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Analysis of primary productivity and phytoplankton abundance across coastal ecosystems: Implications for sustainable aquaculture and ecosystem management

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ABSTRACT
Background: The coastal waters of Maros, encompassing ponds, estuaries, and open seas, exhibit diverse environmental conditions influencing primary productivity and phytoplankton abundance. Understanding these variations is crucial for sustainable management of coastal ecosystems and the optimization of aquaculture activities. This study analyzed primary productivity and phytoplankton abundance across three distinct **Methods:** ecosystems: ponds, estuaries, and seas in the coastal waters of Maros. Sampling was conducted using a stratified approach, measuring key environmental parameters such as nutrient concentrations, salinity, and temperature. Phytoplankton abundance was quantified using microscopy, while primary productivity was assessed through light-dark bottle techniques. **Results:** The findings revealed significant differences in primary productivity and phytoplankton abundance among the ecosystems. Ponds exhibited the highest primary productivity due to elevated nutrient input from anthropogenic activities, while estuaries displayed moderate productivity influenced by fluctuating salinity and nutrient mixing. The sea, despite having lower productivity, showed higher phytoplankton diversity due to stable environmental conditions. Each ecosystem was dominated by distinct phytoplankton species adapted to their specific environmental characteristics. **Conclusion:** This study highlights the substantial impact of environmental factors on primary productivity and phytoplankton distribution in the coastal waters of Maros. The findings provide insights into the ecological dynamics of these ecosystems, emphasizing the importance of tailored management strategies to balance aquaculture practices and ecosystem sustainability. **Novelty/Originality of this article:** This research provides a comprehensive comparative analysis of primary productivity and phytoplankton abundance across three interconnected ecosystems in Maros, offering novel insights into their ecological interactions and implications for sustainable aquaculture and coastal management.

KEYWORDS: coastal ecosystems; environmental factors; phytoplankton abundance; primary productivity; sustainable aquaculture.

1. Introduction

The coastal zone is the transitional interface between terrestrial and marine environments (Seibert et al., 2020; Prampolini et al., 2020). The designation “transition” encompasses a variety of interpretations, including movement from terrestrial spaces, along with associated activities that require transportation mechanisms such as fluvial systems, towards the marine domain. Consequently, while terrestrial activities may not exert a direct influence on the marine environment, the function of rivers as channels

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becomes paramount. Instead, the transition from marine to terrestrial environments is facilitated by fluvial systems, especially in scenarios where phenomena such as sea level rise or inundation events result in direct impacts in terrestrial areas. This transition interface is often designated as an estuary, an area characterized by the confluence of marine and terrestrial influences. The marine environment exerts its influence on estuaries through hydro-oseanographic processes, while terrestrial influences manifest through anthropogenic activities (Iriarte et al., 2016; Zhang et al., 2025).

Hydro-oseanographic processes within estuaries encompass a wide range of parameters, including current velocity, salinity, temperature, turbidity, carbon dioxide, nitrate and phosphate levels, all of which require significant adaptive responses from resident biota (Russel, 2013). Concurrently, anthropogenic activities introduce organic and inorganic substances, derived from production or pollution processes (Zhang et al., 2025; Yao et al., 2022; Briffa et al., 2020; Kumar et al., 2023; Bashir et al., 2020). Empirical data and field investigations reveal that two main activities predominate in estuarine contexts: agriculture and quarrying. These activities can increase the productivity of ecological systems or, on the contrary, exacerbate pollution levels. Notably, early efforts undertaken by local communities remain dependent on technologies derived from hydro-oseanographic systems, underscoring the critical role of water quality in facilitating successful aquaculture practices. Beyond the natural hydro-oseanographic and anthropogenic systems, the life forms, including humans, that inhabit estuaries collectively form what are called ecosystems. Coastal ecosystems can be categorized based on their inherent characteristics, distinguishing between natural and anthropogenic varieties (callaway et al., 2020). The types of ecosystems commonly encountered in estuaries comprise marine ecosystems, freshwater ecosystems, mangrove ecosystems, pond ecosystems, and the activities of decomposers and microorganisms (Parveen et al., 2024). These ecosystems are involved in dynamic interactions in coastal areas. The viability of these systems can be effectively maintained provided that their utilization is in line with the ecological carrying capacity of the respective systems.

However, applicable ecosystem management in coastal areas continues to face many challenges, one of which arises from the lack of information or data regarding the quality of the aquatic environment, as assessed through methodologies related to primary productivity and phytoplankton abundance. This statement is in line with the perspective articulated, who explained that the productivity of coastal aquatic systems can be measured through metrics of energy (sunlight) absorption and storage by the autotrophic communities inhabiting these waters. Autotrophic organisms have the ability to convert inorganic substances into organic compounds that can be utilized by themselves or by other organisms, either through the utilization of solar energy or through the process of chemosynthesis. The various factors that influence primary productivity and abundance of phytoplankton include sunlight, nutrient availability, chlorophyll-a concentration, temperature, turbidity, water current, and depth. These parameters are prevalent in many aquatic environments, serving as both supporting and limiting elements that are closely linked to the level of primary productivity. This investigation is particularly important as it seeks to compare primary productivity between natural and artificial ecosystems within coastal areas. Primary productivity levels observed within water bodies can serve as an indicator of high water productivity status. Primary productivity is largely derived from the photosynthetic activity of phytoplankton, which serves as a major contributor to the aquatic food web. Some of the determinants that affect the level of phytoplankton primary productivity include phytoplankton abundance in aquatic systems, which also serves as an indicator of water fertility. Corroborated that the abundance and distribution of phytoplankton are closely linked to factors such as temperature, light intensity, salinity, and the concentration of nitrate and phosphate present in the water column (George et al., 2012; Stumpner et al., 2020; Mohammed et al., 2023).

