UNIVERSIDADE TÉCNICA DO ATLÂNTICO
INSTITUTO DE ENGENHARIA E CIÊNCIAS DO MAR

WEST AFRICAN SCIENCE SERVICE CENTRE ON CLIMATE CHANGE AND ADAPTED LAND USE

Master Thesis

UNDERSTANDING THE POTENTIAL OF THE MACROALGAE SARGASSUM FOR CARBON DIOXIDE REMOVAL IN THE CABO VERDE ISLANDS

DEGBE DESIRE FIOGBE ATTANNON

Master Research Program on Climate Change and Marine Sciences

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Master's thesis presented to obtain the master's degree in Climate Change and Marine Sciences, by the Institute of Engineering and Marine Sciences, Atlantic Technical University in the framework of the West African Science Service Centre on Climate Change and Adapted Land Use

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FIOGBE ATTANNON DEGBE DESIRE

Panel defense

President

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Examiner 1

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Examiner 2

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São Vicente
2022

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Dedication

To my mother, father, and sister. This work is also yours.

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Resumo

O Sargaço pelágico (*S. fluitans* e *S. natans*) originário do mar do Sargaço tem sido observado florir todos os anos desde 2011 através do Atlântico tropical e na região de Cabo Verde. O Sargaço constitui um habitat importante para muitas espécies de peixes e tartarugas no oceano e desempenha um papel muito importante também no ecossistema marinho devido à sua capacidade de absorver carbono da superfície do oceano e de o exportar para o oceano profundo quando se afunda naturalmente. Este processo natural, se aperfeiçoado, poderia ser aplicado como um método de Remoção de Dióxido de Carbono oceânico (CDR). Para compreender o potencial do sargaço em torno da captação e exportação de CO_2 de Cabo Verde, foram feitas diferentes estudos, tais como a composição da matéria orgânica particulada, a análise do Sargaço pelágico recolhido em torno de Cabo Verde, bem como a sua abundância sazonal através de dados de satélite. Além disso, para testar a hipótese de que o ferro proveniente das plumas de pó do Sahara poderia aumentar o crescimento de Sargaço, foi realizada uma experiência de crescimento com Sargaço bentónico disponível perto da costa do Mindelo. A quantidade de CO_2 sequestrada durante esta breve experiência foi calculada. A média de partículas orgânicas de carbono, azoto e fósforo em Sargaço pelágico foi de 338 ± 40 $\mu g.mg^{-1}$, 14 ± 2 $\mu g.mg^{-1}$, e 2 ± 0 $\mu g.mg^{-1}$ de peso seco, respetivamente. O PIC médio: POC, que fornece informação sobre o grau de calcificantes ligados ao Sargaço, era de 0,07 ± 0,11. As razões molares C: N, C:P, e N:P são respectivamente 24 ± 4, 149 ± 29, e 6 ± 1. O período de pico da biomassa de Sargaço nos últimos 4 anos é principalmente em junho e julho. O ganho diário de biomassa do Sargaço bentónico (*Sargassum cynosom*) é de 2,42 g/dia e 3,01 g/dia com adição de poeira, mostrando o impacto positivo da poeira do Sahara na taxa de crescimento do Sargaço. Além disso, verificou-se que durante a experiência de 14 dias a absorção de CO_2 pela biomassa de Sargaço foi, em média, de 3.58 kg de CO_2. Estimativas baseadas nos resultados obtidos mostram que na região de Cabo Verde, nos últimos 4 anos, Sargaço absorveu uma média anual de 4.28 Mt de CO_2.

Palavras-chave: Sargaço pelágico, remoção de dióxido de carbono, absorção de CO_2, poeira do Sara, calcificadores.

Abstract

Pelagic sargassum (*S. fluitans* and *S. natans*), originally from the Sargasso Sea, has been blooming every year since 2011 across the tropical Atlantic and in the Cabo Verde region. sargassum is an essential habitat for many crustaceans, fish, and turtle species. It also plays a crucial role in the marine ecosystem due to its capacity to take up carbon from the ocean surface and export it to the deep ocean when it sinks naturally. This natural process, if enhanced, could be applied as an ocean Carbon Dioxide Removal (CDR) method. To understand the potential of Cabo Verde's sargassum for CO_2 uptake and export, different investigations were made, such as particulate organic matter composition analysis of pelagic sargassum collected around Cabo Verde, as well as sargassum seasonal abundance obtained from a satellite data. In addition, to test the hypothesis that iron coming from the Saharan dust plumes might enhance sargassum's growth, a growth experiment was performed with benthic sargassum available close to the coast of Mindelo. The mean particulate organic carbon, nitrogen, and phosphorus in pelagic sargassum were found to be 338 ± 40 $\mu g.mg^{-1}$, 14 ± 2 $\mu g.mg^{-1}$, and 2 ± 0 $\mu g.mg^{-1}$ of dry weight, respectively. The average Inorganic Carbon: Organic Carbon ratio, which provides information on the degree of calcifiers attached to the sargassum, was 0.10 ± 0.09. The molar C:N, C:P, and N:P are respectively 24 ± 4, 149 ± 29, and 6 ± 1. The peak biomass period of sargassum around Cabo Verde in the last four years is mainly in June and July (note that some benthic species were found floating together with pelagic species in Cabo verde). The relative growth rate of benthic sargassum (*Sargassum cymosom*) was 2.42 g/day in control and 3.01 g/day for the addition of dust, showing the positive impact of the Saharan dust on the growth rate of the sargassum. Furthermore, it was found that during the 14-day experiment, the CO_2 uptake by the sargassum averaged 3.58 kg of CO_2 for every 0.9 kg of wet biomass. Estimations based on the results obtained show that in the Cabo Verde region over the last four years, sargassum has taken up between 2.56 Mt and 4.28 Mt of CO_2 annually.

Keywords: Pelagic sargassum, Carbon Dioxide Removal, CO_2 uptake, Saharan dust, calcifiers.

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Abbreviations and acronyms

C	Carbon
CO_2	Carbon dioxide
CDR	Carbon Dioxide Removal
C:P	Carbon and phosphate ratio
C: N	Carbon and nitrogen ratio
ESA	European Space Agency
GT	Gigatons
GASB	Great Atlantic Sargassum Belt
HYCOM	HYbrid Coordinate Ocean Model
HCl	Hydrogen Chloride
Kg	Kilogram
MERIS	Medium Resolution Imaging Spectrometer
Mt	Megatons
NEER	North Equatorial Recirculation Region
N:P	Nitrogen and phosphate ratio
N	Nitrogen
NAO	North Atlantic Oscillation
pCO_2	Partial Pressure of Carbon Dioxide
P	Phosphate
PO_4	Phosphorus
PIC	Particulate Inorganic Carbon
POC	Particulate Organic Carbon
POP	Particulate Organic Phosphorous
PON	Particulate Organic Nitrogen
RV MSM 105	MARIA S. MERIAN, Research Vessel
TON	Total Organic Nitrogen
µg/mg	Microgram per Milligram
µmol/L	Micromole per litter
µatm	Micro atmosphere
wwdr	Wet weight to dried weight ratio

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1. Introduction

The brown seaweed *Sargassum* is a cosmopolitan, exceptionally species-rich genus. Whereas most species of this genus only grow attached to a solid substrate, two perform their entire life cycle in a free-floating state: *Sargassum fluitans* and *Sargassum natans*. Both species reproduce solely vegetatively by fragmentation (Brooks et al., 2018) and grow either by increasing the size of the thalli or by making new floating thalli (Smetacek & Zingone, 2013). Neither *S. fluitans* nor *S. natans* have been observed to reproduce sexually.

Holopelagic *Sargassum* essentially originated in the Sargasso Sea. It is endemic to the subtropical and tropical North Atlantic; it is widely recognized as a keystone taxon that provides habitat for diverse assemblages of invertebrates, fish, sea turtles, pelagic birds, and marine mammals (Witherington et al., 2012). At least 145 species of invertebrates and over 100 of fish are found in or associated with the pelagic sargassum community (Lapointe et al., 2014). Its presence and the periodic bloom recorded since 2011 in the North Atlantic and the tropical Atlantic or the Great Atlantic Sargassum Belt (GASB) could be related to the current and wind transport mechanism (Johns et al., 2020). The GASB extended from West Africa to the Gulf of Mexico during the summer, with the highest densities between May and September (Johns et al., 2020).

Throughout this document, the name "pelagic sargassum" will be used for *Sargassum fluitans* and *Sargassum natans*, the floating species and the name "benthic sargassum" for *Sargassum cymosom.* Since the first occurrence of these massive blooming events of pelagic sargassum, much research has focused on the macroalgae, their distribution and potential importance in aquaculture and agriculture, and the factors that influence their growth (Wang et al., 2019), (Martin et al., 2021), (Fidai et al., 2020), (Brooks et al., 2018; Davis et al., 2021; Wang et al., 2019) and (Bach et al., 2021). These works mainly covered the regions of the Gulf of Mexico and the Caribbean. Although algal blooms invade some of the West African coastal countries annually (Adetoun Fakoya, n.d.), there is little or no research on pelagic sargassum, as in the case of Cabo Verde. However, the geographical situation of Cabo Verde, the advantage that it offers in terms of water resources and the lack of scientific papers on pelagic sargassum are some of the reasons why it is an attractive study area.

The Cabo Verde archipelago is grouped with the Azores, Madeira, the Selvagens, and the Canary Islands in the Macaronesia region, which is situated in the North Atlantic Ocean, close to the West African coast and the West Mediterranean region. The archipelago is spread over 58,000 km^2 of ocean and has about 1050 km of coastline (Filmer, 2006). This area is interesting to study because of its location and the fact that it is exposed to strong winds, Saharan dust, a source of iron, hypothesized to be a limiting factor to the growth of pelagic sargassum (Gouvêa et al., 2020b). Both pelagic and benthic sargassum are found in Cabo Verde. Although pelagic sargassum is much more frequent on the southern islands, the distribution of benthic sargassum appears to be random in the Cabo Verde Islands. While the benthic sargassum (*Sargassum cymosum*) grows around the coast, the pelagic sargassum grows at the surface and can be found anywhere in the open ocean, which makes it more interesting as a CDR (Carbon Dioxide Removal).

Through photosynthesis *Sargassum* takes up CO_2 stored in its biomass as Carbon bound in tissue (C). The grow of epibionts on *Sargassum* produce Inorganic Carbon bound in tissue, which is use to estimate the calcification ratio. Even though *Sargassum*'s capacity for CO_2 uptake is well known, very few studies have examined their potential involvement in carbon dioxide removal (CDR) on a large scale. the existing studies are based on lots of assumptions and very little in situ data (Bach et al., 2021). Analysis of organic carbon composition and determination of Inorganic Carbon (IC) : Organic Carbon (OC) ratios will be of great interest in understanding the amount of carbon dioxide removed by *Sargassum* in the Cabo Verde region and the impact of the epibionts calcification associated with pelagic sargassum.

1.1 Research Questions

The results obtained will help with the preliminary assessment of the carbon dioxide sequestration potential of pelagic sargassum in the Cabo Verde region. By addressing the following research questions, this work provides information on the possibility of pelagic Sargassum sequestering CO_2 at the ocean surface:

1- What are the C bound, N bound, and P bound in pelagic sargassum tissue contents and their ratio around Cabo Verde?

2- During which period of the year are pelagic sargassum most abundant around Cabo Verde? Where does the population come from, and what are the potential nutrient sources driving the algal bloom?

3- Does the addition of Sahara dust influence benthic sargassum's growth?

4- How much carbon dioxide can pelagic sargassum take up annually on average, and how much does benthic sargassum take up?

1.2 General Objective

This work aims to investigate the seasonal abundance of pelagic sargassum species around Cabo Verde, their particulate organic matter content, their potential for Ocean CDR, and the factors limiting the growth of benthic sargassum.

1.2.1 Specific objectives:

- Analyse the chemical composition of pelagic sargassum biomass (Organic Carbon (OC), Nitrogen (ON), and Phosphorus (OP)) under different nutrient regimes in the waters around Cabo Verde.
- Assess the seasonal Ocean cover of pelagic sargassum around Cabo Verde from 2018 to 2021 based on satellite data.
- Investigate sea surface pCO_2 values around Cabo Verde.
- Determine the growth rate of benthic sargassum during an in-situ experiment in Mindelo with dust addition for iron.
- Synthesis: Assessment of the carbon dioxide sequestration potential of *Sargassum* in the Cabo Verde region via the estimation of the amount of CO_2 captured by pelagic sargassum biomass cover each year.

1.3 Research Hypothesis

These are the assumptions that support the research questions and the objectives of the master thesis.

