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Research Article

# Assessment of ecosystem services provided by lagoonal seaweeds and seagrasses along the Moroccan coast

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## Abstract

This study assesses the ecosystem services provided by algae and seagrass species structuring the lagoonal ecosystems along the Moroccan Atlantic coast, with a focus on the Oualidia Lagoon. A comprehensive literature review was conducted to identify and evaluate the contributions of key native species (*Gracilaria gracilis*, *Ulva* spp., *Cystoseira humilis*, *Fucus spiralis*, and *Zostera noltei*) and the invasive species *Sargassum muticum* to Marine and Coastal Ecosystem Services (MCES). A semi-quantitative approach was applied to integrate the functional and spatial value of each species into the overall assessment of MCES. Results indicate that 70–85% of potential services are documented, with native species mainly contributing to regulating and supporting services, while *S. muticum* shows a negative impact on about 43% of them. Current exploitation remains limited, except for agar-agar extraction from *Gracilaria*, confirming the low use of provisioning services. Overall, 25–30% of potential services are underutilized, aligning with the Ramsar site's emphasis on sustainable use. Promoting native algae cultivation could enhance local economic and ecological outcomes while contributing to multiple SDGs, including food security, climate action, and biodiversity conservation.

**Key words:** Algae, ecosystem services, invasive algae, lagoon ecosystem, Moroccan Coast, seagrass

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## Introduction

The 2021 United Nations Food Systems Summit highlighted the need to advance towards healthier, more sustainable, and equitable food systems, as outlined in the 17 Sustainable Development Goals (SDGs) (United Nations 2021; Webb et al. 2023). Achieving these goals requires food systems that contribute less to greenhouse gas (GHG) emissions while meeting the food needs of a continuously growing global population (Von Braun et al. 2021). However, current food systems are estimated to contribute approximately one-third of GHG emissions and negatively impact freshwater resources, biodiversity, and soil quality (Crippa et al. 2021; Webb et al. 2023). One proposed solution is to focus more on water-based food systems, particularly algae, which could

represent a transformative change in the global food security equation (Bjerregaard et al. 2016; Webb et al. 2023). As highlighted by Webb et al. (2023) and Msuya et al. (2022), algae could represent a major new crop opportunity for low- and middle-income countries. As for seagrass, they indirectly support food security by providing habitat and nourishment for numerous species targeted by fisheries, while also contributing to carbon sequestration and climate regulation. However, significant gaps remain in understanding the potential benefits of algae and seagrasses within marine and coastal ecosystems. . In a recent study, Webb et al. (2023) demonstrated that in low- and middle-income countries, there are still gaps in the available information and understanding of the potential benefits of algae on nutrition and health, as well as concerns about potential toxic effects and exceeding tolerable upper intake levels for certain nutrients. This is particularly relevant in the North-West African region, including the Moroccan Coast which possesses a natural wealth of algae and seagrasses, yet little is known about their potential to combat food insecurity and reduce the carbon footprint (Webb et al. 2023) .

Coastal areas, contribute more than 60% of the total economic value of the biosphere (Costanza et al. 1997; Martínez et al. 2007). Among these coastal areas, lagoons are widely recognized for their biological interest. These delicate and diverse wetland complexes hold ecological, socio-cultural, and economic values (Schuyt and Brander 2004; de Groot et al. 2010). They provide numerous services that contribute to human well-being and poverty reduction (MA 2005; Maresca et al. 2011; Briner et al. 2013; IPBES 2018).

Coastal lagoons are typically dominated by seaweeds and seagrass meadows, which are recognized as some of the most valuable ecosystems on our planet due to the numerous functions and ecosystem services they provide (Costanza et al. 2014; Ruiz-Frau et al. 2017; Doo Hwan et al. 2021; Cotas et al. 2023). These ecosystems offer a variety of benefits, including food for human consumption, habitats for marine species, coastal water quality control through nutrient recycling, sediment stabilization, pathogen removal, and oxygen production (Costanza et al. 1997; Nordlund et al. 2016; Lamb et al. 2017; Belondo et al. 2021). However, these ecosystem services are not utilized uniformly across different regions of the world,

The lagoon ecosystems in the North-West African region, renowned for their significant biodiversity, are rich in algae and seagrass. Preservation efforts in these areas are fully aligned with the United Nations Sustainable Development Goals (SDGs) for 2030. Unfortunately, there is a lack of exploring the benefits of their marine plant resources.