Coastal areas along the western coastline of South Sulawesi are classified as highly productive coastal zones, characterized by ecosystems such as mangrove forests, seagrass beds and coral reefs located in the Spermonde Islands (Lukman et al., 2014). Despite this, the quality of marine and coastal waters has been degraded, mainly due to the influx of terrestrial effluents containing nutrients. Previous investigations conducted along the west coast of South Sulawesi have revealed that nutrient and organic matter concentrations, such as NH3-N, ranged from 6.37 to 13.6 μm, and PO4 concentrations between 0.21 and 0.35 μm (Nasir et al., 2015), along with silicate levels varying from 9.59 to 24.1 μm (Lukman et al., 2014). The coastal waters of Maros, located on the west coast of Sulawesi, are also under significant stress due to nutrient runoff from the mainland, mainly resulting from the discharge of nine rivers into the marine environment, with the Maros River being a major contributor to this ecological stress (Tambaru, 2008). The Maros River ranks as the second longest river in South Sulawesi, stretching over 7673 km2 and draining an area of 64,636 km2 (Tambaru, 2008). Many Maros residents are involved in various activities along the Maros River, including port operations, fishing, rice cultivation and.

Problems stemming from agricultural practices, particularly the inappropriate application of pesticides and other toxic substances, show that the dominant category of pesticides used in Indonesia is the organophosphate group, accounting for 22.29% (Ardiwinata & Nursyamsi, 2012). In the maritime sector, the discharge of waste fuel and oil into the aquatic environment worsens the prevailing conditions. Simultaneously, in the fisheries sector, the use of ecologically harmful fishing gear jeopardizes coral reef ecosystems. An investigation conducted by CoreMap-CTI in 2017 on the condition of coral reefs in Makassar waters revealed that among 13 monitoring stations, five were classified as being in good condition, while eight were rated as being in a state of disrepair, with none indicating good or fair condition (CoreMAP-CTI, 2017). In addition, the degradation of mangrove ecosystems has also been attributed to land use change for the establishment of aquaculture ponds as well as semi-intensive and intensive pond culture practices.

Primary productivity is defined as the rate at which potential energy is sequestered by autotrophic organisms through photosynthesis and chemosynthesis, producing organic matter that serves as a viable food source. Characterized primary productivity as the level of solar energy storage in organic matter, resulting from photosynthetic and chemosynthetic activities of primary producers. That primary productivity signifies the rate at which photosynthesis, or the process of carbon fixation, occurs. A large number of investigations of primary productivity and phytoplankton abundance in Maros waters resulted in various interpretations. According to Tambaru (2008), phytoplankton community abundance showed a significant correlation with nutrient concentration; however, primary productivity was not consistently directly correlated with phytoplankton abundance. That increased primary productivity in aquatic environments is caused by phytoplankton proliferation coupled with high chlorophyll-a concentrations, which then increases dissolved oxygen levels. Its illustrated a strong relationship between primary productivity and light intensity. Therefore, this study was designed to provide insight into the condition of coastal waters west of the Makassar Strait and coastal waters of Maros Regency, information that can be utilized for marine resource and fisheries management in the region. The main emphasis of the investigation centered on the analysis of primary productivity and phytoplankton abundance in ponds, estuaries, and marine sites within the coastal waters of Maros.

2. Methods

2.1 Research location and sampling

This research was conducted in May-July 2022, located in the coastal waters of Maros Regency. This study consists of field data measurements consisting of salinity, temperature, current velocity, CO_2 and primary productivity measurements. Phytoplankton sampling and water sampling at the research site and phytoplankton identification at the Plankton Laboratory and water quality analysis at the Chemical Oceanography Laboratory, Department of Marine Science, Faculty of Marine Science and Fisheries, Hasanuddin University. Research location and sampling of Maros coastal waters.

The delineation of observation stations within the Maros coastal waters was systematically categorized into three different observation stations, each of which was subdivided into three substations, simultaneously serving as replicates. The initial station was located in the main zone, followed by the second station, which was positioned at the mouth of the river parallel to the shoreline, and finally, the third station was located towards the sea exit. The spatial interval between substations was set at 500 meters. Phytoplankton and zooplankton sampling was conducted at each of the designated stations. Each substation also had an important role as a mock. Collection of phytoplankton and zooplankton samples occurred daily between 10:00 and 14:00 (Tambaru, 2002). The phytoplankton and zooplankton sampling methodology involved the acquisition of seawater using 5-liter buckets, executed ten times, culminating in a total water volume of 50 liters. Subsequently, the collected water samples underwent filtration using a plankton net with a mesh size of 25 micrometers. The resulting filtered material was transferred into 100 mL sample bottles and treated with 2 mL of 1% Lugol's solution before being transported to the laboratory for subsequent identification. At all stations and substations, parameters of light intensity, temperature, current velocity, salinity, pH, CO_2, and turbidity were measured directly, along with water sampling for laboratory analysis that included nitrate (NO_3) and phosphate (PO_4) assessments.

Primary productivity assessment was conducted using the Winkler method, which is based on the quantification of oxygen produced during the photosynthesis process. It is said that the volume of oxygen produced is commensurate with the amount of carbon dioxide (CO_2) consumed during photosynthesis. Measurements relating to primary productivity were conducted during the morning to afternoon transition (10:00-14:00). Samples designated for primary productivity analysis were immersed in the water column at 10:00 am and then measured at 2:00 pm, allowing for a four-hour incubation duration.