- H1: Pelagic sargassum biomass, with tissue bound C, N, and P has a potential for ocean carbon sequestration Cabo Verde.
- H2: The Cabo Verde region's pelagic sargassum is most abundant during the early spring and summer months
    - ✓ H2a: The pelagic sargassum population of Cabo Verde comes from both the coast of Brazil and Great Atlantic Sargassum Belt and is transported by strong currents.
    - ✓ H2b: Saharan dust and the Congo River are the primary nutrients sources driving benthic sargassum growth, and dust addition positively impacts the benthic sargassum grow rate.
- H3: Pelagic sargassum take up a significant amount of CO_2 in Cabo Verde.

C,N and P bound in tissues analysis, satellite data analysis on pelagic sargassum abundance, analysis of CO_2 data available on SOCAT and conclusions based on the results and literature will help justify or reject these hypotheses.

1.4 Structure of the work

The present work is structured in six parts. Indeed, the first part introduces the master's thesis topic, the problem, the study area and the fixed objectives. The second part based on the literature summarize existing knowledge on the subject in the study area and elsewhere. The third part based on the materials and methods used during this study describes the different measurement procedures used in the laboratory, the devices and the software used during the data analysis. The fourth part presents the results obtained after analyzing the samples and satellite data. The fifth part discusses the results obtained by comparing them with those obtained by the literature in the area and the last part presents a summary of the whole work and ends with the perspectives (Outlook).

2. Literature review

2.1. Holopelagic Sargassum species

Sargassum is a brow seaweed genus belonging to the Phylum Ochrophyta, Class of Phaeophyceae, Subclass Fucophycidae, Order Fucales, and Family Sargassaceae. Two species are pelagic (Figure 1). Pelagic sargassum is usually 20–30 cm long with a 0.4–1.8 mm thick cylindrical axis (1), smooth or with few spines near the apex, with a well-formed midrib in the centre surrounded by rounded cells (3) and a single layer cortex of cells (Godínez-Ortega et al., 2021).

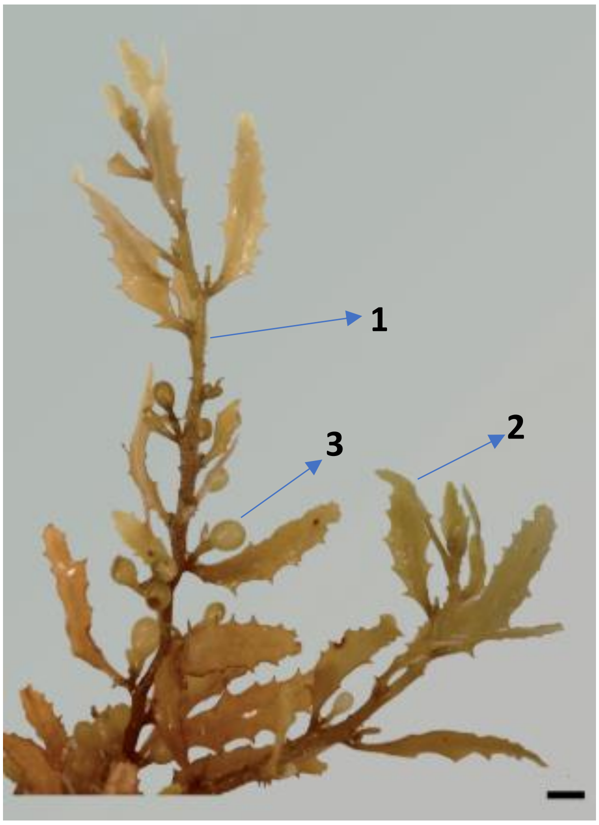

Figure 1: General presentation of pelagic sargassum(Godínez-Ortega et al., 2021). 1) a stem, 2) a lamina, 3) an aerocysts or pnematophore

Different morphotypes of pelagic sargassum exist (Figure 2) and are named by Albert Eide Parr, 1939.

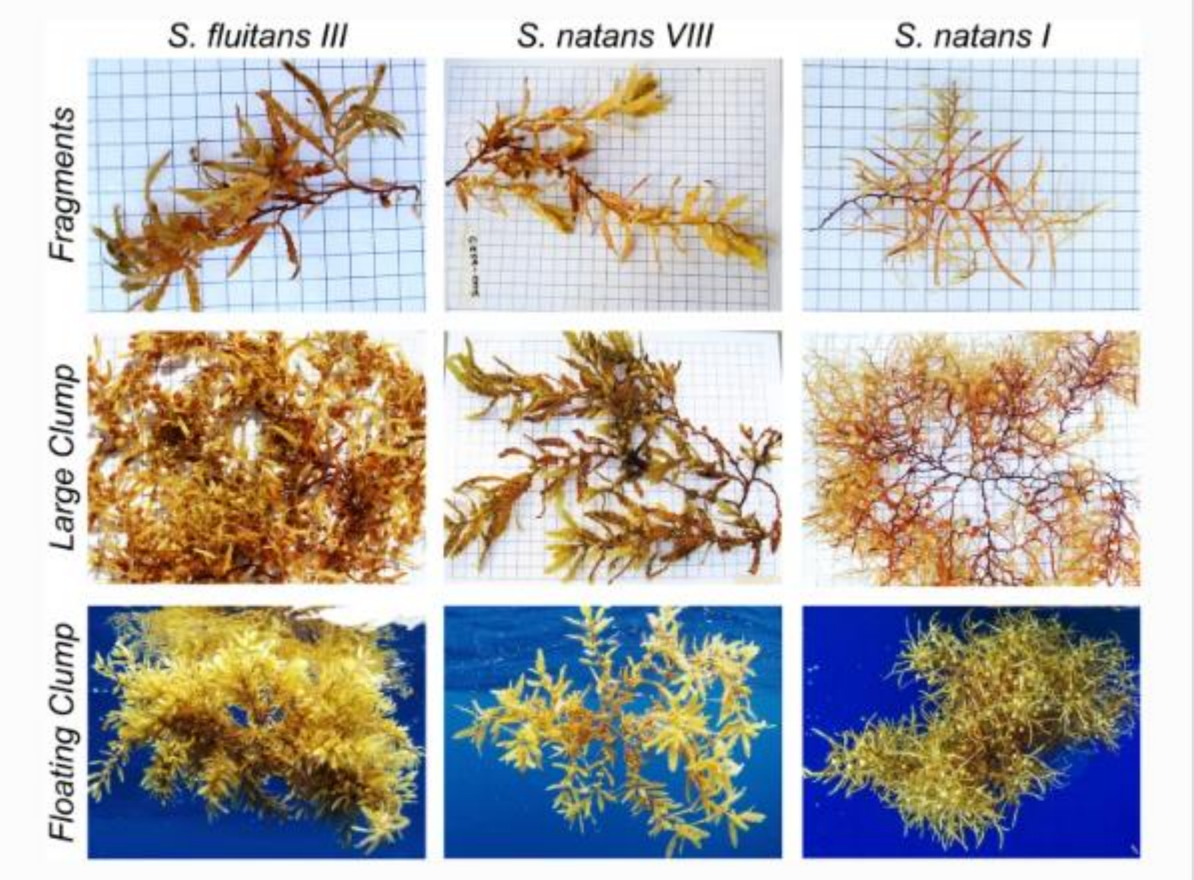

Figure 2: Different morphotypes of pelagic sargassum according to (Martin et al., 2021)

Pelagic sargassum grows by floating on the water's surface with pneumatophores (vesical containing air). Like other species of the genus *Sargassum*, pelagic sargassum has a diploid thallus and reproduces by cloning. In contrast, benthic sargassum species have female oogonia exposed outside the conceptacle, remaining attached to the receptacle, a modified terminal structure of the thallus whose function is to produce reproductive cells (Godínez-Ortega et al., 2021), (Martin et al., 2021). Outside the Antarctic Ocean, the genus *Sargassum* is widespread in all oceans, and the Sargasso Sea is known to have the highest concentration of pelagic sargassum (Godínez-Ortega et al., 2021).

2.2 Sargasso Sea and functions of the ecosystem

The Sargasso Sea is located in the Noth Atlantic delimited by the subtropical clockwise circulating gyre on the western edge by the Gulf Stream, the North Atlantic Current in the north, the Canary Current in the east and the North Atlantic Equatorial Current in the south (Godínez-Ortega et al., 2021). Since 2011 in the middle Atlantic, the Great Atlantic Sargassum Belt

(GASB) is formed in the summer. The resulting biomass extend to the Gulf of Mexico, where the belt follows the Loop Current and Gulf Stream to enter the North Atlantic. At the same time, some pelagic sargassum is transported directly into the North Atlantic from the Central West Atlantic following the Antilles Current. The population of pelagic sargassum in Cabo Verde is part of the GASB and transported by currents essentially North Equatorial Current (NEC), northern branch of the South Equatorial Current (nSEC), North Brazil Current (NBC) and the intensified North Equatorial Counter Current (NECC) to West Africa and the southern part of the Cabo Verde islands (Wang et al., 2019), (Berline et al., 2020).

2.3 The Great Atlantic Sargassum Belt and possible causes of the bloom

A coupled modelling approach that integrates output from a data-assimilating 1/12° HYCOM simulation, a 1/4° coupled HYCOM–biogeochemical model, and individual-based Lagrangian pelagic sargassum growth models were used to investigate what controls the pelagic Sargassum seasonal distribution. Satellite imagery from the European Space Agency (ESA) Medium Resolution Imaging Spectrometer (MERIS) optical sensor can detect the entire distribution of the population of pelagic sargassum in the Gulf of Mexico and the western Atlantic. Ocean circulation and pelagic sargassum physiology appear to be essential in the model as factors to predict the seasonal distribution of biomass. Brooks et al. (2018) developed a model suggesting that the Gulf of Mexico and Western Tropical Atlantic are regions where pelagic sargassum populations may disproportionately influence the basin-wide biomass.

Pelagic sargassum is not new to the southern tropical Atlantic, as indicated by the historical reports, but its sudden increase observed since 2011 is a very recent phenomenon (Godínez-Ortega et al., 2021). The current blooms may have been caused by a combination of various events. It has been attributed to climatological changes in sea surface temperature (SST) and a North Atlantic Oscillation (NAO) anomaly in 2009-2010, which may have introduced large "seed populations" of pelagic sargassum into the African part of the NERR (Northern Equatorial Recirculation Region).

Blooms are thought to be associated with increased nutrient input to the Sea. The warm temperature and availability of nutrients that characterize the NERR compared to the Sargasso Sea provide a more favorable environment for algal growth. Change in upwelling patterns along the African coast and the increase in dust storms from the Sahara would have contributed to increased NERR associated with nutrient loading from river discharges, such as the Congo in Africa or the Amazon in Brazil (Godínez-Ortega et al., 2021). It would have contributed to a faster growth rate of pelagic sargassum since it has been shown that the doubling time of pelagic sargassum in nutrient-rich waters is 11 days, while in less nutrient-loaded oceanic water, it's 50 days (Lapointe et al., 2014).

The Eastern equatorial Atlantic, African coastal upwelling and the Congo River and Amazon River floods are suggested to be nutrient sources for pelagic sargassum bloom since 2011 (Setthamongkol et al., 2015). Wang et al. (2019) highlighted that the growth of pelagic sargassum is mainly influenced by warmer sea surface temperature and nutrient availability, and the recent bloom events show connections to nutrient enrichment and climatic variations (Lapointe et al., 2021). The GASB is likely supported by nitrate (N) and phosphate (P) inputs from a variety of sources, including discharges from the Congo, Amazon, and Mississippi rivers, upwelling off the coast of Africa, vertical mixing, equatorial upwelling, and biomass burning of vegetation in central and south Africa (Lapointe et al., 2021).

Pelagic sargassum is most abundant in the Western Equatorial Atlantic in spring and summer. Although multiple sources of pelagic sargassum may exist, transport of the pelagic sargassum in the spring is most likely associated with the Guiana Current, whereas in the summer, North Brazil Current Rings are the primary pathway (Putman et al., 2018). Through particle-tracking and numerical model experiments that account for both physical transport and biological growth, the July GASB were well reproduced by forward-tracking simulated pelagic sargassum particles for six months (Wang et al., 2019a).

After 2011, the pelagic sargassum abundance in the central Atlantic showed similar seasonality as in the Gulf of Mexico, with increased mass from January to June and decreased abundance from July to December. Considering the weak seasonality in insolation in the tropics, this might result from an innate biological clock (circannual rhythm), as in other brown seaweeds, combined with the seasonal nutrient supply (Wang et al., 2019).

Pelagic sargassum contains higher amounts of protein, essential and non-essential amino acids, essential fatty acids, and minerals than kelp (Laminariales) (Redmond et al., 2014). It also contains phycocolloids, bioactive compounds (e.g., alginic acid and fucoidan), and polyphenols that may have potential nutraceutical and medical applications (Gupta & Abu-Ghannam, 2011). *Sargassum* is used in Chinese medicine as an expectorant for bronchitis and to treat laryngitis, hypertension, infections, fever, and goiter (Redmond et al., 2014).