This research contributes to demonstrating the potential of seaweed and seagrass of lagoonal ecosystems for the development of coastal populations in the North-West African region, as well as their role in combating food insecurity and reducing CO2 emissions. We used the Marine and Coastal Ecosystem Services (MCES) classification, adapted from Liquete et al. (2013a), to evaluate the specific contributions of certain species of algae and seagrass commonly found along the North-west African coastlines. The species studied include *Gracilaria gracilis* (Stackhouse) Steentoft, L.M.Irvine & Farnham, 1995, *Ulva* Linnaeus, 1753, *Cystoseira humilis* Schousboe ex Kützing, 1860, *Fucus spiralis* Linnaeus, 1753, *Sargassum muticum* (Yendo) Fensholt, 1955 and *Zostera noltii* Hornemann, 1832. These species, while diverse in habitat

and distribution, share overlapping ecological roles, particularly in lagoon and coastal environments. *Gracilaria gracilis* is a cosmopolitan species found in tropical and temperate seas, commonly observed in the Northeast Atlantic. It thrives in shallow, calm waters (up to 15 m depth) and is highly tolerant of salinity variations, making it a frequent inhabitant of lagoons (Lamare and Verlaque 2022). Similarly, *Ulva lactuca*, known as sea lettuce, is a globally distributed green algae that colonizes various coastal environments, including lagoons, estuaries, and rocky shores (Hamon et al. 2024).

*Ulva fasciata*, another green algae species, also shares this adaptability to coastal environments. It thrives in tropical and subtropical intertidal and subtidal zones and exhibits a high tolerance to salinity and temperature fluctuations, particularly in the Atlantic Ocean (GBIF 2023). Additionally, *Ulva intestinalis*, commonly referred to as "*Enteromorpha*," is highly adaptable to a variety of coastal habitats, ranging from intertidal zones to estuaries with fresh or brackish water, further linking it to temperate and tropical regions (Sabourin et al. 2022).

In contrast, *Fucus spiralis* is a brown algae primarily found in the upper parts of the intertidal zone on rocky substrates in the Atlantic Ocean, never extending beyond 6 meters in depth (Freitas et al. 2020). *Cystoseira humilis*, another brown algae, is more commonly associated with rocky areas in the Mediterranean region but also grows along the Atlantic coast, inhabiting shallow waters between 0 and 20 meters deep (Belattmania et al. 2016).

*Zostera noltei*, a marine seagrass, occupies a similar ecological niche, found in shallow coastal areas such as lagoons, estuaries, and bays. It typically grows in muddy or sandy substrates, and is widely distributed along the Atlantic and Mediterranean coasts (Martel et al. 2021). However, the invasive species *Sargassum muticum*, originally from the Pacific coasts of Asia, presents a contrast. Now widespread in the eastern Atlantic, it colonizes diverse marine habitats, including lagoons, bays, and estuaries, where it often forms dense stands that can disrupt local ecosystems (Hannachi et al. 2020). Together, these species, although differing in taxonomic group and specific ecological preferences, are interconnected by their presence in coastal environments. They play complementary roles in lagoon and estuarine ecosystems, with many of them sharing a resilience to environmental variability, which contributes to their widespread distribution.

In this study, we used the Oualidia lagoon along the Atlantic Moroccan coast as a case study to assess the role of lagoonal algae and seagrasses in supporting potential ecosystem services and to compare these contributions with the benefits currently observed.

## Material and methods

### Ecosystem Services (ES) classification approach

The MCES classification was developed through a critical analysis and integration of various classifications from sources such as MEA (2005); TEEB (2010); Haines-Young and Potschin (2011) and Beaumont et al. (2007). The MCES classification encompasses 14 categories of ES which are summarized in Table 1. For a more comprehensive description, refer to Liquete et al. (2013a, 2013b) and Katsanevakis et al. (2014).

## Study area

The Oualidia Lagoon, located on the Atlantic coast of Morocco in the Northwest African region (Fig. 1), was chosen as a demonstration site to quantify ecosystem services (ES) provided by algae and seagrass, following the methodology outlined by Liquete et al. (2013a) (Table 1). This lagoon is renowned for its ecological significance and biodiversity and has been protected under the RAMSAR Convention since 2005 (https://rsis.ramsar.org/fr/ris/1474). Historically, it has served as a major site for oyster farming, with a tradition dating back to the 1950s. In addition to oyster farming, various other activities have emerged in the area, including agriculture (primarily focused on cereals and vegetables), pasture (practiced by over 90% of the population), shore fishing (15%), and tourism. However, these activities have expanded without adequate consideration of their environmental impacts on biodiversity and other ecosystem services (Maanan et al. 2014; Houssa et al. 2020).