The methodology for measuring primary productivity involved the utilization of light and dark bottles, following procedural steps by Brower (1990). Two 250 mL Winkler bottles were prepared, consisting of one light and one dark bottle, with each bottle filled with seawater samples collected at the specified depth. Incubation of the light and dark bottles was carried out at their respective depths for an optimal period of four hours. After incubation, the light and dark bottles were neutralized by the addition of 2 mL manganese sulfate ($MnSO_4$) and 2 mL sodium hydroxide (NaOH) mixed with potassium iodide (KI), and the mixture was stirred until a brown precipitate formed. Next, 1 mL of sulfuric acid (H_2SO_4) was added, and the mixture was shaken until the precipitate dissolved. After this, 3-4 drops of amyl alcohol are introduced until a yellow color is achieved, after which a titration with sodium thiosulfate ($Na_2S_2O_3$) is performed and recorded as the initial oxygen (O_2) condition (I). The titration of the light and dark bottles, which had been incubated for four hours, mirrored the initial bottle procedure, in which 1 mL of H_2SO_4 was added, and the mixture was shaken until a soluble precipitate was observed. Finally, 3-4 drops of amyl alcohol were introduced until a yellow hue was achieved, followed by titration with sodium thiosulfate until the solution became colorless. The measured Gross Primary Productivity sample was then calculated by the Equation 1 (Kaswaji. 1993).

$$Gross\ Primary\ Productivity = \frac{[(O_2BT)-(O_2BG)(1000)]}{(PQ)(t)} \times 0.375 \qquad \text{(Eq. 1)}$$

The measurement of dissolved oxygen (O) is expressed in milligrams per liter (mg/l) and is assessed using both a bright bottle (BT) and a dark bottle (BG). The incubation period for this process is set at 4 hours (t). A photosynthesis constant (PQ) of 1.2 is applied in the calculations, while a conversion factor of 1000 is used to change units from liters to cubic meters (m^3). Additionally, the coefficient of 0.375 is employed to convert oxygen values into their equivalent carbon measurements.

2.2 Measurements of physical and chemical parameters

Measurements of physical and chemical parameters in this study include temperature, current speed, acidity, carbon dioxide (CO_2), turbidity, phosphate (PO_4), and nitrate (NO_3). Temperature measurements in Maros coastal waters were carried out at each sampling station using a mercury thermometer. The thermometer was immersed in the water column for several minutes, then the temperature value seen on the thermometer scale was recorded (Mainassy, 2017). To measure current velocity, a current kite was used in Maros coastal waters. Measurements were taken by timing the movement of the current kite until the rope was fully extended using a stopwatch. Current direction was measured with a compass, and the current velocity value was calculated using the Equation 2 (Sudarto et al., 2013):

$$V = \frac{s}{t} \quad \text{(Eq. 2)}$$

The current speed (v) is measured in meters per second (m/s) and is calculated based on the distance (s), expressed in meters, traveled within a specific duration of time (t), measured in seconds. Salinity measurements in Maros coastal waters were carried out at each sampling station using a hand refractometer. Seawater samples were taken with a drop pipette, then dripped onto the top of the hand refractometer. After that, observations were made on the tool lens and the value read on the scale was recorded (Mainassy, 2017). To measure acidity (pH) in Maros coastal waters, a pH meter was used. Before use, the pH meter was calibrated with distilled water, then the device was dipped into a container containing water samples, and the pH value indicated on the pH meter display was recorded. Measurement of carbon dioxide (CO_2) levels in Maros coastal waters is important to observe the life of marine biota and its relation to pollution, because high or low CO_2 levels are directly related to the amount of organic waste in these waters. Total CO_2 levels in seawater can be determined if salinity, temperature, and pH are known. Free CO_2 measurement is carried out by the titration method, where 25 ml of sample is put into Erlenmeyer, then 1-2 drops of PP indicator are added. If the water is red, it means that it does not contain CO_2, while if the water remains colorless, titration is carried out with 0.0454 N Na_2CO_3 until the color changes to pink.

$$CO_2 \text{ free (mg/l)} = \frac{ml\ titran\ x\ Nitran\ x\ 22\ x\ 1000}{ml\ water\ sampel} \quad \text{(Eq. 3)}$$

Turbidity measurements in Maros coastal waters were carried out using the Nephelometric method using a Turbidity Meter tool. Measurements were made in the laboratory at all stations and substations, with units of measurement results in NTU (Tambaru, 2008). To determine phosphate levels, the ascorbic acid method was used. A 10 ml water sample was filtered using Whatman filter paper no.42. A total of 2 ml of filtered water was put into a test tube, then 2 ml of 1% H_2SO_4 was added and stirred.

Next, 3 ml of phosphate oxidizing solution (a mixture of 2.5 M sulfuric acid, ascorbic acid, and ammonium molybdate) was added, then stirred and left for one hour to ensure complete reaction. Phosphate levels in the sample can be determined by inserting a test tube containing a blank into the DREL 2800 Spectrophotometer at a wavelength of 660 nm, and the results are measured in mg/L. Nitrate levels were measured based on the APHA (1998) method. Water samples of 25-50 ml were filtered using Whatman paper no.42, then the filter results were transferred to an erlenmeyer tube. A total of 5 ml of illustrative water was put into a test tube, then 0.5 ml of Brucine solution was dripped and allowed to stand for 2-4 minutes. After that, 5 ml of concentrated sulfuric acid was added, and the solution was allowed to cool before measuring the nitrate content using a DREL 2800 Spectrophotometer at a wavelength of 410 nm.

2.3 Phytoplankton and zooplankton

Identification of phytoplankton and zooplankton samples was carried out using a microscope and SRCC after the samples were homogenized. Phytoplankton samples to be observed as much as 1 ml were taken using a drop pipette, then placed on the SRCC and covered with a cover glass. The SRCC was then placed on the preparation table to be observed with a magnification of 10x10, and was done three times. After the phytoplankton samples were identified, the remaining volume of water samples was measured. The abundance of phytoplankton species was calculated using a formula adapted from APHA (1998), and identification was done up to genus level with the help of a plankton identification book.

$$N = n \times \frac{Vt}{Vcg} \times 1/Vd \quad \text{(Eq. 4)}$$

The abundance (N) of phytoplankton and zooplankton, expressed in cells per liter (cells/l), is determined by observing the total number of cells present in a sample. This calculation takes into account the volume of the precipitated or filtered sample (Vt) in milliliters, the volume of the Sedgwick-Rafter Counting Chamber (SRC) used for analysis (Vcg) in milliliters, and the volume of the precipitated sample converted into liters (Vd). Then, the diversity index for calculation of the diversity index was carried out using a Equation 5 based on Shannon Wiener.