2.4 Sargassum influx in Africa

In a brochure published by Dr Kafayat Adetoun of the University of Lagos on pelagic sargassum in West Africa, pelagic sargassum first appeared in Ghana in 2009 and then in 2011 in other West African countries. The origin of this pelagic sargassum masses has been suggested to be NERR. The severity of the influx is less in Benin, Guinea and Togo than in Ghana, Nigeria, Cote Ivoire and Sierra Leone. The pelagic sargassum influx in West Africa reached a critical threshold in 2015 and three essential factors have been suggested as influencing this phenomenon, namely, the nutrients from local or distant sources, variability in ocean climate and ocean circulation and the ability of pelagic sargassum to disperse and colonize new habitats through fragmentation. The influx of pelagic sargassum (*Sargassum hystrix var. fluitans* named by Guiry and Guiry, 2012 as *Sargassum fluitans*, the accepted specie name) that occur mainly in the rainy season (May-August) (Solarin et al., 2014) has negatively impacted the economic activities of coastal populations, risking diseases and infections and causing beach erosion. According to a study conducted in Nigeria, very little knowledge exists on pelagic sargassum, and the only mitigation is harvesting (removing the algal masses at sea or from the shores) (Adet et al., 2017). In the Cabo Verde region, although very little is known about pelagic sargassum, it is known that pelagic sargassum is much more common on the southern islands and in addition to being abundant between May and August, it sometimes peaks in mid-November and January[1].

2.5 Carbon Capture by pelagic sargassum

Based on the literature, large-scale seaweed farming can act as a CDR if the fixed CO_2 through photosynthesis by the seaweed is transported into the deep sea or sediments (Carbon & Removal, 2021). The air-sea flux of CO_2 (delta CO_2) is mainly seasonal and relatively constant over the years (Fiedler, 2013). Figure 3 presents the variation of the Delta CO_2 (air-sea CO_2 flux) in recent past years. Pelagic sargassum increase biomass in the presence of light and nutrients and fix Carbon through photosynthesis, a process during which sea surface CO_2 is absorbed from the water. Phosphate, iron and a minimum temperature and salinity are thought to increase growth rate and thereby play a role in the abundance or variation of pelagic sargassum. Of these factors, iron has been identified to influence pelagic sargassum distribution

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[1] https://www.icare.univ-lille.fr/sargassum-near-cape-verde/

(Gouvêa et al., 2020a). The Sahara Dust is the largest source of iron deposition in the oceans, particularly in the North Atlantic and Mediterranean.

Furthermore, pelagic sargassum provides a habitat for calcifying organisms such as bryozoans which reduce the alkalinity of seawater and emit CO_2 (Maine, 1985), (Bach et al., 2021).

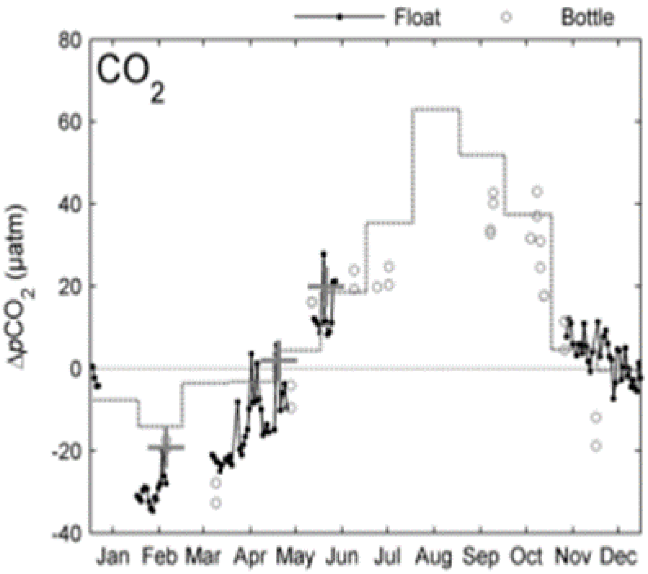

Figure 3: ΔpCO_2 (Differences between atmospheric and oceanic levels for pCO_2) from 2006 to 2012 (Fiedler,2013)

However, it is assumed that even if pelagic sargassum contains lots of calcifying epibionts, the net flux of CO_2 may still absorbing because pelagic sargassum takes up more CO_2 through photosynthesis than the calcifiers can emit during calcification (Bach et al., 2021). The literature reviews revealed that no work had been done on pelagic sargassum in Cabo Verde, leaving open questions about its importance and impacts on the marine ecosystems in this area. Hence, this thesis contributes to an improved understanding of *Sargassum*'s abundance and role in the marine ecosystem of Cabo Verde. As highlighted early, many other studies have focused on the *Sargassum*'s ecological and sometimes even economic importance. However, in the context of the challenge of climate change and ocean acidification, it is appropriate to consider the possibility that *Sargassum* plays the roles, namely ecological (Brooks et al., 2018) and chemical by absorption of CO_2 (Maine, 1985), (Gouvêa et al., 2020a), (Bach et al., 2021). From this perspective, the master thesis aims to "understand the potential of the pelagic macroalgae sargassum to remove atmospheric CO_2 in the waters of Cabo Verde islands".

3. Materials and Methods

3.1 Study area

The Cabo Verde islands are located a few hundred kilometers (988 km) to the west coast of Africa in the North Atlantic Ocean. The islands are at the crossroads between Europe, Africa and America. The archipelago belongs together with the Canary Islands, Azores and Madeira to the Macaronesia region. The total area of all islands are over 4,000 square kilometers, of which the island of Santiago is the largest. The distance to Cabo Verde is only 664 kilometers from Dakar (Senegal), and its geographical coordinates are 16.5388 ° N and 23.0418 ° W. It consists of 10 islands, of which nine are habited.[2].

The islands where pelagic sargassum have been observed more often in Cabo Verde are those in the south, such as Fogo, Brava, and Santiago. Therefore, the pelagic sargassum sample were collected from the Fogo Island. Additionally, some pelagic sargassum samples were collected during the expedition MSM-105 (5.49 ºN and -16.85 ºE)) on board the R V Maria S. Merian. The benthic sargassum (*Sargassum cymosum*) used for the growth experiment was collected at Calhau in Sao Vicente Island (Figure 4).

3.2 Sample collection

The sargassum samples used during this work were collected at different sites, particularly for analyzing the particulate organic matter. In total, 14 representatives from 3 sampling sites (Faja, Bacabaleru, and MSM105 (5.49 ºN and -16.85 ºE)) were obtained. The first sampling was conducted at Sea in the vicinity of Faja/Fogo Island beach on 06th February, and a second on 09th February 2022. The second site was sampled on 07th February in Barcabaleru/beach, Fogo Island. Sampling was carried out by boat to collect pieces of pelagic sargassum in plastic buckets containing seawater. Water samples were also taken for nutrient analysis (triplicate samples per station). Nutrient samples were frozen within two hours and measured at GEOMAR (Germany) with a Seal Quatro autoanalyzer (Seal Analytical, Norderstedt, Germany).

Once back on shore, the collected pelagic sargassum biomass was rinsed with fresh water and dried with kitchen paper before being packed in labelled plastic bags (Figure 5-b). Approximately 2 kg of fresh pelagic sargassum biomass was packed in 4 plastic bags, frozen at

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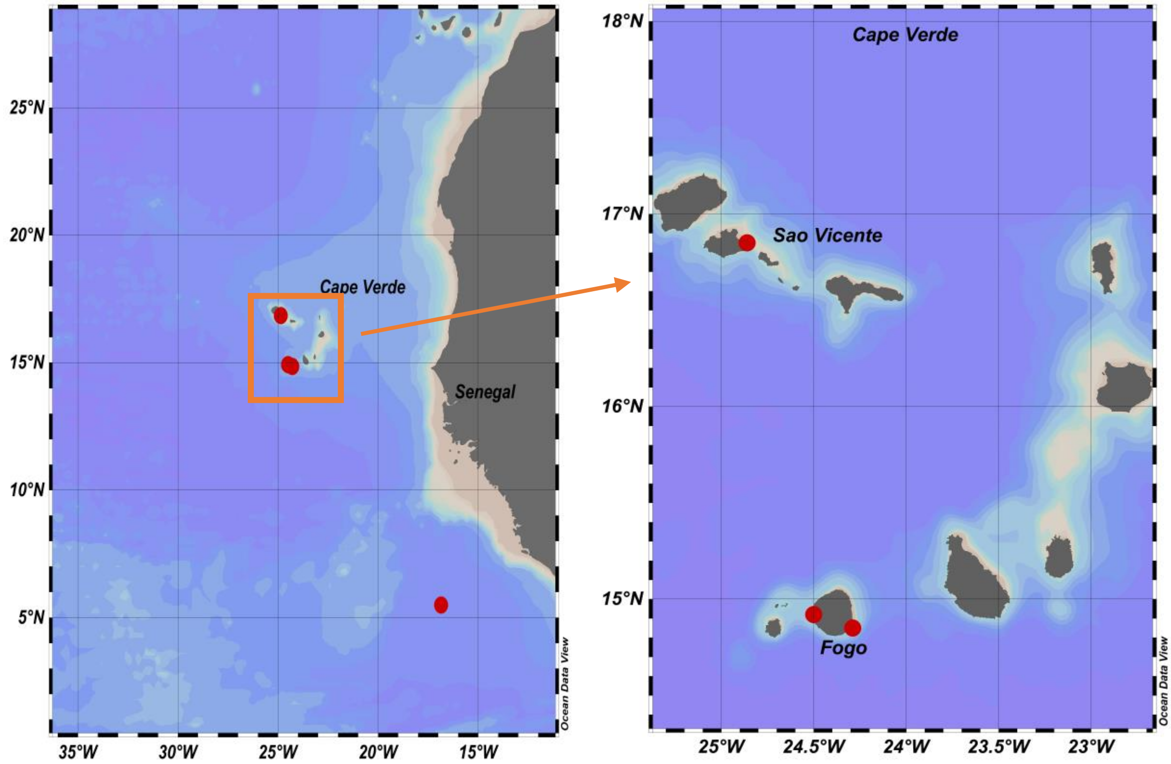
[2] https://www.capeverdeislands.org/location-and-islands/

-20º C to avoid decomposition, and transported on board the RV Maria S. Merian (expedition MSM-106) to Germany for analysis.



a **b**

Figure 4: Map of the Sampling sites (red dots represent locations where samples were collected. Figure a) the areas of sampling sites within the archipelago of Cabo Verde. B) the upper dot shows where benthic sargassum was collected in Jun 2022, and the lowest dots show where the pelagic sargassum was collected in February

Approximately 2 kg of fresh pelagic sargassum biomass was collected during the MSM-105 expedition, processed and preserved as described above. Figure 4-b shows the study area map, including the different sampling sites (red dots). The nutrient samples were collected for each sampling site to know the environmental condition. The collection consisted of rinsing the test tubes with seawater three times, filling them to 3/4 with seawater and closing them carefully without touching the tube openings and the lower parts of the lids to avoid contamination. A triplicate of tubes was collected for each station and frozen (-20°C) approximately 2 hours after collection for the Fogo samples. In contrast, the MSM-105 samples were chilled and frozen at the same temperature five days later because the samples were taken with support of the MSM 105 scientists that arrived in Mindelo only five day later. Table 1 informs about the sampling sites, the date and geospatial coordinate.

Table 1: Sampling sites data

Date	Latitude (ºN)	Longitude (ºE)	Stations Names
20/02/20222	5.49	-16.85	MSM105
06 and 09/02/2022	14.92	-24.5	Faja
7/2/2022	14.85	-24.29	Bacabaleru
21/06/2022	16.85	-24.86	Calhau


a b

Figure 5: Pelagic sargassum samples from Faja, 06-02-2022. a- is the new catch of Sargassum with all species comprised, b- packed sargassum samples after rinsing twice with fresh water, all species comprise and no herbarium specimen.

3.2.1 Identification and classification of pelagic sargassum in morphological groups

The pelagic sargassum has two species and several morphological form. In this work, the pelagic sargassum samples collected were divided into morphotype groups different from those already described in the literature because of the lake of time and adequate logistic to identify different species during the sampling. The key characteristics used in the classification in this work were:

- Lamina size (large, short, wavy)

- Size of aerocysts or pneumatophores (with or without “peak”)
- Lamina color (brown, green and/or dark)
- The disposition of the leaves on the stem (dense or spaced).

For the benthic sargassum, the identification was made based on the Atlantic Ocean Seaweed Identification Key of the Atlantic Technical University Laboratory (The Marine Algae and Coastal Environment of Tropical West Africa by G.W. LAWSON and D.M. JOHN)

3.3 Organic matter composition

Prior to chemical analysis, the samples were treated as follows:

- The fresh biomass of pelagic sargassum was defrosted overnight, rinsed twice with fresh water, dried with kitchen paper, and weighed. Then, the samples were separated in group base on the characteristics listed above. before drying in an oven at 60°C.
- The drying process was stopped when the weight remained constant for 12 hours. The dry materials of the pelagic sargassum were carefully weighed and packed in a labelled Ziplock bag for each sample before grounding (Figure 6-a).
- Each sample was grounded separately, and the grinding machine was cleaned after each sample with dry air to avoid contamination.