## Database

The database used to assess the MCES of the Oualidia Lagoon is based on sampling conducted in February 2021 using scuba diving techniques (Rezzoum et al. 2022). Sampling was carried out at 68 stations distributed throughout the lagoon (Fig. 1). The most abundant seaweed and seagrasses include the seagrass *Zostera noltei*, native algal species such as *Gracilaria gracilis*, Ulva (*Ulva lactuca*, *Ulva fasciata*, and *Ulva intestinalis*), *Cystoseira humilis*, *Fucus spiralis*, and the invasive algal species *Sargassum muticum*. In terms of Spatial Coverage Rate (SCR) relative to the total area of the main channel within the lagoon, *Gracilaria gracilis* is the dominant algal species, occupying over 50%, followed by *Ulva* (17%), *Zostera noltei* (10%), and finally *Fucus spiralis*, *Cystoseira humilis*, and *Sargassum muticum*, each with 6% coverage (Rezzoum et al. 2022).

## Ecosystem services: literature review

To ensure comprehensive coverage of the literature, searches were conducted across multiple scientific databases including Science-Direct, Scopus, Web of Science, and Google Scholar, as well as widely used academic platforms such as ResearchGate and Academia. We used three combinations of keywords related to different studied species of algae and seagrasses, the 14 categories of MCES classification and the names of studied areas. Boolean operators (AND, OR) were employed to refine the queries, and results were not limited to any date. Table 2 summarizes the databases consulted and the specific search strings used.

The PRISMA flowchart in Fig. 2 illustrates, step by step, the process of bibliographic analysis, from identification to use in the manuscript

## ES Assessment approach

To quantify the relative contribution of algae and seagrass species to Marine and Coastal Ecosystem Services (MCES) in the Oualidia Lagoon, a semi-quantitative multi-criteria approach was applied. Following the literature review, each species was evaluated according to its contribution to the different MCES

**Table 1.** Categories of the Marine and Coastal Ecosystem Services (MCES) classification, as adapted from Liquete et al. (2013a).

| | | |
|---|---|---|
| Provisioning services | Food provision | Supply biomass for human consumption through fishing and aquaculture activities. |
| | Water storage and provision | The provision of water for human consumption and other uses. |
| | Bioactive materials and<br><br>Biofuels | Supply biomass for non-food purposes, including medicinal, ornamental, commercial, and industrial uses. |
| Regulating and maintenance services | Water purification | Removes wastes and pollutants through biochemical and physicochemical processes like dilution, sedimentation, bioremediation, filtration, and decomposition. |
| | Air quality regulation | Regulation of atmospheric pollutant concentrations in the lower atmosphere. |
| | Coastal protection | Protects naturally the coast from flooding and erosion through structures that stabilize sediments and create protective buffers. |
| | Climate regulation | The ocean acts as a sink for greenhouse gases and climate-active gases. Large perennial algae and higher plants can store carbon for longer periods. |
| | Weather regulation | Influence on local weather conditions. |
| | Ocean nourishment | Involved in the natural cycling process leading to the availability of nutrients in seawater for the production of organic matter. |
| | Lifecycle maintenance | Biological and physical support to facilitate healthy and diverse reproduction of species. |
| | Biological regulation | Pathogen control |
| Cultural services | Symbolic and aesthetic values | The exaltation of the senses and emotions by seascapes and the values accorded to coastal natural and cultural sites. |
| | Recreation and tourism | The opportunities the marine environment provides for relaxation and entertainment (swimming, scuba diving, recreational fishing ...). |
| | Cognitive effects | Inspiration for arts, research and education |