$$H^{\wedge\prime} = -\sum pi \ ln \ pi \quad \text{(Eq. 5)}$$

The Shannon-Wiener diversity index (H') is a measure used to evaluate the biodiversity of a plankton community. It is calculated using the proportion of each plankton species (Pi), which is derived by dividing the number of individuals of a specific species (Ni) by the total number of individuals observed (N). The classification of biota community conditions based on the H' value is as follows: a value of H' less than 2.30 indicates small diversity, a value between 2.30 and 6.91 signifies medium diversity, and a value greater than 6.91 reflects high diversity. The distribution of the number of individuals in each organism can be determined by comparing the uniformity index value with its maximum value. Calculation of phytoplankton uniformity index in Equation 6.

$$E = \frac{H'}{ln} S \quad \text{(Eq. 6)}$$

The species uniformity index (E) is a metric used to assess how evenly individuals are distributed among different species within a community. It is calculated by dividing the species diversity index (H') by the maximum possible diversity value (H' max), where H' max is determined as the natural logarithm (ln) of the total number of phytoplankton species (S). This index provides insight into the balance of species representation in the ecosystem.

From the results of this comparison, a uniformity index (E) value will be obtained which indicates the level of uniformity between 0 and 1. The smaller the E value, the lower the uniformity of a population, indicating that the distribution of the number of individuals per genus is uneven and there is a tendency for domination by one particular genus in the population. Conversely, the larger the E value, the higher the uniformity of the population, which means that the number of individuals of each genus is relatively uniform or not significantly different. The dominance index is used to determine whether there are certain species that dominate in the observed population. The calculation of the dominance index was carried out in Equation 7.

$$C = \sum \left(\frac{\text{ni}}{\text{N}}\right) 2 \quad \text{(Eq. 7)}$$

The dominance index (C) is a measure used to evaluate the extent to which one or a few species dominate a community. It is calculated based on the proportion of each phytoplankton species (Pi), which is determined by dividing the number of individuals of a specific species (ni) by the total number of individuals (N). A higher value of C indicates greater dominance by certain species within the community.

The dominance index (D) has a value between 0 and 1, where values close to 1 indicate the dominance of certain individuals in the population, while values close to 0 indicate the absence of dominance. The higher the D value, the more dominant one individual is over another in the community. Conversely, a low D value indicates a more even distribution of individuals among species. To analyze differences in primary productivity levels, phytoplankton abundance, and other parameters between observation stations, One Way Anova data analysis was used. This method allows a clear comparison between variables measured at different observation sites.

3. Results and Discussion

3.1 Overview of the research location

Maros Regency is one of the regencies in the southern Sulawesi Province of Indonesia. One of the potential and marine resources of Maros Regency is the coastal area, within the coastal area of Maros Regency, the potential that has not been managed properly is the estuary. Maros coastal waters are one of the estuaries in Maros Regency which borders the Makassar sea or Makassar strait. Maros coastal waters are influenced by several ecosystems including natural, artificial ecosystems and aquatic polluting waste. Natural ecosystems consist of marine, mangrove and river ecosystems, while artificial ecosystems include pond ecosystems and aquatic polluting waste consisting of household waste, port waste and agricultural activities.

Maros coastal waters are geographically located at 119° 28' 45“ East longitude and 45°96' 50” South latitude. Maros coastal waters are administered in the new Maros sub-district of Maros Regency, this sub-district also has one village with coastal topography, namely Borimasunggu Village. The population of Borimasunggu is 1,800 with an area of 23.57 km2, the livelihood of the new Maros community is fishermen with a total production of 959,708.3 tons in 2020.

3.2 Primary productivity

Primary productivity in waters is fundamentally dependent on the photosynthetic activity of autotrophic organisms or photosynthetic organisms that can convert CO^2 into organic matter. Therefore, the estimation of primary productivity in natural waters is based on the measurement of photosynthetic activity, which is mainly carried out by phytoplankton. Based on the calculation of primary productivity, the highest value is found in the sea and the lowest in ponds (Table 1 and Figure 1).

Table 1. Average primary productivity of Maros coastal waters.

Station	Average (mgC/m^3/hour)
Pond	28.07
Estuary	38.28
Sea	48.49

From the results of calculations in the coastal waters of Maros, the highest average value of primary productivity was obtained at the sea location of 48.49 mgC/m^3/hour and the lowest average value of productivity in ponds 28.07 mgC/m^3/hour. This research is in line Vanilla et al. (2017) and Rahayu et al. (2016) found the primary productivity of the sea is higher than the pond area. The value of primary productivity in Maros coastal waters is smaller than in the Bancaran estuary with a range of 63,498-120,053 mgC/m^3/hour (Sofyan & Zainuri, 2021).