The OC, IC, and ON content of the dry pelagic sargassum material was analyzed using the following protocol:

- Two subsamples (2 to 3 mg) of the homogenized pelagic sargassum samples were weighed in a tin cup (Figure 6-b) to analyze the C and IC content.
- One subsample was closed directly for IC. The other sample was acidified to pH 2 using 37 % HCl to remove inorganic carbon (IC) and be able to measure the OC.
- Samples were analyzed with an elemental analyzer (EUROVECTOR S.P.A., EURO EA 3000).

The OP analysis was performed using a subsample of dry ground pelagic sargassum as follows:

- 15 to 20 mg of ground material were weighed and put into Schott Duran bottles with 40 mL of Milli-Q water and one spoon of oxisolv (Avantor®, a Fortune 500 company).
- Three standard solutions were prepared with 40 mL of Milli-Q water and one spoon of oxisolv. The Standards contains 0, 5, and 10 µM dissolved phosphate.

- The bottles were put in a pressure cooker (Figure 6-c) and were boiled on a cooking plate with maximum pressure for 30 minutes to transform all OP to phosphate.
- The bottles were cooled down over the night.
- After that, 1.2 mL of ascorbic acid was added, mixed, and the subsamples were left open for 1 min. Then 1.2 mL of mix reagent was added and mixed well, and the lids were left open for 10 minutes.
- The mixture turned blue, and 12 mL of each sample was put in a 15 mL falcon tube.
- After that, the tube lids were closed, and the bottles were centrifugated for 10 min at 5000 rpm to get rid of suspended particles (Figure 7-a)
- The samples' absorption and standards were measured against Milli-Q at 882 nm in 2 cm cuvettes with the photometer (Figure 7-b). The intensity of the blue color
- is directly proportional to the amount of orthophosphate in the water. After each measurement, the cuvette was rinsed with Milli-Q water and dried to avoid contamination.
- A calibration curve was performed with three standards prepared (0, 5 and 10 µmol L^{-1}).
- The linear regression of the standard curve was used to calculate the concentration of phosphate in each sample by multiplying the measured value by the molecular weight and then dividing it by the dry weight to obtain the concentration of P in µg.mg^{-1} dry weight.

a B c

Figure 6: Materials used for sample grinding (Alfred Wegener Institute lab), a- Grinder, b- precision scale for IC and OC samples, c- pressure cooking pot.


a b

Figure 7: Materials used to analyze the OP sample (Alfred Wegener Institute lab, April 2022). a) the centrifuge and b) the photometer used to measure phosphate in the subsamples.

3.4 Growth experiment

To better understand the impact of Saharan dust (rich in iron) on *Sargassum* growth, a benthic sargassum growth experiment was set up in Marina Mindelo, Sao Vicente. Benthic sargassum was collected and put in a floating cage in the Marina Mindelo, monitored daily. Benthic sargassum biomass gain was measured by weighing with a scale. The rock-bound benthic specie (*Sargassum cymosum*) was used instead of *Sargassum fluitans* and *Sargassum natans* for the growing experiment due to the lack of adequate logistics to return to Fogo for the collection of pelagic sargassum.

The experimental set-up consisted of 2 cages of one square meter. Each cage was divided in three compartments (pseudo replication) , with 40 cm height to facilitate good light penetration (Figure 8-a). The two cages were fixed at a distance of 5 m each. The benthic sargassum used in the experiment was collected in the morning and at low tide (Figure 8-b), placed in a bucket containing seawater, and transported to Marina Mindelo, where the cages were put in water and then the seaweed. Total biomass of 300 g of wet weight was placed in the triplicate of each cage. One cage was supplied with 5 g of dust every 48h, obtained by sieving sand collected in Mindelo / Sao Vicente (no elemental analysis done for the dust). The biomass gain of each piece of cage was recorded every 48h in the afternoon (5 to 6 pm).

The growth rate was calculated as the difference between the initial and maximum final biomass (for every piece of cage and then the average per cage). The difference obtained was divided by the number of days (09 days), and then the rate was deduced from each cage's average value of biomass gain.

$$GR(wet\ in\ g) = \frac{(B_{max} - B_i)}{09}$$

Where:

- B_{max}: Biomass maximum obtained during the experiment.
- BI: Initial Biomass (300 g)
- A: average biomass gain obtained for each cage.
- GR: Growth rate in g

a

b

c

d

Figure 8: Experimental set-up and benthic sargassum species (*Sargassum cymosum*). a) Sampling site of Sao Vicente/ Calhau, b) Experiment cage floating at the ocean surface at Marina Mindelo, c) single steam of sargassum showing the lamina of the specie after five days of the experiment, d) benthic sargassum during day 1 of the experiment, two hours after sampling.

3.5 Data analysis

Once in the laboratory, the benthic sargassum fresh biomass data was recorded in Excel. The concentrations measured for OC, IC, ON, OP, were recorded in different Excel sheets and then linked together. The different C:N, C:P, and N:P ratios were calculated in Excel to generate a data frame that was analyzed in R. The Carbon uptake was estimated in Excel using EcoMatcher method.[3]

The software R (R version 4.1.2 (2021-11-01)) was used for the statistical analysis and visualization of data related to the chemical composition of sargassum and the calculation of C, N and P ratios. The Tukey test was used to compare different morphotypes and different stations. The analysis and visualization of satellite data on the average biomass of pelagic sargassum, as well as the monthly average of pCO_2 (from SOCAT), was performed with the software Python (Python version 3.9.12 (main, 04th April 2022, 05:22:27) [MSC v.1916 64 bits (AMD64)].

Ocean Data View (Schlitzer, R., Ocean Data View, https://odv.awi.de, 2022) was used to generate the map showing the study area and sampling sites.

3.6 Satellite data and pCO_2 data

The monthly average of pelagic sargassum biomass has been recorded over the last years using Satellites (Satellites: Terra and Aqua, Sensor: MODIS, Resolution: 1 km, Swath: 2800 km, Revisit frequency: 1-2 days, Spectral bands for ocean color: 9). For this study, monthly average biomass Satellite data of 2018-2021 covering the Cabo Verde region was obtained. The defined geospatial boundaries of this region were Longitude (-35.15, -15) and Latitude (4.65, 25.97). The data was obtained from Satellite-based sargassum maps, and digital data Sargassum Watch System (SaWS) developed and operated by the Optical Oceanography Lab, University

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[3] https://www.ecomatcher.com/how-to-calculate-co2-sequestration/#:~:text=The%20atomic%20weight%20of%20Carbon,in%20the%20tree%20by%203.67.

of South Florida[4], courtesy of Professor Chuanmin Hu. Sea surface $p\mathrm{CO}_2$ data were obtained from SOCAT[5] and a wave glider mission (courtesy of Dr Bjorn Fiedler).

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[4] https://optics.marine.usf.edu/projects/SaWS

[5] https://www.socat.info/index.php/data-access/

4. Results

This chapter reports on the results obtained after the analysis of the data, provides information on the samples collected, the growth experiment of benthic sargassum, and informs on the results of the analyses carried out at the Laboratory.

4.1.1 Morphology and characterization of sargassum samples

The pelagic sargassum samples from Faja were found to also content species from benthic origin that presented green color. The samples were divided into three groups due to the diversity of morphology found at this station. The most notable factors in morphology are the color (brown and green), size of the lamina (long-short) and pneumatophores or aerocysts (large or small). There are no distinct differences between the four samples from MSM-105. However, the Bacabaleru samples also show morphological differences (Figure 9). For the chemical analysis, the Faja and Bacabaleru samples were grouped by morphology as well as the ones from MSM-105. Each morphologic group was defined based on the criteria described in the previous chapter and had nothing to do with the official morphotypes described by (Godínez-Ortega et al., 2021).

Morphotype 1: characterized by small lamina, small aerocysts and brown color (Figure 9 a).

Morphotype 2: characterized by large lamina and larges aerocysts. They are darker brown than the previous and bushy (Figure 9 b).

Morphotype 3: characterized by large lamina, larges aerocysts and green color (probably from benthic origin). This morphotype is dense (Figure 9 c).

Morphotype 4: characterized by small lamina and lighter and bushy aerocysts (probably from benthic origin) (Figure 9 d).

Furthermore, Figure 10 show how each morphotype is represented from the samples collected per station. The most represented morphotype is morphotype 1 and the least represented is the morphotypes 4.

a b

d c

Figure 9: Different morphotypes observed in the samples. From a- to d- indicated each morphotype as described following. The most represented morphotype is morphotype 1 from MSM-105 Figure 9-a. Morphotype 2 Figure 9-b from Bacabaleru, morphotype 3 Figure 9-c, and morphotype 4, less represented Figure 9-d, are mainly in the samples of Faja.

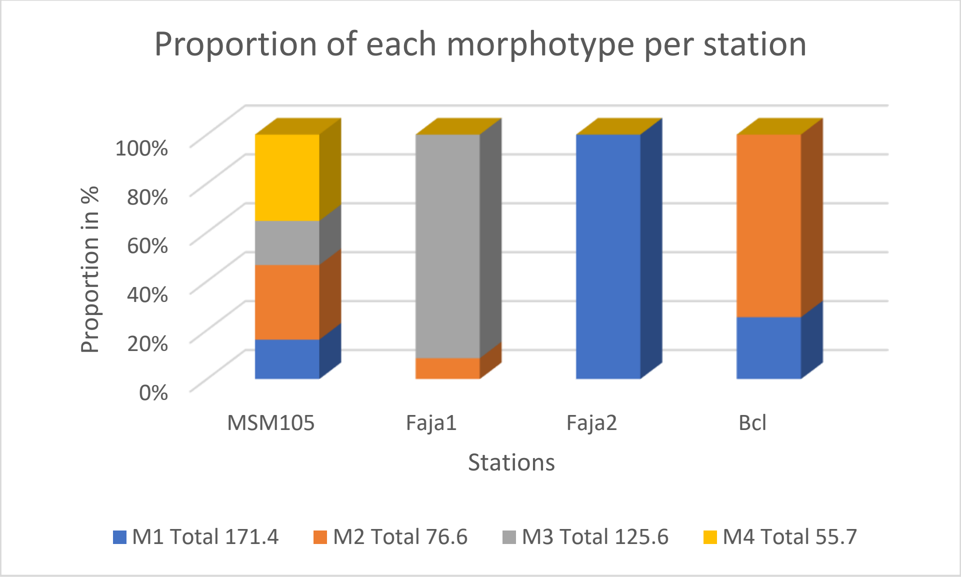


Figure 10: Proportion of each sargassum samples morphotype per station, deduced from dry weight

4.1.2 Environmental conditions of the water surrounding pelagic Sargassum.

Nutrient concentrations in the water at the locations where pelagic sargassum was collected were very distinct. Nutrient concentrations close to Fajas and Bacabaleru were deficient (0.65 ± 0.05 µmol L^{-1} of TON, 0.7 ± 00 µmol L^{-1} of PO_4 and 0.03 ± 00 µmol L^{-1} nitrite) while close to the Namibian Upwelling system nutrient concentrations were high (5.83 ± 0.07 µmol L^{-1} of TON, 0.68 ± 0.01 µmol L^{-1} of PO4 and 0.06 ± 00 µmol L^{-1} nitrite) due to fresh upwelling.