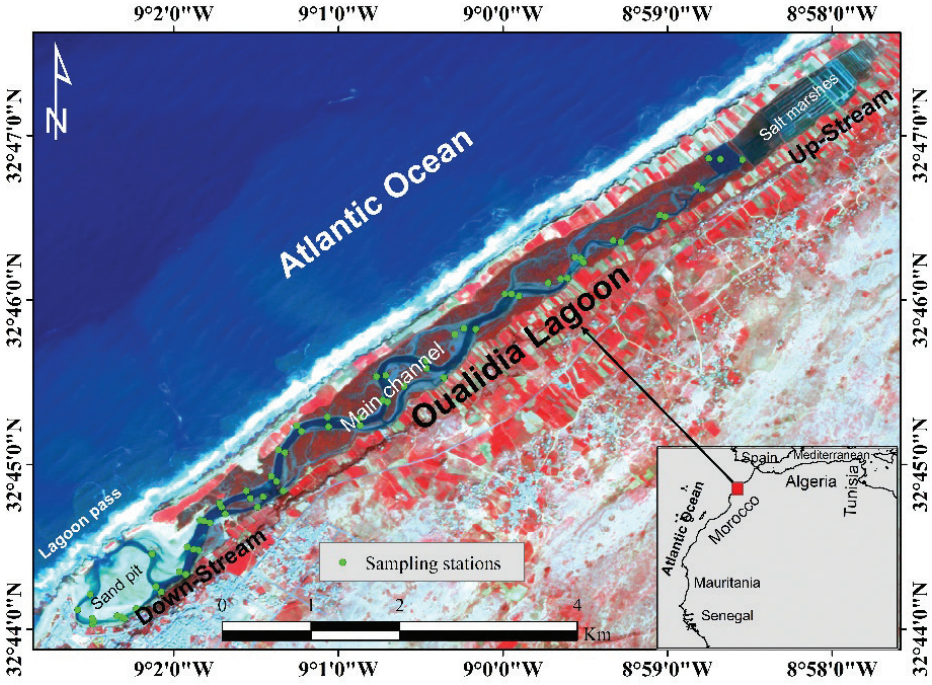



**Figure 1.** Geographic location of Oualidia lagoon and spatial distribution of sampling stations.

categories. A value of +1 was assigned when the species provided a positive contribution, −1 for a negative contribution, and 0 when no measurable effect was observed. This score was then weighted by a factor representing the species' Spatial Coverage Rate (SCR) relative to the total surface area of the

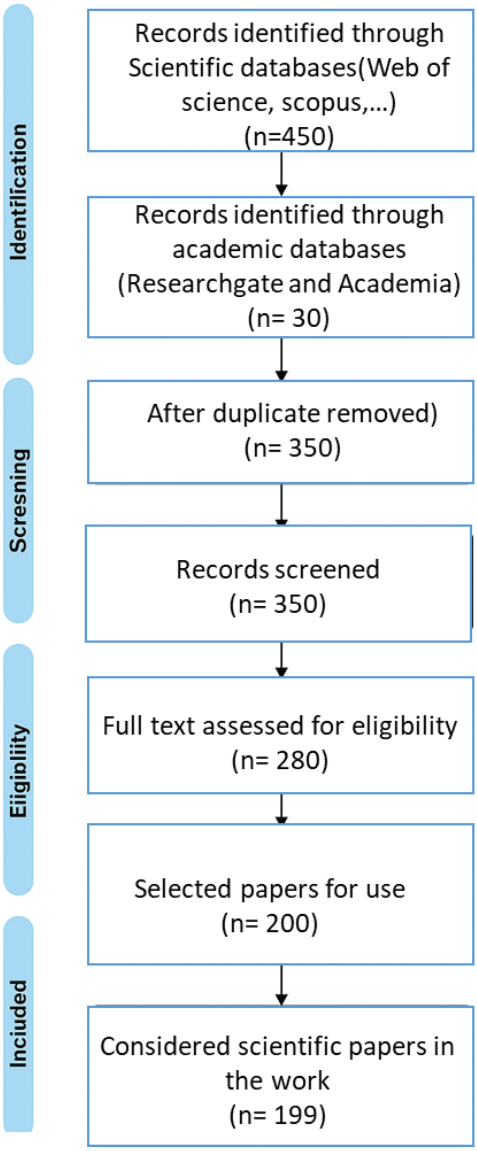



**Figure 2.** Assessment of Ecosystem Services Provided by Lagoonal Seaweeds and Seagrasses along the Moroccan Coast: A Semi-Quantitative Review.

lagoon's main channel. The overall MCES assessment provided by algae and seagrass species was obtained by summing the weighted scores across the 14 ecosystem service categories described in Table 1.

The weighting factor based on the Spatial Coverage Rate (SCR) was defined as follows (Table 3):

- 1: SCR ≤ 5%
- 2: 5% < SCR ≤ 10%
- 3: 10% < SCR ≤ 25%
- 4: 25% < SCR ≤ 50%
- 5: SCR > 50%.

This method integrates both the functional and spatial importance of each species into the overall evaluation of ecosystem services, while accounting for their relative role in the structure and functioning of the lagoon ecosystem.