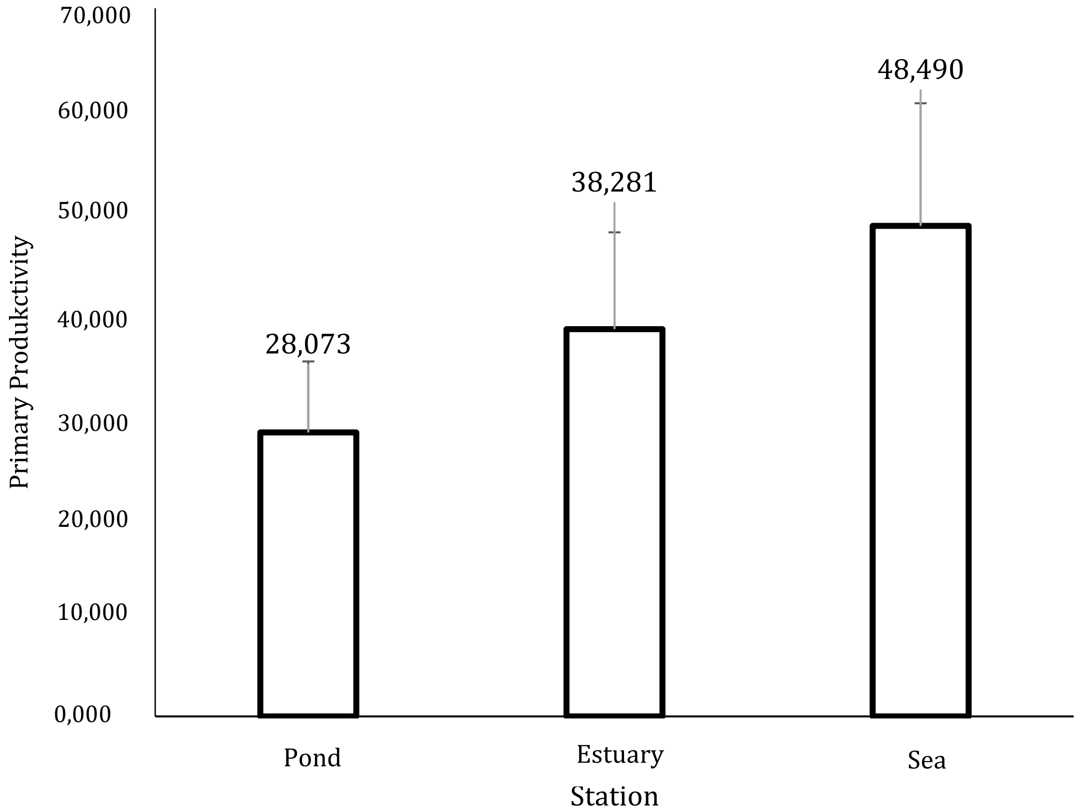

Fig. 1. Comparison of primary productivity of Maros coastal waters

Similarly, the productivity of Maros coastal waters is smaller than that of Karimun Jawa waters with a range of 37.5-75 mgC/m^3/hour (Nuzapri et al., 2019). Meanwhile, there are differences in the value of primary productivity measurements at the location of ponds, estuaries and the sea, but based on the results of way one anova shows a sig value of 0.102 there is no significant difference in the value of primary productivity of the three stations. Due to primary productivity in Maros coastal waters has a stable distribution so that phytoplankton are still able to adapt. The high value of primary productivity at marine locations based on the results of Principal Component Analysis (PCA) can be explained that the comparison between the F1 and F2 axes can explain 100% of marine stations with the characteristics of current velocity and phosphate. That based on the results of observations at the sea site the value of current velocity is the highest at 35 m / sec from the location of the pond and estuary. Similarly, the value of phosphate at the marine site is the highest value of 0.9 from the location of the pond and estuary.

Primary productivity is smaller in value when compared to the abundance of phytoplankton found at the observation site. Previous research found that primary productivity was lower with a range of 74,002-102,551 mgC/m^3/hour while the abundance of phytoplankton found ranged from 611-4,666 cells/l (Sofyan & Zainuri, 2021). In line with the research of Yulianto et al., (2014) Primary productivity has a lower range of 25-75 mgC/m^3/hour while phytoplankton abundance is higher in the range of 13,053-23,040 cells/l. However, the marine site had the lowest phytoplankton abundance when compared to the pond and estuary sites. There are several reasons why primary productivity is high in the marine location of the photosynthesis process by decomposing organisms in this case bacteria that utilize nutrients so that oxygen in this location is high, then at this location the lowest value of turbidity so that the photosynthesis process is quite optimal without any interference. This research is in line with previous research by Febriana et al. (2017) that primary productivity is inversely proportional to phytoplankton abundance, meaning that the relationship between primary productivity and phytoplankton abundance is negative. Based on the results of the one way anova test, there is no significant primary productivity between research stations p-value 0.102 > 0.05 (Table 2).

Table 2. Results of one way anova analysis of primary phytoplankton productivity of maros coastal waters

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	625.260	2	312.630	3.427	0.102
Within Groups	547.333	6	91.222		
Total	1172.593	8			

Based on the results of linear regression analysis of primary productivity of phytoplankton with a significant value of <0.002 model 2, factors that affect primary productivity include turbidity, temperature, nitrate, phosphate and phytoplankton abundance, although in this observation the significant value of abundance is higher than 0.26, phytoplankton abundance still has a role to influence primary productivity, unlike the physical and chemical meters which have a value smaller than <0.005. Thus it can be concluded that primary productivity is more influenced by brightness, temperature and nutrient factors. This research is in line with Tambaru's research (2008) which found a similar thing where primary productivity does not have a significant relationship with phytoplankton abundance but with Chlorophyll-a. In line with research by Febriana et al., (2017) Primary productivity is directly proportional to chlorophyll-a, meaning that the relationship between primary productivity and chlorophyll-a is positive. In the location of the lowest primary productivity value while the value of phytoplankton abundance is quite high. Based on the analysis of the characteristics of the location of the pond area is characterized by a fairly high CO_2 is 99.73 ppm. The value of carbon dioxide is still able to be tolerated by phytoplankton.

3.3 Phytoplankton abundance and composition

The results of research in the coastal waters of Maros Borimasunggu Village, Maros Baru Subdistrict found phytoplankton genus as many as 31 genus which is divided into 4 classes namely *Bacillariophyceae* (diatoms), *Cyanophyceae*, *Dyanophyceae* and *Dinophyceae*. The number of genus found had different values between each station. Phytoplankton abundance ranged from 54.00-158.00 cells/l.

Table 3. Average abundance of phytoplankton in maros coastal waters.

Station	Average
Pond	82.00
Estuary	158.67
Sea	54.00

The total phytoplankton abundance was 866 cells/l. The waters that have phytoplankton abundance of 0-2,000 ind/ml include oligotrophic waters; 2,000-15,000 ind/ml mesotrophic and > 15,000 ind/ml is eutrophic. The highest phytoplankton abundance at the estuary site was 158 cells/l and the lowest phytoplankton abundance was 54.00 cells/l at the sea site. Based on observations and calculations of phytoplankton abundance, the highest value was found in the estuary and the lowest in the sea (Table 3 and Figure 2).