Table 2 : Nutrients composition of sea water from the sampling sites

Location	TON	PO_4	Nitrite	N:P ratio
Unit	µmol L^{-1}	µmol L^{-1}	µmol L^{-1}	
Faja 1	0.71 ± 0.00	0.09 ± 0.0	0.04 ± 0.00	6.36 ± 0.40
Faja 2	0.61 ± 0.00	0.07 ± 0.00	0.03 ± 0.00	5.19 ± 0.49
Bacabaleru	0.59 ± 0.00	0.07 ± 0.00	0.03 ± 0.00	5.48 ± 1.34
MSM 105	5.83 ± 0.07	0.68 ±0.01	0.06 ± 0.00	6.44 ± 1.61

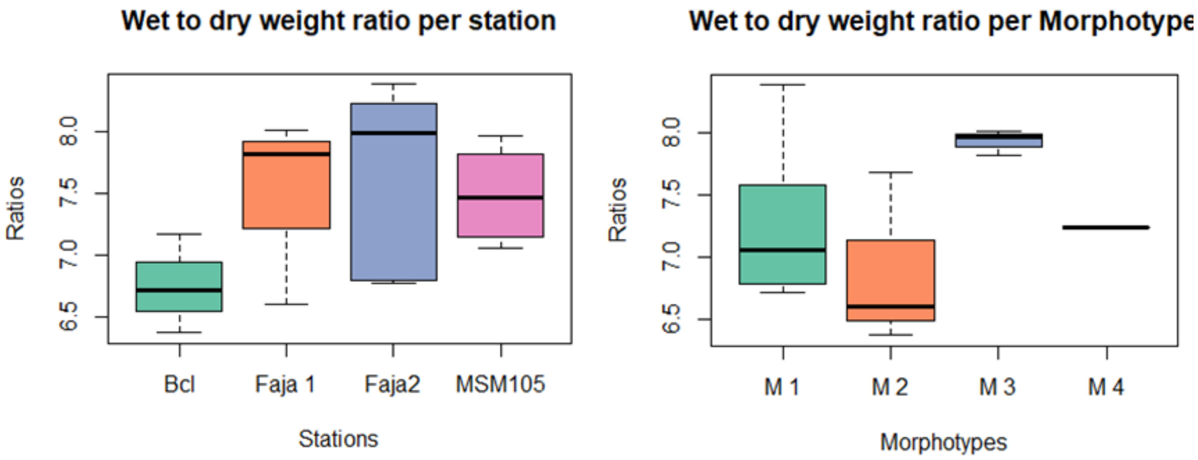
The average concentrations in µmol L^{-1} of nitrate (TON-Nitrite) are higher for the MSM 105 station (5.83 ± 0.07 µmol L^{-1}) than for the Fogo stations (0.71 ± 0.00 µmol L^{-1}). Indeed, at the 2 Fogo stations, the pelagic sargassum collected was in small stems scattered on the ocean surface. However, at the MSM-105 station, a significant accumulation of pelagic sargassum was observed (Figures 11 a and b). The high concentration of nitrate observed associated with the high density of pelagic sargassum could be related to an upwelling sometimes before sampling.

a b

Figure 11: Pelagic sargassum patch of MSM-105 sampling site, 20th February. a) RV MSM close to the sargassum patch, b) some fishes inside the sargassum patch.

4.2 Wet weight to dry weight ratio

The pelagic sargassum samples had an average wet to dry weight ratio (WWDR) of 7.34 ± 0.63 (the wet weight of sargassum was measured after rinsing with fresh water and dry taping with kitchen paper to remove extra water on sargassum sample). Note that the ratio varies between 6.37 and 8.38. Figure 12 shows the ratios of samples grouped by the station (Figure 12-a) and by morphotypes (Figure 12-b).



a b

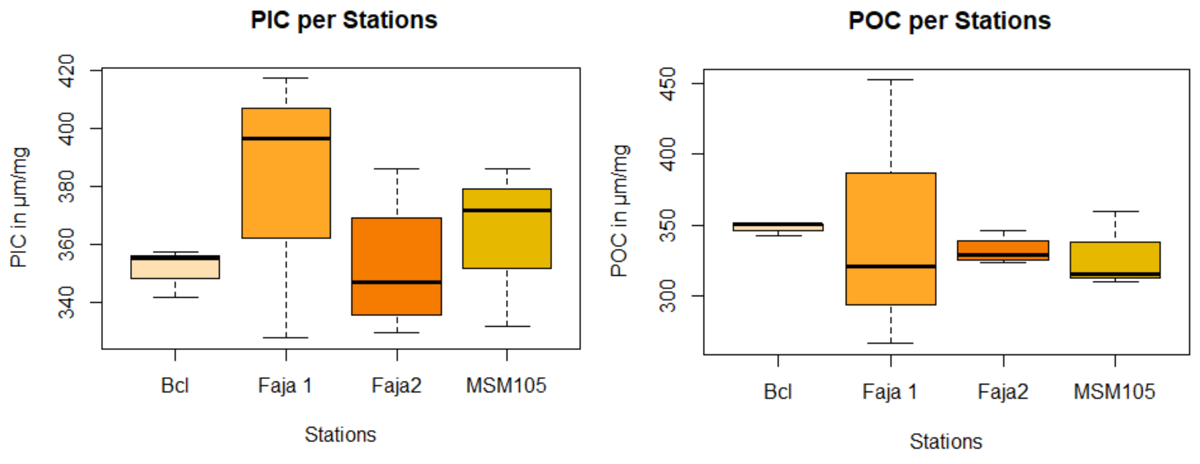
Figure 12: Wet weight to Dry weight ratio of pelagic sargassum per Station (a) and per Morphotype (b)

There is no significant difference between the samples from each station (the lowest P-value is P>0.46). Similarly, there is no difference between the wet weight to dry weight ratio per morphotypes

4.2 Chemical composition of Sargassum samples

4.2.1 Organic Carbon

The carbon composition of the samples is presented in two forms: Organic Carbon (OC) and Inorganic Carbon (IC). The variation of IC and OC per morphotypes (Figure 14-a and b). The IC varies between 327.66 and 417.26 µg.mg^{-1} with an average of 361.13 ± 27.24 µg.mg^{-1} dry weight (Figure 13-b). The OC varies between 226.64 and 452.21 µg.mg^{-1} dried weight with an average of 338.36 ± 40,19 µg.mg^{-1} of dried weight per station, as we can see in Figures 13.

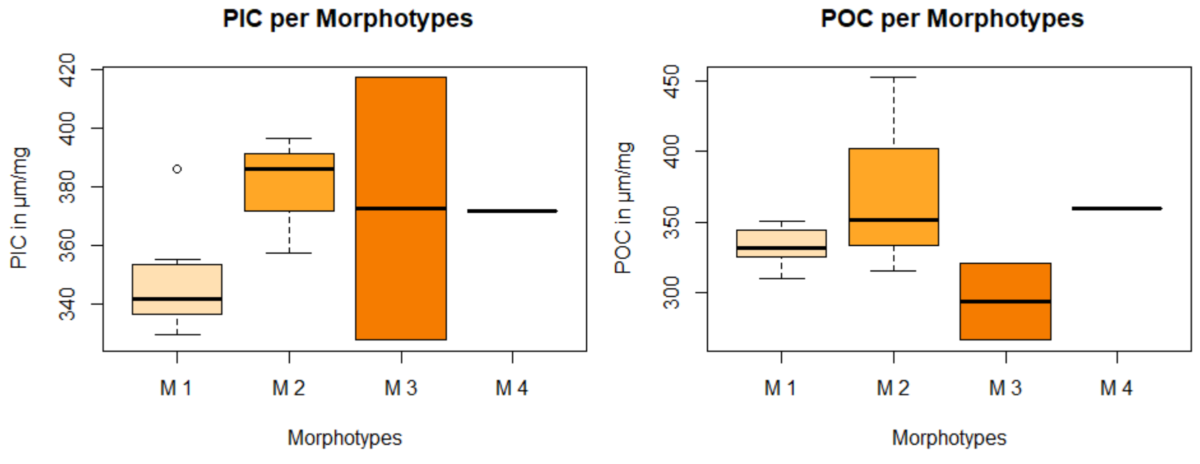


a

b

Figure 13: Inorganic Carbon (IC) in a- and Organic Carbon (OC) in b. The IC and OC of pelagic argassum here are per station.

There is no significant difference between samples per station for both IC and OC. The lower p-value is respectively 0.84 and 0.22 for IC and OC.



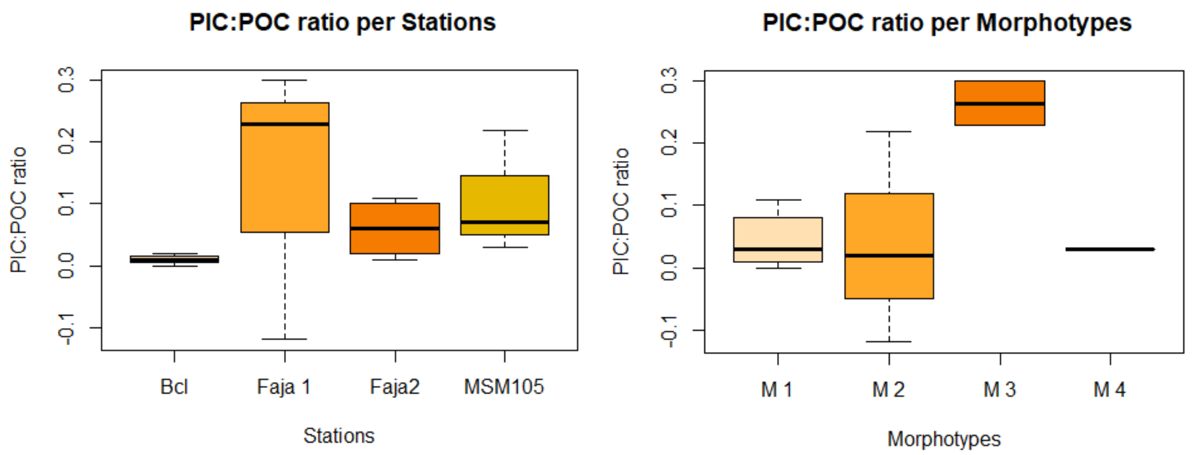
a

b

Figure 14: Organic Carbon on left and Inorganic Carbon on right. The IC and OC of pelagic Sargassum here are per Morphotype.

IC and OC per morphotypes also do not present any significant difference; the lower p-value is 0.64 and 0.24 for IC and OC, respectively.

Two of the samples (Faja and Bacabaleru) found a negative IC:OC ratio, meaning no calcifying materials were on them. The IC:OC ratio with ((IC + OC) = IC value used to calculate the ratio) shows an average of 0.10 ± 0.09. The maximum IC:OC ratio of 0.29 is observed in Faja populations, as well as the minimum of 0.009 (Figures 15-a and b).



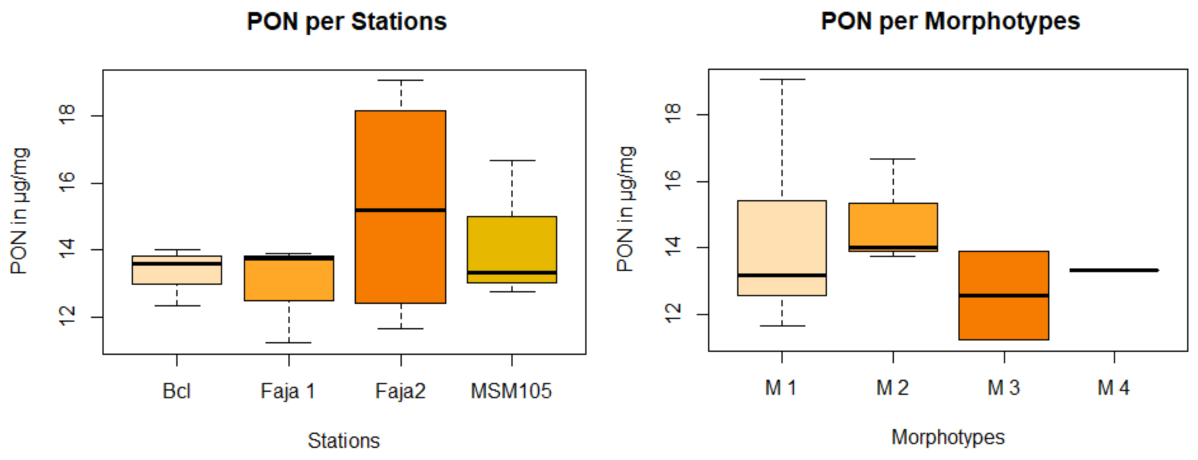
a b

Figure 15: IC:OC ratio of pelagic Sargassum per stations(a) and per Morphotypes (b)

The IC:OC ratio doesn't show any statistical difference between stations or morphotypes (p>0.5)

4.2.2 Organic Nitrogen

The mean Organic Nitrogen (ON) sample is 14.04 ± 2.18 µg.mg^{-1}. Figure 16 shows the different ON of the Samples per station (a) and per morphotypes (b). The ON of all samples ranged from 11.63 to 19.05 µg.mg^{-1} dry weight.