**Table 2.** Table of search strings used in the literature review.

| Combinations | Databases | Search string (keywords and Boolean operators) | Period |
|---|---|---|---|
| Combination 1 | - Scientific databases (ScienceDirect, Scopus, Web of Science, and Google Scholar)<br>- Academic databases (ResearchGate and Academia) | ("algae" OR "macroalgae" OR "seaweed") AND ("ecosystem services" OR "ecological functions" OR "habitat function") AND ("lagoon" OR "coastal lagoon") | Any date |
| Combination 2 | | (*Gracilaria gracilis* OR *Ulva* OR *Cystoseira humilis* OR *Fucus spiralis* OR *Sargassum muticum* OR *Zostera noltei)* AND (Human consumption OR Water storage OR medicinal OR industrial use OR Air quality OR Coastal protection OR Climate regulation OR local weather conditions OR Ocean nourishment OR Lifecycle maintenance OR Pathogen control OR Cultural services) | Any date |
| Combination 3 | | (*Gracilaria gracilis* OR *Ulva* OR *Cystoseira humilis* OR *Fucus spiralis* OR *Sargassum muticum* OR *Zostera noltei)* AND (Human consumption OR Water storage OR medicinal OR industrial use OR Air quality OR Coastal protection OR Climate regulation OR local weather conditions OR Ocean nourishment OR Lifecycle maintenance OR Pathogen control OR Cultural services) AND (Oualidia OR Morocco OR Algeria OR Tunisia OR Mauritania OR Senegal OR Spain OR Portugal OR France OR North west Africa) | Any date |

**Table 3.** Weighting factor determined by the Spatial Coverage Rate (SCR) in relation to the total area of the main channel within the lagoon: 1 (SCR<= 5%), 2 (5 < SCR <= 10), 3 (10 < SCR <= 25), 4(25 < SCR <= 50) and 5 (SCR > 50).

| Ecosystem services | Native algal species | | | | Seagrass | invasive algal species |
|---|---|---|---|---|---|---|
| | *Gracilaria gracilis* | *Ulva (U. lactuca, U. fasciata & U. intestinalis)* | *Fucus spiralis* | *Cystoseira humilis* | *Zostera noltei* | *Sargassum muticum* |
| Spatial coverage rate (%) | 54 | 17 | 6 | 6 | 10 | 6 |
| Weighting factor | 5 | 3 | 2 | 2 | 2 | 2 |

## Results

### Contribution of the studied algae and seagrass species to marine and coastal ecosystem services

#### Provisioning services

##### Food provision

*Gracilaria gracilis* is commonly harvested for food supply in many countries, especially in Asian countries. It is consumed both fresh and processed (Norziah and Ching 2000; Barsanti and Gualtieri 2006; Pereira 2011). This red seaweed is rich in nutrients and offers several health benefits. It is low in calories and fat while being a good source of dietary fiber. It contains essential vitamins and minerals, including vitamin C, vitamin E, vitamin K, folate, calcium and magnesium. It also contains antioxidants, which help protect the body against oxidative stress (Ortiz et al. 2009; Guerra-Rivas et al. 2010; Pereira 2011; Francavilla et al. 2013; Rasyid et al. 2019). *G. gracilis* contains a gelling agent called agar, which is extracted from the cell walls of algae. Agar is commonly used in the food industry as a thickening and stabilizing agent. It is used in the production of jellies, puddings, ice creams, sauces and other food products that require a gel-like consistency (Pereira 2011; Francavilla et al. 2013).

The three *Ulva* species are promising varieties of green seaweed, each with considerable potential as sustainable food sources, providing distinct nutritional and bioactive profiles. *Ulva lactuca* is well-documented for its rich content of bioactive compounds, including polysaccharides, phenolic compounds, and essential minerals such as potassium and magnesium, making it a versatile food ingredient with applications in functional foods (Putra et al. 2024). Additionally, *U. lactuca* is renowned for its high nutritional value, comparable to conventional vegetables, especially when grown under controlled conditions (Roleda et al. 2021). *U. fasciata* is also rich in essential nutrients, particularly amino acids and fatty acids, which are beneficial for aquaculture, especially in abalone farming, highlighting its role in enhancing the growth and health of marine organisms (Latuihamallo et al. 2016). *U. intestinalis*, characteristic of arid regions, has been recognized for its rich mineral profile, providing a sustainable food source (Farzanah et al. 2022).

*Fucus* species are not commonly used as food, but their extracts would be useful as dietary supplements (Lopez et al. 2011, 2012, 2013, 2014; Pereira 2011; Ferreres et al. 2012; Andrade et al. 2013). *Fucus* species are reported to contain polysaccharides mucilage with algin, fucoidan and laminarin; polyphenols, trace elements and minerals, potassium, bromine, chlorine, magnesium, calcium, iron and silicon, mannitol, vitamins and pro-vitamins A and D, ascorbic acid and lipids (glycosylglycerides) (Guiry and Blunden 1991; Holds and Kraan 2011). According to Lopes et al. 2011, *F. spiralis* is one of the macroalgae species that have been shown to be good sources of bioactive phytosterols that are a good choice for healthy diets, especially for people with high cholesterol levels. However, the freeze-drying process can reduce the bioaccessibility of some antioxidants and polyphenols (Francisco et al. 2020).