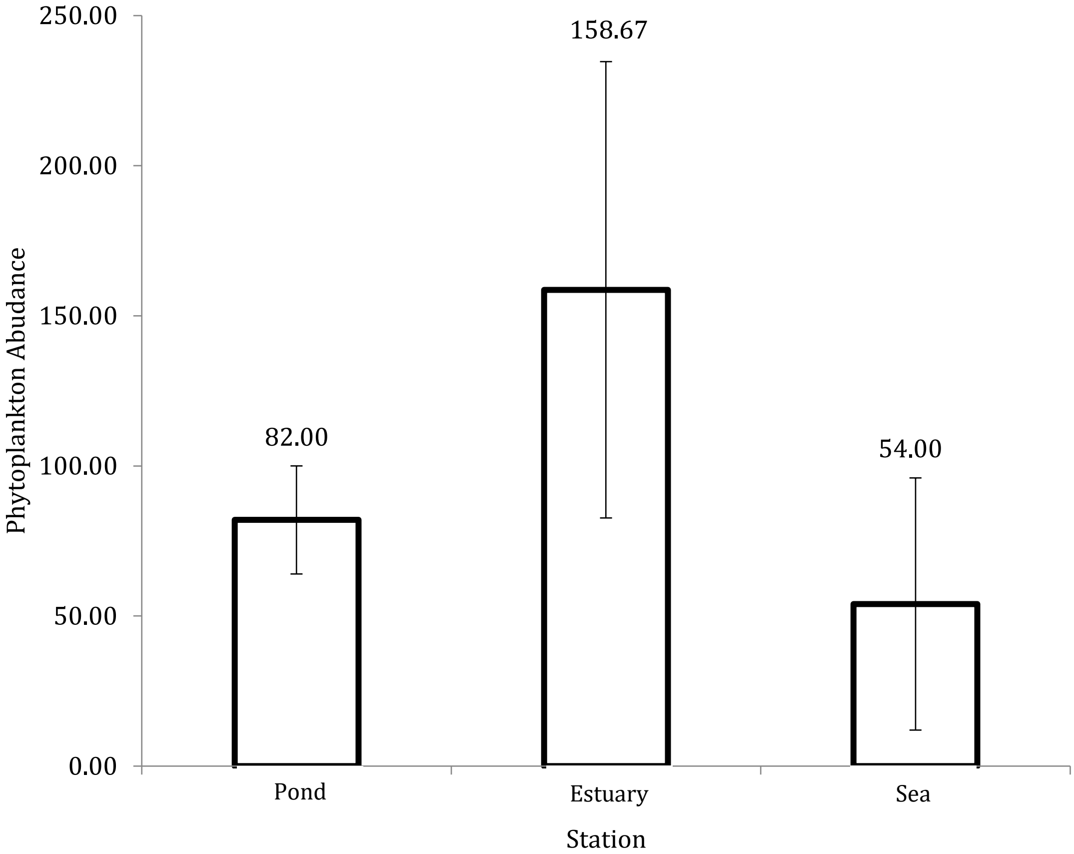

Fig. 2. Phytoplankton abundance in Maros coastal waters.

While the results of way one anova analysis at the three observation locations found no significant or real differences, so it can be stated that the distribution of phytoplankton in Maros coastal waters is quite stable. The condition of the physical and chemical parameters of Maros coastal waters is classified as supporting phytoplankton growth. Based on the results of the One Way Anova test, there is no significant phytoplankton abundance between research stations P-value 0.105> 0.005 (Table 4).

Table 4. One way anova test results phytoplankton abundance in Maros coastal waters.

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	17616.889	2	8808.444	3.363	0.105
Within Groups	15714.667	6	2619.111		
Total	33331.556	8			

The percentage of species composition of each class at the pond station with the composition of *Bacillariophyceae* (65%) (Atom) *Cyanophyceae* (7%), *Dyanopceae* (4%) and *Dinophyceae* (24%) While the composition of the class at the estuary station *Bacillariophyceae* (82%) (Atom) *Cyanophyceae* (6%), *Dyanopceae* (3%) and *Dinophyceae* (9%) and class composition at marine stations *Bacillariophyceae* (86%) (Atom) and *Dinophyceae* (14%) (Figure 4). The species composition of each class found at all stations shows that Bacillariophyceae (diatoms) is a class that has the highest percentage consisting of 19 genus, then *Dinophyceae* class consisting of 7 genus, while the least class of *Cyanophyceae* and *Cyanophyceae* consists of 3 and 1 genus. There are differences in phytoplankton composition at all stations due to each genus having different tolerance to environmental influences and the presence of genus that dominates in the station. This is in accordance with the statement of Khaqiqah et al., (2014) explained that the class of *bacillariophyceae* (diatoms) is a type of phytoplankton that is commonly found in the sea despite changing weather conditions. Based on observations and calculations of class composition, the most classes are in the estuary and the least classes are in the sea (Figure 4).