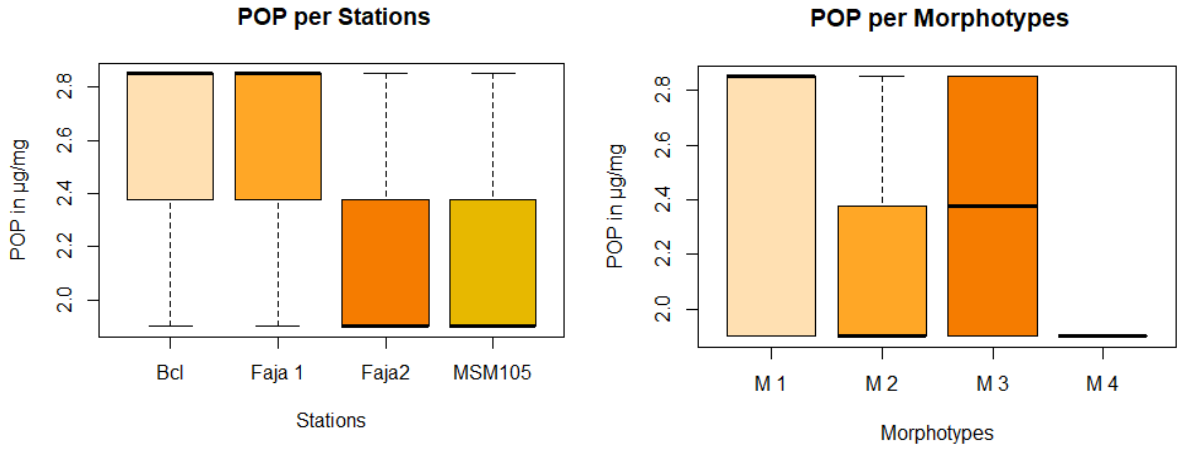
a b

Figure 16: Organic Nitrogen of pelagic Sargassum per Station (a) and Per Morphotypes (b)

The ON contents of the samples per station and morphotype are not significantly different; the lower p-value is 0.09 and 0.67.

4.2.3 Organic Phosphorous

The mean Organic Phosphorous is 2.33 ± 0.47 μg.mg^{-1} of dried weight. For all the samples, the OP varied from 1.9 to 2.85 μg.mg^{-1} dry weight, as shown in Figure 17. Only two of the samples presented different values for OP sample, this explain why the mean value is not in the middle of the boxplot.



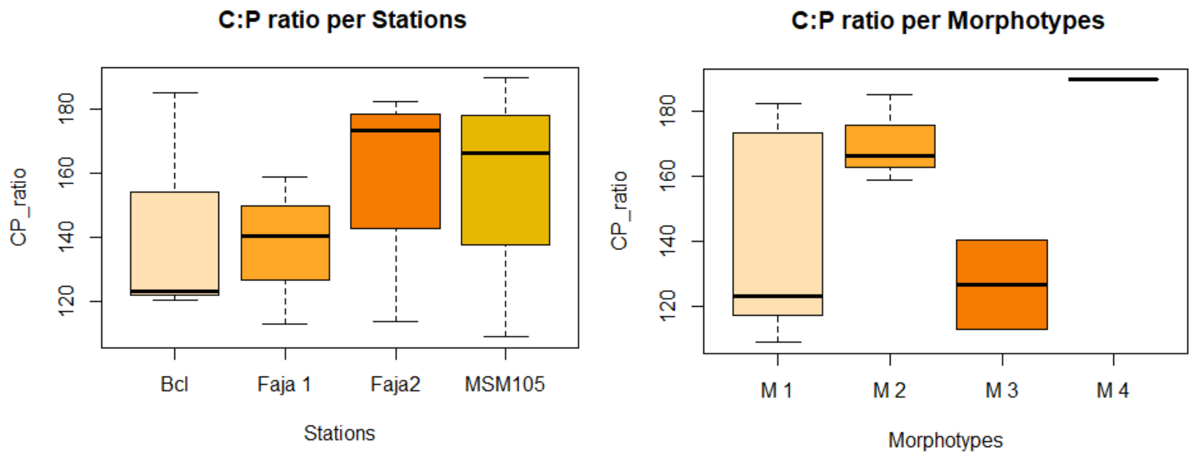
a b

Figure 17: Organic Phosphorous (OP) of pelagic Sargassum per Station (a) and per morphotype (b). Most OP values are equal, and the means values are not in the middle of the boxes as usual.

There is no significant difference between the samples per station and morphotypes. The p-value is respectively 0.09 and 0.67.

4.3 C, N and P ratio

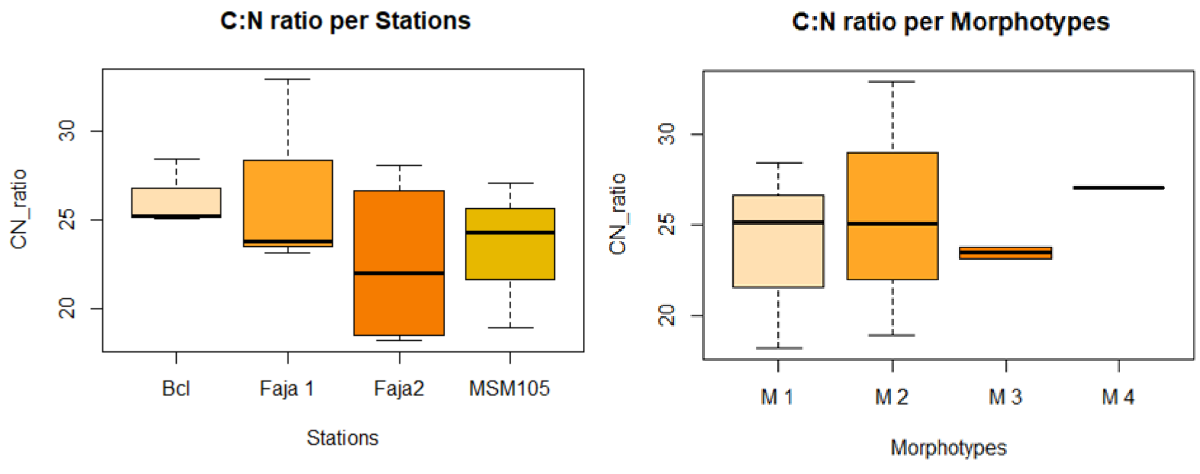
The mean C:P ratio of the samples is 149.78 ± 29.57, ranging from 108.76 to 185.02 (Figure 18). There is no significant difference between the samples either per station or per morphotypes (p-value >0.005 for morphotypes as well as for stations).



a b

Figure 18: Carbon and Phosphate (C:P) ratio of pelagic Sargassum per Station(a) and per morphotypes (b)

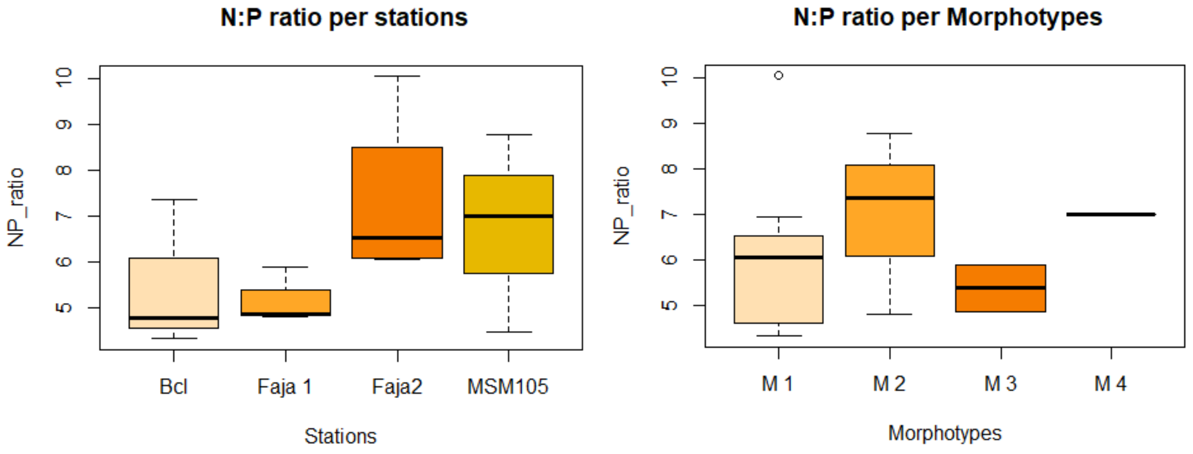
The samples' mean C:N ratio is 24.55 ± 4.04, with all the C:N ratios ranging from 18.18 to 32.94 (Figure 19).



a b

Figure 19: Carbon and Nitrogen (C: N) ratio of pelagic Sargassum per station (a) and per morphotype (b)

The mean N:P ratio is 6.26 ± 1.66, with all the sample ratios ranging from 4.32 to 10.02 (Figure 20). The C:N and N:P ratios do not present any significant difference either per Morphotypes or per station.



a b

Figure 20: Nitrogen and Phosphate ratio of pelagic Sargassum per Station (a) and per morphotype (b)

4.4 Growth experiment with benthic sargassum

The benthic sargassum growth experiment (Figure 8-b) lasted 09 days (21st to 30th June 2022). Throughout the experiment, we noticed the growth of new lamina even though the weight remained unchanged for the first five days. This is probably because the benthic sargassum regularly lost all old leaves during the experiment (Figure 22-a). They did not float but settled at the bottom of the cages. An average biomass gain of 2.54 ± 0.42 g per day is found in the three replicates of cage without dust addition (control), and an average daily gain of 3.33 ± 0.10 g in the three replicates for the cage receiving dust in nine days.

The average growth rate expressed in % shows the proportion of the gain on the total biomass cultivated deduced from the biomass gain is 0.80% of 300 g of initial biomass (2.54 g per day) for cage 1 without dust and 1.01 of 300 g (3.33 g per day) for the cage receiving dust (Figure 21). Although there was a lot of dust in the atmosphere during the experiment, it is noticeable that the additional supply of dust in the cage positively impacted the benthic sargassum's growth rate. After 09 days, new lamina grew (Figure 8-c) with a more noticeable loss of old lamina in the cage without dust addition (Figure 22-b). Biomass variation was relatively low in all triplicates of both cages until the 09th day (322.92 ± 18.72 g and 330.03 ± 16.11 g), when it decreased significantly (342.66 to 300 g for cage 1 and 346.33 to 300 g for cage 2). Figure 21 shows the growth rate of benthic Sargassum during the 14 days. The water samples collected during the experiment for nutrient analysis will be analyzed to complete the results.

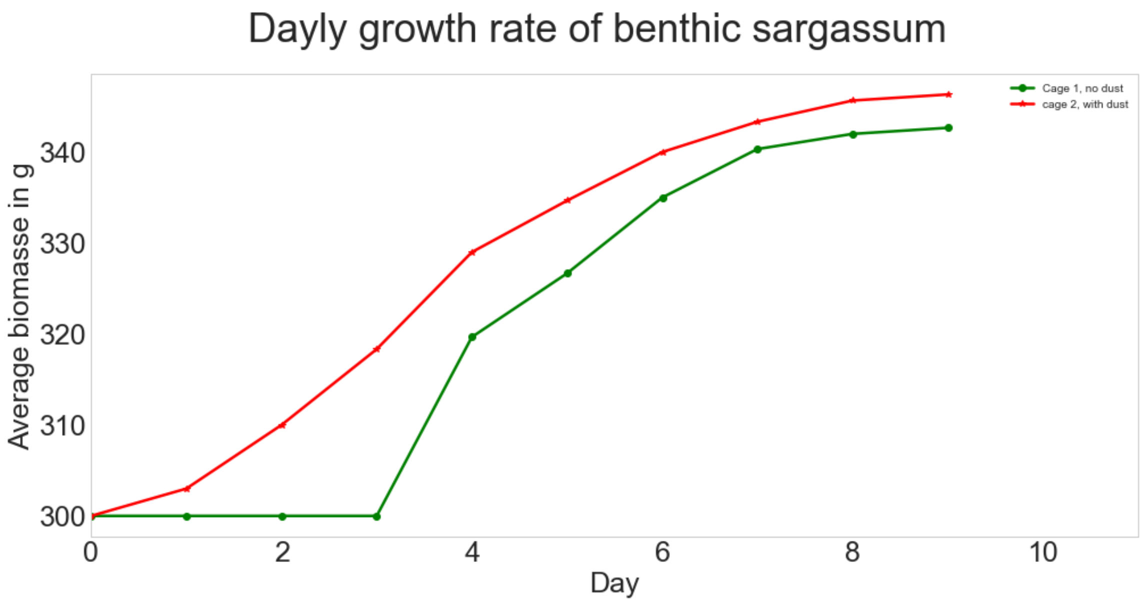


Figure 21: Benthic sargassum (*Sargassum cymosum*) growth rate during the 09 days experiment at Marina Mindelo, June 2022. An average biomass gain of 2.54 ± 0.42 g per day is found in the cage without dust addition (control), and an average daily gain of 3.33 ± 0.10 g is found I cage receiving dust.

a b

Figure 22: sargassum leaves and bare stem. A) Old leaves loosed throughout the experiment and b) Bare stem at the end of the experiment

4.5 Seasonal abundance and relationship with $p\mathrm{CO}_2$

The analysis of the monthly average pelagic sargassum data reveals annual mean biomass of 0.87 Megaton (Mt) covering an average area of 401.61 km^2 in 2018, an annual mean of 0.65 Mt covering an average area of 195.40 km^2 in 2019, an annual mean of 1.19 Mt covering an average area of 358.29 km^2 in 2020 and an annual mean of 1.07 Mt covering an average area of 322.90 km^2 in 2021.