*Cystoseira humilis* is not commonly used as food, but recent scientific research has shown that eicosapentaenoic acid (EPA) is a major constituent of the total lipid fraction of *C. humilis* which also exhibited a low ω-6/ω- ratio. 3, as well as a high unsaturation index (191.42) and low atherogenicity and thrombogenic indices (Belattmania et al. 2016; Koutsaviti et al. 2018), which can be used as nutritional food supplement in food industries.

Concerning *Zostera*, there has been limited research exploring their promising potential as a source of natural bioactive compounds that can be used as food additives and preservatives in functional food industries. However, some literature confirms that *Zostera* seeds collected in the spring constituted a significant part of the diet and traditional culture of the Seri Indians living along the Gulf of California (Felger and Moser 1973; Hemminga and Duarte 2000; Nihal et al. 2013). Concerning the benefits for aquaculture, Howarth et al. (2022) reported that shellfish farming can have positive, neutral, and negative effects on seagrass. Few studies have demonstrated the positive interactions that can be generated by the filter-feeding activity of cultivated bivalves. However, more frequently, research studies have reported negative interactions that occur directly under and in the immediate vicinity of shellfish farms and decrease as one moves away from them.

Although *Sargassum muticum* is a traditional food in Korea (Yang et al. 2013), it does not appear to have been commercially exploited as a food source in Western countries (Milledge et al. 2016). A study using *Sargassum muticum*

as a dietary supplement found that it led to an increase in natural killer lymphocytes (Park et al. 2015; Milledge et al. 2016). However, this brown algae contains high levels of heavy metals, hence the need to use it with carefulness (Lodeiro et al. 2004; Carro et al. 2015; Ungureanu et al. 2015). Katsanevakis et al. (2014) considered that *Sargassum muticum* has an indirect negative impact on food supply through fishing and aquaculture because it causes degradation of essential fish habitats and pollutes shellfish farming installations.

### Water storage and provision

The primary negative impact of algae and seagrass on water supply is the clogging of intake pipes in industrial facilities (Katsanevakis et al. 2014). The Oualidia lagoon is particularly renowned for its shellfish farming activities. Currently, no published information exists on the issue of pipe clogging in these facilities due to algae, nor are there any reports on the positive impact native algae and seagrass in the Oualidia lagoon on water supply and storage. The negative impact of *Sargassum muticum* on the clogging of intake pipes in industrial facilities was recorded by Katsanevakis et al. (2014) as direct observation by experts. This is an undesirable effect generally observed in all non-native species.

### Biotic materials and biofuels

While there may not be many patents involving the use of *Gracilaria* worldwide, recent studies have demonstrated that *Gracilaria* serves as a source of various natural marine products for diverse biotechnological applications. *Gracilaria gracilis* is a source of agar and other bioproducts, which are utilized across the pharmaceutical and cosmetic industries. Its bioactive compounds, including polysaccharides and antioxidants, exhibit significant antimicrobial and cytotoxic properties, contributing to its application in healthcare and biorefinery approaches (Martins et al. 2023). Several studies have shown that the green algae *Ulva lactuca* and *Ulva fasciata* represent significant resources of antioxidants and antibacterial agents (Chakraborty et al. 2010; Princely and Dhanaraju 2017; Anjali et al. 2019), as well as a rich source of vitamin B, proteins, minerals (calcium, potassium, magnesium, sodium, copper, iron, and iodine), and dietary fibers (Harsha Mohan et al. 2023). Regarding *Fucus spiralis*, multiple research works have demonstrated its dermo-cosmetic applications due to its antioxidant and anti-enzymatic properties, along with photoprotective attributes, coupled with its role in maintaining skin microbiota homeostasis (Freitas et al. 2020; Grina et al. 2020). Boutjagualt (2022) has shown that *Fucus spiralis* could be a novel source of natural antitumor agents and may be utilized in the production of promising drugs for cancer treatment. Research on the brown algae *Cystoseira humilis* has revealed its intriguing antioxidant activities, high degree of total unsaturation, and low atherogenic and thrombogenic indices. Consequently, *C. humilis* could be regarded as a promising compound for pharmaceutical and cosmetic industries (Belattmania et al. 2016).

The bioactive components of algae have also attracted interest in research and development within the aquaculture and agronomy sectors. With the intensification of aquaculture, the emergence of antibiotic-resistant

bacteria associated with fish diseases has become a global issue. Therefore, the search for solutions and the development of sustainable aquaculture feeds with immunostimulant properties has become a necessity. In this regard, several research studies have demonstrated that algae can serve as an ecologically sustainable dietary supplement to enhance overall health and combat pathogenic epidemics (Lomotey 2011).

