net suffered any damage when the current velocity reached 0.3 m s^{-1}. Since every studied area had a current velocity that exceeded 0.3 m s^{-1}, using a larger mesh in these areas would reduce the drag from the waves and currents. In case of an emergency, [148] set an experiment where the mooring system failed, and the cage was subjected to waves and currents. The conditions of this experiment were quite extreme, where the significant wave height reached 6 m and the current velocity reached 2 m s^{-1}. The experiment concluded that, for these conditions, when the mooring system failed, the cage system was subjected to far greater tension, but it stabilized after a while. If combined with an anchor failure as well, the whole aquaculture system becomes unfit for the sea. All studied areas had significant wave heights that exceeded 6 m. According to [119], until further technological solutions allow offshore aquaculture to be developed, the coastal modality is a more pragmatic option for the North Region (Area A) in Portugal. Area E comes close to the wave height studied by [148] with a significant height of 6.97 m. In this area, if the anchor system does not fail, the aquaculture production system should endure storm conditions, and if the aquaculture cage can be successfully placed, other variables need to be added for the biological necessities of the selected species. For example, [59] mention that the Atlantic salmon behaves differently in no light conditions, which results in sub-optimal higher densities (in high-density stocks) but the placement of artificial lights in 15 m depth cages resulted in a lower density. The study of [149,150] identified that Atlantic salmon in submerged cages swam 1.6 times faster

than nearer the surface (submerged cages at 3 m depth). For bivalves and macroalgae, the assessment needs to be reformed, as they need different aquaculture structures such as longlines and have different biological patterns and requirements, the *Mytilus galloprovincialis* can be grown in longlines on the south coast of Portugal (Area E) from depths between 3 and 15 m with no significant differences in growth and fatty acid composition [151].

5. Conclusions

The results obtained in this study demonstrate the possibility of increasing offshore production on the Portuguese coast. However, more studies are needed taking into consideration the systems and structures available on the market that can withstand the oceanographic conditions of each location. For fish farming, the temperature is the main parameter influencing the survival and growth, since ammonia and nitrite concentrations data were low, and all selected species tolerate the variations observed in dissolved oxygen, salinity, and pH. For species requiring lower temperatures, such as the Atlantic cod, the production is compromised since, at the surface level, the temperature is too high to produce this species. The Atlantic salmon requires lower temperatures and can be considered to be produced in Areas A, B, and C. For species that need warmer temperatures, Area E has been demonstrated to be adequate to produce gilthead sea bream, sea bass, meagre, and the greater amberjack. For bivalves, the concentration of chlorophyll *a* plays an important role to determine the best location to implement new structures. The blue mussel can grow in a variety of temperatures, but without looking at the oceanographic conditions, Area A had the highest concentration of chlorophyll *a* which would benefit its growth performance and reduce the rearing period. The same applies to the scallop, where the lower temperatures and high concentration of chlorophyll *a* would likely benefit this species. For the oyster, due to specific water temperatures, Area D is the best choice to allow the production of this species and area E offers a warmer temperature and a sufficient concentration of chlorophyll *a*. Area A seems adequate to implement nori and wakame coastal productions and Area E appears suitable for the production of *Gracilaria gracilis*. Looking at the oceanographic conditions, the more promising Area is E as it presents smaller wave heights. However, higher current velocities were observed in Area E. The drag from the currents can be mitigated using a net with a larger mesh size and structures that reduce the possibility of current dragging. The implementation of aquacultures in harsh open sea conditions seems possible, and thus, offshore and coastal aquaculture in Portugal shows potential, but the implementation of new structures must be preceded by dedicated studies that consider the type of structure and the specific location.

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