The seasonal biomass pattern shows that over the last four years, the peak of pelagic sargassum biomass is between June and July around Cabo Verde, corresponding to early summer (Figure 23). Similarly, a new increase in the monthly average biomass starts every year from November. The shaded areas indicate the months where the peaks are recorded. Note that news peaks appeared later in February 2018 and in January 2021.

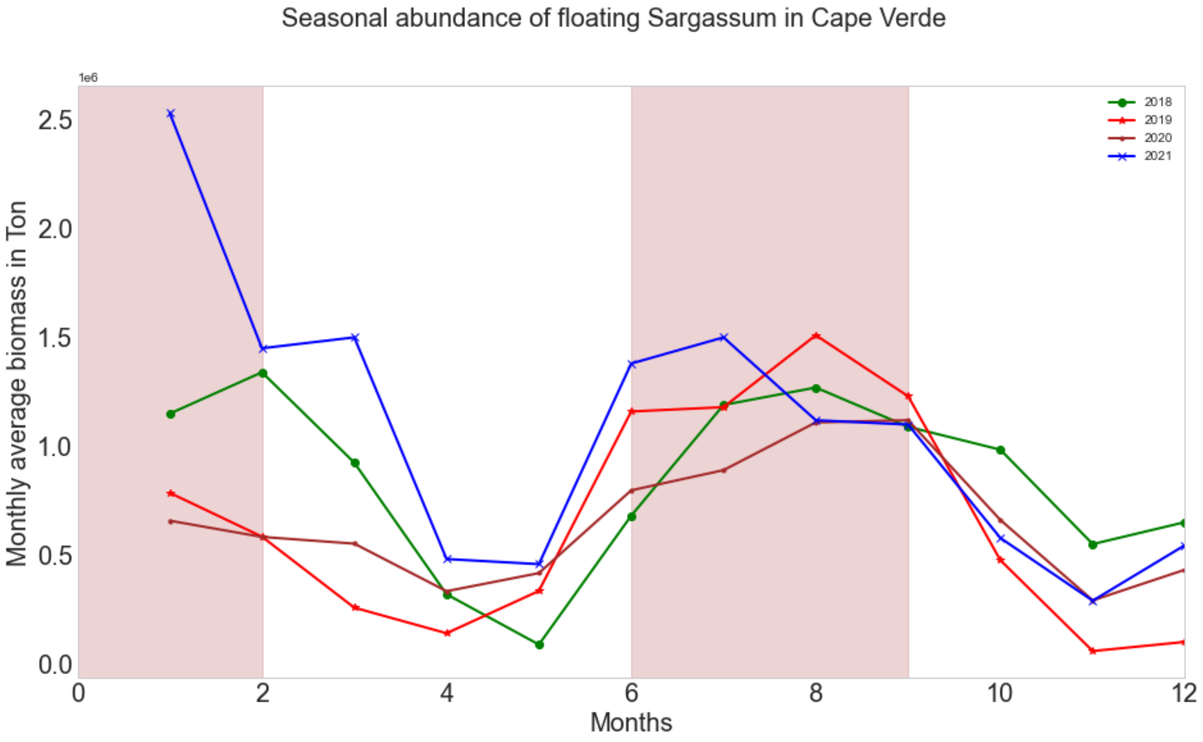


Figure 23: Grouped plot of the monthly average of Sargassum biomass over the last four years. The brown shaded area shows the years where the peak of Sargassum biomass appeared for each year.

Between 2018 and 2021, relatively high monthly averages biomass of pelagic sargassum were recorded in particular in July, August and January. The peak observed starts in May and drops off in September before starting to increase slightly again in November.

In addition, the $p\mathrm{CO}_2$ data available on SOCAT and the one collected by the wave glider mission in the Cabo Verde region cover some months of years from 2018 to 2020. The analysis of the annual mean *p*CO_2 reveals respective values in µatm of 384.32 ± 26.00 µatm, 386.79 ± 10.07 µatm and 402.57 ± 19.03 µatm for March and April 2018, March 2019, and November 2020 respectively (Figure 24).

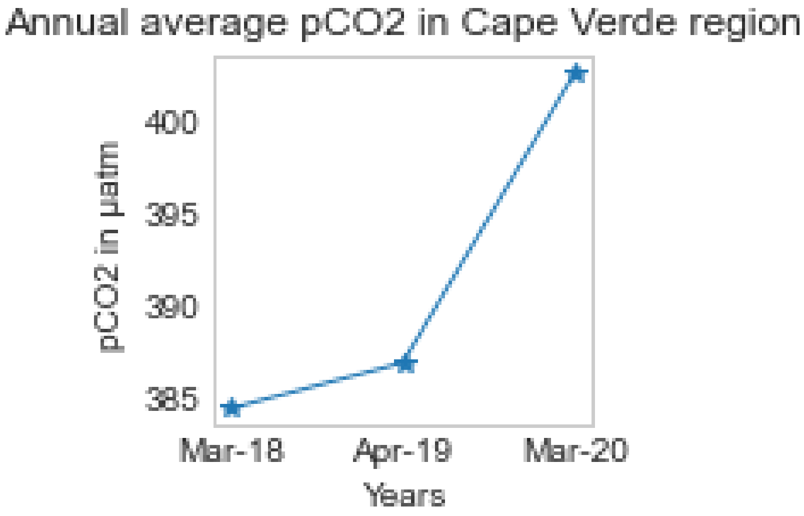


Figure 24: Average *p*CO_2 of the years 2018-to 2020 around Cabo Verde (Data obtained from SOCAT and Wave glider mission 2020).

There was a slight increase in the amount of *p*CO_2 over the different months of the three years. Although the average *p*CO_2 values observed have increased slightly, it only shows a seasonality because of the lack of data in the region. Moreover, from Figure 1 (Fiedler, 2013), we can see that the seasonality of delta *p*CO_2 aligns well, showing the variability other the years. However, the absolute *p*CO_2 would have increased over the years (Fiedler, 2013). This supports the values observed in the analysis of SOCAT data, even if these data are insufficient to conclude because of the lack of spatial-temporal data around pelagic sargassum bloom.

5. Discussion

To understand the capacity of the oceans to absorb and store atmospheric CO_2 this work's main objective is to evaluate *Sargassum*'s potential capacity as a CO_2 sink around the Cabo Verde Islands. Much work in the past has demonstrated the ability of plant communities to absorb CO_2 through photosynthesis, such as seagrass, macroalgae and phytoplankton. Recently, the introduction of seaweed into the North Atlantic and its seasonal bloom has become a standard that presents an unprecedented opportunity for CO_2 sequestration in the ocean. Indeed, these algae are pelagic and therefore can be found offshore, their growth is primarily iron-limited, and they can grow abundantly in oligotrophic waters such as their native Sargasso Sea habitat. This gives them the ability to CDR by photosynthesis, a process in which CO_2 is stored as OC in the algal tissue. This work in the same concern aims to investigate the seasonal abundance of pelagic sargassum around Cabo Verde (which may differ from the usual one in the GASB because of some benthic species saw together with pelagic species during the sampling), to study the factors limiting the abundant growth of pelagic sargassum in the Cabo Verde region, and to determine the capacity of *Sargassum* to absorb or play its role of CDR in the region.

5.1 Chemical composition of pelagic sargassum

The mean wet weight to dry weight ratio of pelagic sargassum around Cabo Verde was 7.34 ± 0.63. This average is higher than that observed by (Thielecke, 2021) (5.9 ± 1.5) and lower than that recorded by (Salter et al., 2020), which is 8.49. The differences in the observed ratio could be related to the drying methods and the duration of drying, which is either longer or shorter, depending on the case. However, although relatively short (1 day), the drying method of this study was stopped when the dry weight of the pelagic sargassum remained unchanged for half a day (12h). The average POC of 327.3 $\mu g.mg^{-1}$ obtained with Cabo Verde pelagic sargassum samples is in the ranges of those obtained by (Thielecke, 2021), (Lapointe et al., 2021) and (Wang et al., 2018) for fresh sargassum from Puerto Morelos, Mexico. On the other hand, this average is very close to that obtained for *Sargassum natans VIII* in the same area.

To understand the potential of pelagic sargassum for carbon sequestration, one needs to quantify the amount of carbon taken up by photosynthesis and stored in its biomass as OC, as well as the amount of IC stored by calcifying epibionts growing on it who emit CO_2 during calcification (Bach et al., 2021). The number of calcifiers on the Sargassum samples was assessed by calculating the IC: OC ratio.

The average ON composition of 14 ± 2.44 µg.mg^{-1} dry weight of Cabo Verde pelagic sargassum is higher than that recorded from Mexico in September 2021 that analyzed stranded sargassum at different stages of decomposition (Thielecke, 2021). Nevertheless, this average is close to that obtained by (Thielecke, 2021) recorded for pelagic sargassum in Mexico (Puerto Morelos) seawater (in deterioration), which is 15.0 ± 2.9 µg.mg^{-1} dry weight and lower than the one of (Hanson, 1977) from Gulf Stream and Sargasso Sea which is 16.9 9 µg.mg^{-1}. The ON would be high in Cabo Verde samples because of increased N and P assimilation of pelagic sargassum that shows an increased N:P ratio as demonstrated by (Brand et al., 1992), especially for the MSM 105 site samples, which presented a higher TON level (5.83 µmol L^{-1}).

Similarly, the average Organic Phosphorus (OP) content of the samples is 2.33 ± 0.47 µg.mg^{-1} of dried weight is much higher than those obtained by (Thielecke, 2021) for both in situ Sargassum (0.55 ± 0. 21 µg.mg^{-1}) and the Atlantic pelagic sargassum samples (0.87 ± 0.24 µg.mg^{-1}). As with the ON, further investigations are required to understand if OP is limited factor for the abundance of pelagic sargassum in Cabo Verde.

5.1.1 C, N and P ratio

The average IC: OC ratio of the samples is 0.10 ± 0.09. This ratio is higher than those obtained by (Thielecke, 2021) in Mexico (0.037 ± 0.039) and by (Salter et al., 2020) (0.058) and lower than the one obtained by (Bach et al., 2021) (0.11-0.9) for samples from the Sargasso Sea. The IC:OC ratio provides information on the degree of calcification of pelagic sargassum. Depending on the high or low value of the ratio, calcification may be a factor reducing the ability of pelagic sargassum to sequester CO_2. This implies that a high IC:OC ratio indicates high calcification and a reduction in the sequestration capacity of pelagic sargassum as a CDR, as indicated by (Bach et al., 2021). The samples of Faja and Bacabaleru, in which no IC could be measured, are probably a young population where the epibionts do not have time to grow before the sampling.

The average C:N ratio of the samples is 24.55 ± 4.04, less than the one obtained by (Baker et al., 2018) and (Wang et al., 2018) for sargassum surface materials (30) collected in Southern North Atlantic and are comprised in the range 15 – 50 as stated by (Brand et al., 1992, Atkinson & Smith, 1983) for holopelagic sargassum depending on the location (neritic or open Ocean water). The low ratio observed in this study could be related to the N accumulation at the location where pelagic sargassum is collected. The average C:P ratio of 149.78 ± 29.57 obtained is lower than that obtained by (Atkinson & Smith, 1983), (Wang et al., 2018) and (Brand et al., 1992) for *Sargassum natans* collected in neritic water or open Oceanic water. Similarly, the N:P ratio (10.7 ± 1.9 and 28.6 ± 9.3 respectively for neritic and oceanic) obtained by (Brand et al., 1992) are more significant than the one observed in pelagic sargassum samples of this study (6.26 ± 1.66), explaining the enrichment of P in these stations compare to the historical limit suggested in the base line of (Lapointe et al., 2014). The low N:P ratio would mean a reduced P-limitation in contrary to the one highlighted by (Wang et al., 2018).

5.2 Benthic Sargassum growth experiment

The main objective of this experiment was to obtain a daily biomass gain of benthic sargassum, i.e., the growth rate of benthic sargassum over time and under different environmental conditions (with or without dust). As benthic sargassum species were used for this growth experiment, a direct comparison of these rates with pelagic sargassum has to be taken with care. However, based on what was observed, the loss of the leaves of the benthic sargassum species during the first five days of the experiment would be a natural phenomenon that occurs due to the change of substrate and readaptation. The average biomass gain obtained for each cage was 2.54 ± 0.42 g/day (0.80%) and 3.33 ± 0.10 g/day (1.01%) per day for cage 1 and cage 2 (receiving the dust), respectively. Although low, the growth rate indicates that the addition of 5 g of dust every 48 hours contributed to increasing the growth of benthic sargassum (cautionary interpretation).

The addition of Saharan dust would have supplied with an additional source of nutrients (Iron and Phosphate) that favored higher growth, even though the C, N and P contents of benthic sargassum were not measured. Iron and phosphate are known to influence the growth of pelagic sargassum (Gouvêa et al., 2020a), which explains the higher biomass gain observed in cage 2 receiving dust. These growth rate values are lower than the maximum recorded for *Sargassum fusiforme* (6.04%) (Li et al., 2019). This may be because the benthic sargassum has had to adapt to its new habitat rather than grow significantly. Despite the low growth rate, It is important to mention that the addition of dust promoted the growth of benthic sargassum, as was explained in the case of pelagic Sargassum by (Bach et al., 2021) and (Brooks et al., 2018).