Passos et al. (2021a, b) demonstrated that supplementation of *Gracilaria gracilis* as a dietary complement led to improved growth, health, and bacterial resistance of the sea gilthead bream *Sparus aurata*. However, in the case of the European sea bass *Dicentrarchus labrax*, this addition did not impact species growth but positively stimulated the immunological and antioxidant response. *Ulva lactuca* has been evaluated as a feed ingredient for gilthead bream, replacing fishmeal-derived proteins and thus reducing operating costs by 10% (Shpigel et al. 2017). Studies on *Ulva fasciata* have shown its potential as a nutritional supplement source to enhance sea bass aquaculture performance (Liao et al. 2021; El-Sayed et al. 2022). Limited studies conducted on *cystoseira humilis* have demonstrated its potential in aquaculture as an immunostimulant (Lomotey 2011).

In the field of agriculture, algae extracts are recognized as environmentally friendly biostimulants and biofertilizers that help mitigate the negative socio-economic and environmental effects of synthetic fertilizers. They contain many growth promoting substances in addition to many organic and inorganic matters that can improve the physical and chemical nature of soil (Zhang et al. 2013; Rebours et al. 2014). Additionally, Doumeizel (2022) suggests that algae can be used as animal feed, particularly for livestock such as cattle, as it could enhance their immune system.

Seagrass *Zostera noltei* detritus has been examined as a new and significant source of rosmarinic and zosteric acids (Achamlale et al. 2009a; 2009b). The later acid has been shown to be effective in preventing biological fouling by inhibiting the attachment of bacteria, yeast, fungi, algae, and bivalves on solid surfaces (Jendresen and Nielsen 2019). This natural anti-adhesive agent can replace other chemical treatments in agriculture and various industrial and medical applications (Kurth et al. 2015; Jendresen and Nielsen 2019). In addition to their medicinal uses, seagrass beds are experimentally used in methane and nitrocellulose production and in agriculture (Karleskint et al. 2009; Nihal et al. 2013). *Zostera noltei* and other seagrasses are extensively harvested for compost and soil fertilizers production (Ben Jenana et al. 2009).

*Sargassum muticum* has been used in traditional Chinese medicine to treat various diseases, including thyroid disorders (Liu et al. 2012). Recent studies have shown that this fast-growing macroalgae has naturally high levels of antioxidants, carotenoids, and phenols, including the anticancer compound fucoxanthin, making it a potential source of a range of pharmaceutically relevant materials (Milledge et al. 2016). The high ash and water content in *Sargassum muticum* prevent it from being a viable source of biofuel (Milledge et al. 2016). However, some published studies have demonstrated its use as aquaculture feed for sea cucumbers and abalones in China (Zhao et al. 2008; Liu et al. 2010) and as a biofertilizer for rice and lettuce plants (Silva et al. 2019; Baltrusch et al. 2023).

## Regulating and maintenance services

### Water purification

The marine species *Gracilaria gracilis*, *Ulva lactuca*, *U. fasciata*, *U. intestinalis*, and *Fucus spiralis* play an important role in water purification, particularly through their ability to absorb and remove various pollutants (Hurd and Dring 1990; Anderson et al. 1999; Dion and Le Bozec 1999; Martínez-Aragón et al. 2002). *Gracilaria gracilis* has shown strong bioremediation potential in aquaculture effluents, absorbing excess nutrients, such as nitrogen compounds, and reducing eutrophication of aquatic systems (Spanò et al. 2022). *Ulva lactuca*, often used in integrated multitrophic aquaculture systems, is effective in absorbing ammonia, nitrates, and other nitrogen compounds, thus acting as a natural biofilter in marine environments (Shpigel et al. 2019). *U. intestinalis* is also used to adsorb phosphate ions in wastewater, contributing to pollution reduction and water quality improvement (Niedzbała et al. 2024). Concerning, *Cystoseira humilis*, specific information available on its impact on water purification is limited. Several authors have associated the decline in *Cystoseira* areas with human pressure (Rodríguez-Prieto and Polo 1996; Mangialajo et al. 2008; Thibaut et al. 2014; Thibaut et al. 2015; Luigi and Giulia 2017).

Like all seagrasses, *Zostera Noltei* play a key role in marine ecosystems (Hemminga and Duarte 2000). Their beds ensure water purification, nutrient cycling, stabilize sediments, and dampen the energy of waves and currents (Haznedaroglu and Zeybeck 2007). However, the reduced resistance of the leaves of these seagrasses, combined with nutrient overload, can lead to a negative feedback response, resulting in a loss of biomass of these species (Cabaço et al. 2008; La Nafie et al. 2012).