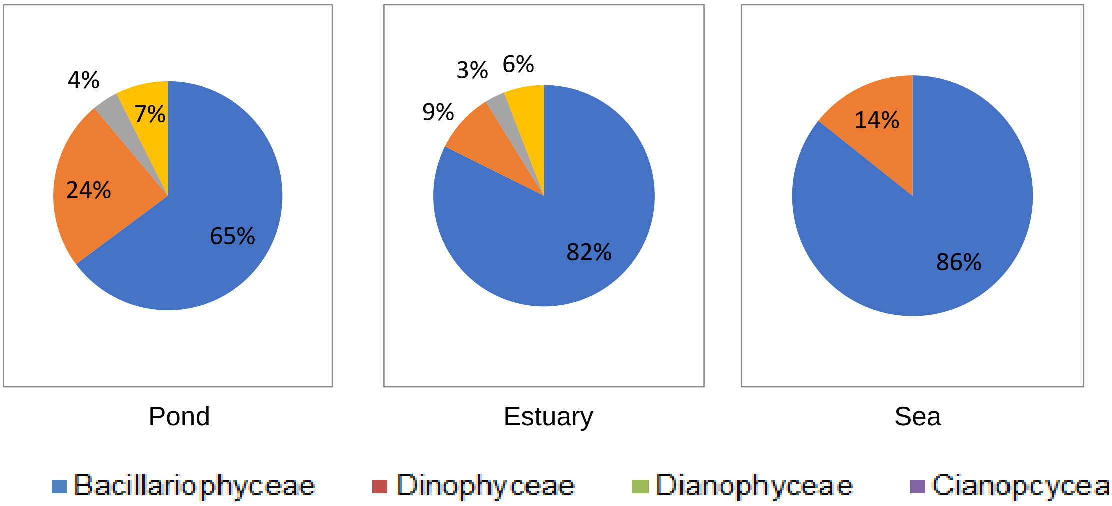

Fig. 4. Phytoplankton composition of Maros coastal waters

The results of phytoplankton observations that have been carried out show that the class of *bacillariophyceae* has the highest abundance at all stations (Figure 4). The high abundance of the *bacillariophyceae* class is because the class is widespread in all aquatic environments and its presence is more dominant in estuarine waters to the sea. The *bacillariophyceae* class in the waters has the nature of being adaptable to the environment, able to resist extremes and have high reproductive power, *bacillariophyceae* can do double cell division within 18-36 hours compared to other classes. Meanwhile, the number of genus and the high composition of phytoplankton species found from the *bacillariophyceae* class is because the *bacillariophyceae* (Atom) class is better able to adapt to existing environmental conditions, this class is cosmopolitan and has high tolerance and adaptability. Diatoms are one of the organisms commonly used as environmental bioindicators. This is because diatoms greatly affect life in the waters because they play an important role as a food source in the food chain for various marine organisms and play a role in the transfer of carbon, nitrogen and phosphate (Siregar et al., 2008).

The phytoplankton genus that has a very high number and frequency of occurrence, based on the results of observations are *Thalassionema* sp, *Navicula* sp and *Pleurosigma* sp. The phytoplankton genus found during the study is presented in appendix 2. While the results of Corenvondesi Analysis (CA) *Navicula* sp and *Thalassionema* sp are associated with the station (Pond). While *Pleurosigma* sp is associated with the station (Estuary and Sea). While the PCA results of pond stations and CO_2 characteristics are quite high. So it can be concluded that the genus of phytoplankton with high numbers and frequencies can grow at CO_2 values ranging from 22-99.73 ppm, and salinity values of 30-31 ppt. The high abundance in the coastal waters of Maros is in line with previous research on the Kuri Lompo Maros estuary with an average abundance value of 21.5 higher than the residential area (Anwar, 2014). Due to the influx of nutrients into the environment which resulted in a relatively higher average abundance at the estuary station. That phytoplankton with high abundance is generally found in estuarine waters (The high abundance of phytoplankton is caused by the large intensity of light available.

3.4 Physics of aquatic chemistry

Primary productivity and phytoplankton abundance are influenced by the condition of physical and chemical parameters of the waters. Measurement of parameters such as current velocity, turbidity, temperature, salinity, pH, CO_2, nitrate, and phosphate in Maros coastal waters showed varied results. Based on the calculation of physical and chemical parameters in Maros coastal waters (Table 5).

Table 5. Calculation of physical and chemical parameters of Maros coastal waters.

Parameters	Pond	Estuary	Sea
	Average	Average	Average
Current	0.15	0.33	0.35
Turbidity	2.88	5.05	1.49
Temperature	30	32	32
Cross	30	30	30
pH	7.83	7.8	7.81
CO^2	99.73	82.13	22
Nitrate	0.21	0.10	0.22
Phosphate	0.04	0.02	0.09

The measurement results of current velocity in this study ranged from 0.15-0.35 m/s. Based on Djurdjani, these current speeds fall into the low to moderate category, with speeds of 0.400-1,000 m/s considered moderate, less than 0.400 m/s considered weak, and more than 1,000 m/s considered strong. The highest current velocity was recorded at the ocean site with a value of 0.35 m/s, while the lowest current velocity was at the pond site with a value of 0.15 m/s. Overall, the current velocity in Maros coastal waters is relatively low, which is about 0.226 m/s (Tambaru, 2008). According to Kawara et al. (2002), in their research in Japan's Asahi Reservoir, phytoplankton showed an increase only in areas with current velocities less than 10 m/s, and began to decline when current velocities exceeded 25 m/s. Given their small size, the movement and distribution of phytoplankton is strongly influenced by currents.

Turbidity describes the extent to which sunlight can penetrate the water. Turbidity is measured in NTU units and is very important because it is related to the photosynthesis process of phytoplankton. Turbidity measurements in Maros coastal waters showed values between 1.49 to 5.05 NTU. The highest turbidity value was found at the 5.05 NUT site, while the lowest value was recorded at the sea site with 1.49 NUT. Turbidity affects the ability of water to transmit light into the water (Suhendar et al., 2020). Turbidity of more than 50 NTU is considered high, and more than 25 NTU can disturb aquatic organisms. Based on the turbidity values obtained, it can be concluded that these conditions are still safe for phytoplankton growth.

Temperature has an influence on the rate of photosynthesis, both directly and indirectly. The direct effect of temperature is seen in its role in organizing enzymatic chemical reactions in the photosynthesis process, while the indirect effect is reflected in changes in the hydrological structure of the water column that affect the distribution of phytoplankton. Changes in temperature in waters have a significant impact on the physical, chemical and biological processes of water bodies, and play an important role in controlling the condition of aquatic ecosystems. Based on the research results, the temperature in Maros coastal waters was recorded between 30-32°C. Temperature measurements showed relatively consistent values at each station. In general, the measured temperature still supports the growth and development of phytoplankton. It is explanation which emphasizes that the optimal temperature for phytoplankton growth in tropical waters ranges from 25ºC-32ºC, as well as the optimal temperature for plankton development is between 20°C to 30°C.