Furthermore, knowing the molecular weights of Carbon and Oxygen, the fresh biomass of *Sargassum*, and the WWDR the amount of CO_2 absorbed by *Sargassum* was determined by multiplying the CO_2:C (3.66) ratio by the dry weight of *Sargassum* tissue. This revealed that during this experiment, the cage with no dust addition contributed to the uptake of 0.03 kg of CO_2 and the cage receiving dust of 0.10 kg of CO_2 despite the fact that they were no significant difference between the average biomass of the two cages (p-value > 0.05 = 0.40).

5.3 Seasonal abundance of Sargassum

The satellite data on pelagic sargassum biomass distribution over the past four years reveals a seasonal variation: the average pelagic sargassum biomass begins to increase substantially in May and peaks, particularly during June and July. Similar results have been reported by (Wang et al., 2019a) and (Johns et al., 2020) (note that the specific composition of pelagic sargassum in Cabo Verde maybe different from that in the other part of the GASB because of the presence of some benthic species in floating state), that mentioned the GASB forms with high density in the Tropical Atlantic every year from May to September. During the summer of Tropical North Atlantic, Satellite data showed that pelagic sargassum is observed on the coasts of Brazil, the Caribbean Island, and the West African coast (Ody et al., 2019). Brooks et al. (2018) model explained the biomass abundance of pelagic sargassum as a factor of transport by currents and the growth of pelagic sargassum in Tropical Atlantic (Brooks et al., 2018), where nutrients availability, especially iron is the most limiting factor of the pelagic sargassum growth.

One of the known sources of nutrients is Saharan dust, which contributes significant amounts of iron, crucial for pelagic sargassum growth as suggested by (Powell et al., 2015). The Congo River, also known to be the second largest source of discharge in the Atlantic, has been identified as the largest source of iron of any of the other large rivers according to a study conducted by (Vieira et al., 2020). This combined with the nutrients from the upwelling system could promote the growth of pelagic sargassum in the Cabo Verde region. It could therefore be assumed that a part of the benthic species accidentally saw floating, the Cabo Verde pelagic sargassum originated from the Middles Atlantic (GASB) (Wang et al., 2019), which, once transported by the currents, grows considerably due to the nutrients provided by the Congo River, the Sahara dust and the upwelling system and extend to west Africa coast. The seasonality observed in this study would therefore be related to the availability of nutrients during the months (early spring to summer) and the favourable sea surface temperature during the period (Average of 24°C in June and 26.6°C in July[6]). It has been mentioned by (Jouanno et al., 2021) that the land-based activities increased the N and P input in the Tropical Atlantic and have been proposed as contributors to the pelagic sargassum proliferation by riverine fertilization toward the ocean.

An impact on surface ocean pCO_2 values is expected locally near pelagic sargassum patches, but that data was lacking at the sub mesoscale level near patches for logistical reasons during this work. On the other hand, the annual means of pCO_2 obtained after the analysis of the data available on SOCAT for the Cabo Verde region, corresponded well to the range of pCO_2 obtained by (Macarena Burgos.,2015) (309 and 662 µatm) in the western and subtropical gyre. Future targeted investigations of the pCO_2 value, together with the local biomass of pelagic sargassum, are needed to confirm if CO_2 uptake of pelagic sargassum influence locally the sea surface pCO_2 values in Cabo Verde.

5.4 Potential of pelagic Sargassum afforestation for CO_2 sequestration in Cabo Verde

Based on the results of Satellite data analysis, taking into account the 0OC concentration of pelagic Sargassum and average wet weight to dry weight ratio of 6.5, the amount of CO_2 absorbed during the years 2018-2021 was 3.47 Mt, 2.59 Mt, 4.75 Mt and 4.26 Mt respectively in the Cabo Verde region (Longitude: -35.15, -15, Latitude: 4.65, 25.97). These values are lower than those (Bach et al., 2021) from 2005 to 2010 for the GASB (112-931 Gt of CO_2). As pointed out earlier in chapter one, this difference is related to the fact that a relatively small amount of pelagic sargassum arrives in the Cabo Verde region. Carbon dioxide uptake by pelagic sargassum occurs first during the growth of pelagic sargassum through photosynthesis, during which CO_2 is stored as OC in the tissue. When temperature, salinity and nutrients fall at the end of the pelagic sargassum life cycle, the pelagic sargassum dies and sinks to the bottom of the ocean, where the OC is stored in the bottom sediments. Apart from the small uninhabited islands, which have shallow waters (less than 50m), the other islands are relatively deep, especially those in the south where pelagic sargassum is often found (3000 and 8000 m deep). These conditions together support the use of pelagic sargassum for CO_2 sequestration. Its large-

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[6] https://www.seatemperature.org/africa/cape-verde/praia.htm

scale cultivation in the marine environment could contribute to the sequestration of significant quantities of CO_2 and the growth of fish populations.

6. Conclusions

The Cabo Verde region is home to a seasonal population of pelagic sargassum of varying origin, which has two periodic peaks during the year in January and July. Different morphotypes of pelagic sargassum are found in Cabo Verde, especially on the southern islands such as Santiago, Fogo and Brava. The composition of the organic matter is similar to that of sargassum sampled in other regions, such as the Gulf of Mexico. This suggests increased adaptability of pelagic sargassum in different habitats.

Chemically, the Cabo Verde pelagic sargassum was found to have a higher carbon, nitrogen and phosphate composition than samples collected from the Caribbean coast of Mexico in September 2021. This indicates high availability of N and P in Cabo Verdean waters. Although non-significant, the growth rate of benthic sargassum shows that the dust input affects the growth of benthic sargassum. This confirms that Saharan dust is an essential source of nutrients (iron) and could also be a limiting factor for the growth of benthic sargassum.

Analysis of the monthly average pelagic sargassum biomass shows that the pelagic sargassum bloom is seasonal and obtained, especially during the summer months when the $p\text{CO}_2$ concentration in the surface waters around Cabo Verde has slightly decreased in recent years. A second irregular peak observed in some cases in November or January would be related to a set of conditions that future research needs to investigate. Furthermore, the IC:OC ratio was generally low (0.10 - 0.09), indicating that calcification is not a factor reducing significantly the CO_2 uptake capacity of pelagic sargassum around Cabo Verde. In conclusion, although a link between pelagic sargassum biomass and CO_2 concentration in the region has been established, the lack of spatially and temporally resolved data does not allow a solid conclusion to be reached.

It can be suggested that dust deposits promote the growth of benthic sargassum and that iron, therefore, appears to be a factor contributing to the growth of benthic sargassum as well. If iron is available in sufficient quantities, 900 g of benthic Sargassum can sequester $9.98.10^{-10}$ Mt of CO_2 per year and hopefully pelagic Sargassum as well.

Outlook

At the end of this work, it appears that a lot of work and investigations are still needed to answer the question behind the title of this Master thesis, among others:

- Repeat the growth experiment using pelagic sargassum under different environmental conditions (with and without the addition of Saharan dust).
- Investigate the Spatio-temporal distribution of pelagic sargassum to geolocate the different accumulations in real-time in the region.
- Monitor the variation in nutrient concentration and sea surface $p\mathrm{CO_2}$ before, during and after the algal bloom to establish a relationship between pelagic sargassum biomass and sea surface $p\mathrm{CO_2}$.
- Studies on the use of pelagic sargassum on a large scale for $\mathrm{CO_2}$ sequestration by targeted investigations on the different impacts of pelagic sargassum sink on the deep-Sea habitats.
- Investigate the carbon deposition process in the ocean floor after the death and decomposition of pelagic sargassum to understand how carbon is stored and the related impacts.
- Investigate the use of pelagic sargassum in Aquaculture for the reproduction and larviculture of certain species of shrimps and fish.

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Appendix

Table 1: Average biomass (in g) of benthic Sargassum per day during the experiment

Cage 1	Cage 2	days
300	300	1
300	300	3
300	326.67	4
303.33	330	5
306.67	333.33	6
306.67	333.33	8
326.67	333.33	9
300	330	11

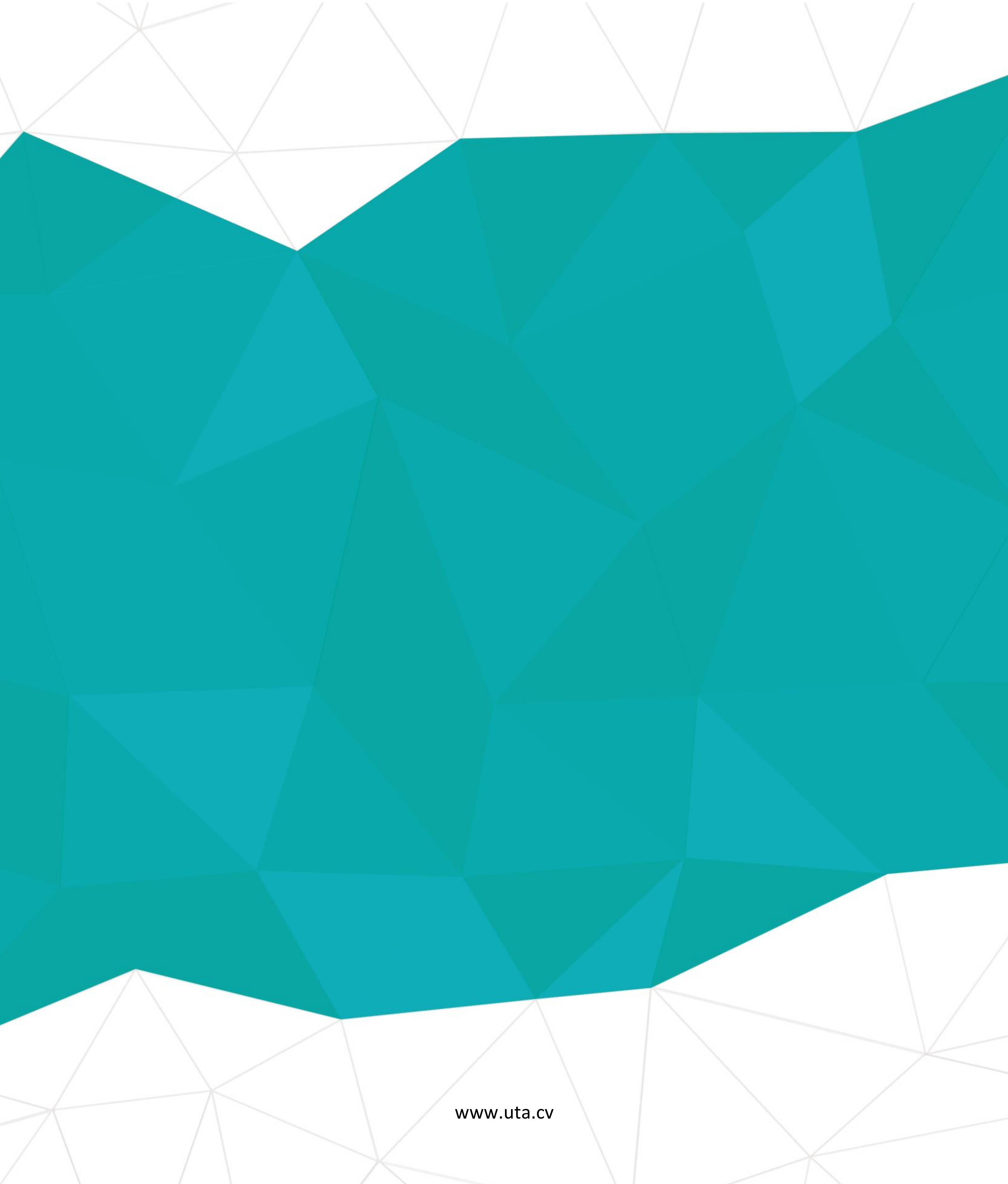
Table2: Wet weight and dry wet (in g) of pelagic Sargassum used for this work

Samples names	Running N	wet W	Dry W
Faja I	2	230.4	30
Faja I	3	223	31.6
Faja I	7	23.1	3.5
Faja II	4	73.8	10.2
Faja II	11	273.2	33.2
Faja III	13	252.3	30.1
Faja III	14	157	23.2
Faja III	15	144.8	21.3
Bacabaleru	8	31.6	4.7
Bacabaleru	9	44.6	7
MSM	1	509.4	64
MSM	5	529.3	66.1
MSM	6	611.3	78.2
MSM	12	445.3	55.7

a b

c d

Figure 1: Lab work photos. a) acid addition to POP samples, b) weighing PIC and POC samples, c) addition of oxisolv to POP samples, and d) Measurement of POP samples with a photometer.



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