Salinity also affects the distribution of plankton, both vertically and horizontally. Salinity is one of the water parameters that affect phytoplankton. Salinity variations affect the rate of photosynthesis, especially in estuaries, especially in phytoplankton that can only survive in a small salinity range (stenohaline). Based on the results of the study, salinity measurements in Maros coastal waters ranged from 30-31 ppt. This value is still within the range of average salinity for Indonesian marine waters. Salinity in Indonesian waters generally ranges from 30-35 ppt, and Nontji (2008) states that salinity in marine waters ranges from 24-35 ppt. Based on the measurement results, this salinity range is considered to still support the growth and development of phytoplankton. The emphasizes that salinity above 20 ppt usually supports the life of marine plankton. The salinity opens the possibility of phytoplankton to survive, reproduce, and continue to photosynthesize actively.

The pH value describes the acidity or basicity level of a water body. In the life of aquatic organisms, pH affects the solubility of some substances. The pH value also plays a role in determining the productivity of waters. Based on the measurement results, the pH value obtained during the study ranged from 7.8 to 7.83, which is still considered good for waters. The highest pH value was recorded at the pond location with a value of 7.83, while the lowest pH value was at the estuary location with a value of 7.8. These measurements show that Maros coastal waters are still fertile enough for phytoplankton growth and do not inhibit their growth rate. Based on KEP MENLH No. 51 of 2004, the optimal pH value for phytoplankton life ranges from 7 to 8.5, so it can be concluded that the pH value in Maros coastal waters still supports phytoplankton growth.

Carbon dioxide (CO_2) in water is essential for the activity of chlorophyll plants. Carbon in water comes from respiration, decomposition of organic matter, and diffusion of CO_2 from the air. Free CO_2 refers to CO_2 dissolved in water, in contrast to CO_2 bound as bicarbonate ions (HCO3) or carbonate ions (CO^{3}_{2-}). Free CO_2 visualizes the presence of CO_2 gas in waters that are in balance with CO_2 in the atmosphere. The results of free CO_2 measurements in Maros coastal waters showed a range between 22 to 99.73 ppm, with the highest CO_2 value recorded at the pond site (99.73 ppm) and the lowest value at the sea site (22 ppm). This is likely due to bacterial activity in the decomposition of organic matter, which is triggered by agricultural, pond and harbor waste entering the waters, producing CO_2. The optimal CO_2 concentration for phytoplankton growth is around 385 ppm, and the limit of CO_2 concentration that can still be tolerated by phytoplankton is up to 750 ppm (Sahabuddin et al., 2014). Waters used for fisheries activities should have free CO_2 levels of less than 5 mg/l, although free CO_2 levels of up to 10 mg/l are still acceptable as long as oxygen is sufficient. Thus, the free CO_2 content in Maros coastal waters is still within normal limits to support the life of aquatic organisms, including fisheries activities.

Nitrate is very important for the growth and development of phytoplankton. Nitrate concentration is one of the factors that affect water fertility. Based on measurements, nitrate concentrations in Maros coastal waters ranged from 0.10 to 0.22 mg/l. The highest nitrate concentration was recorded at the marine site with a value of 0.22 mg/l, while the lowest value was at the estuary site with 0.10 mg/l. This measured nitrate concentration is still sufficient to support phytoplankton growth, although not at an optimal growth level. This is in line with the explanation of Parsons et al. (1984) who emphasized that the minimum nitrate requirement for phytoplankton, especially diatoms, is around 0.001 to 0.007 mg/l. If nitrate levels are lower than that, nitrate can become a limiting factor in the water. Optimal growth of phytoplankton generally occurs in the range of nitrate concentration between 0.9 to 3.5 mg/l.

Phosphate in the ocean can be found in dissolved or suspended form. Dissolved phosphate comes from the decomposition of plants and animals by bacteria and rock erosion (Nontji, 2007). During the study, phosphate concentrations in Maros coastal waters ranged from 0.02 to 0.09 mg/l, with the highest phosphate concentration found at the marine site (0.09 mg/l) and the lowest at the estuary site (0.02 mg/l). Normal seawater has an average phosphate content of about 0.002 mg/l. Similar to nitrate, the phosphate concentration measured during the study was still sufficient to support phytoplankton growth although not in optimal conditions. That the minimum phosphate concentration (0.00 - 0.02 mg/l) still opens the possibility of phytoplankton species that can grow and develop. The optimal phosphate concentration for phytoplankton growth ranges from 0.09 to 1.80 mg/l.

4. Conclusions

Analysis of primary productivity and phytoplankton abundance in ponds, estuaries and the sea in Maros coastal waters showed significant variation between sites. Ponds had the highest primary productivity due to the high nutrient content derived from anthropogenic activities, such as feeding and organic waste. On the other hand, estuaries showed moderate primary productivity, visualizing the effect of mixing between freshwater and seawater that causes salinity fluctuations. Meanwhile, the ocean showed lower primary productivity due to relatively low nutrient content, but higher phytoplankton diversity due to stable and consistent environmental conditions.

Phytoplankton abundance in ponds is dominated by species that are tolerant of environments with high nutrient concentrations, while in estuaries, dominance tends to shift to species that are able to adapt to fluctuating salinity. In the sea, phytoplankton are more diverse, with species that support the sustainability of marine ecosystems. These differences show that environmental factors, such as nutrient content, salinity and human activities, play a major role in determining patterns of phytoplankton productivity and abundance. These findings provide important insights for the sustainable management of coastal ecosystems in the Maros region.

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Author Contribution

This research was conducted by K. Z. D., under the supervision of A. H. N. K. Z. D., was responsible for conceptualization, methodology, data collection, data analysis, and manuscript drafting. A. H. N., provided guidance, critical review, and manuscript editing, as well as overall supervision throughout the research process.

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