*Sargassum muticum* has been proposed for the adsorption of heavy metals and the treatment of industrial wastewater (López-García et al. 2012; Lodeiro and Sastre de Vicente 2019; Florez-Fernandez et al. 2021). Hannachi and Hafidh (2020) demonstrated that *Sargassum muticum* exhibits exceptional performance in removing methylene blue and lead ions from industrial effluents. These various studies have concluded that *Sargassum muticum* could, to some extent, be utilized as a cost-effective ecological biosorbent for real wastewater treatment.

### Air quality regulation

*Gracilaria*, *Ulva*, *Fucus*, and *Cystoseira* algae, photosynthetic organisms, play a crucial role in air quality regulation, primarily due to their interactions with the carbon dioxide (CO2) life cycle and their contribution to oxygen (O2) production (Yang et al. 2015; Costa-Domingo et al. 2022). These algae all play an important role in the process of photosynthesis, but there are differences in how each of these algae contributes to this process. Kaladharan et al. (2009) demonstrated that *Ulva lactuca* and *Gracilaria* recorded 100% and 25%, respectively, in CO2 utilization for carbon fixation from the ambient water up to 15 mg/L. Additionally, these marine algae participate in biogeochemical cycles by regulating nutrient levels, such as nitrogen and phosphorus, in coastal ecosystems. When they absorb these nutrients, they prevent their flow into adjacent terrestrial areas,

where they could contribute to air and water pollution (Fei 2004; Yang et al. 2006; Yang et al. 2015). Few scientific publications have addressed the impact of *Sagassum muticum* biomass on CO2 sequestration from the air and its consequences on air quality. Among these works, there is the study by Longphuirt et al. (2013) which demonstrated that the increase in CO2 absorption by this macroalgae depends on environmental conditions and specific site conditions, highlighting its ability to adapt to climate change. Similar to algae, seagrasses are highly efficient at capturing and storing CO2 from the atmosphere

**Coastal protection**

The various studies evaluating coastal protection as an ecosystem service have focused on the role of mangrove forests, seagrass beds, and coastal wetlands (Boström et al. 2011; Liquete et al. 2013; Çinar et al. 2014). The extensive root systems of seagrasses anchor sediments on the seafloor, reducing coastal erosion and helping maintain water clarity by preventing excessive sediment runoff into the ocean (Haznedaroglu and Zeybeck 2007). Seagrass meadows dampen wave energy and reduce the impact of waves and currents along coastlines. This natural protection helps protect shorelines from erosion during storms (Koch et al. 2007). Scientifics studies indicates that *Zostera noltei* contributes to beach protection by acting as a buffer against currents created by the wind, independently of seasonal patterns of seagrass morphological changes (Paquier et al. 2014). However, there is a lack of information on the direct response of algal ecosystems to coastal protection or whether the responses are similar across ecosystems and taxa. Nevertheless, algal cover can indirectly impact coastal protection by reducing the force of waves and currents, thereby mitigating coastal erosion as a natural barrier. Additionally, algae can contribute to the gradual building of the coastline over time through sediment stabilization processes. Concerning *Sargassum muticum*, its impact on coastal preservation could be considered negative due to its competition with native marine seagrasses. However, when these seagrass beds are in a degraded state, in a stressed environment, dense populations of *Sargassum muticum* can contribute positively to coastal protection (Katsanevakis et al. 2014).

**Climate regulation**

Like all algae and seagrass, the genera *Gracilaria*, *Ulva*, *Fucus*, *Cystoseira*, *Sargassum* and *Zostera* absorb carbon dioxide (CO2) during photosynthesis and convert it into organic matter. This process helps remove CO2 from the atmosphere, a greenhouse gas responsible for climate warming (Duarte et al. 2005; Nellemann et al. 2009; Damien et al. 2013; Cheah et al. 2015; Sharma et al. 2021; Israel and Shpigel 2023). However, it is important to note that the specific impact on atmospheric regulation can vary from one species to another.

Seagrasses rank among the most effective natural carbon sinks on the planet, even outperforming certain terrestrial forests. This process of carbon sequestration plays a crucial role in mitigating climate change (Fourqurean et al. 2012). For instance, organic carbon stocks in *Zostera* sp. accumulate over time scales ranging up to several centuries (Duarte et al. 2010; Arnaud-Haond et al. 2012; Duarte et al. 2013; Röhr et al. 2018).

### Ocean nourishment

Ocean nourishment typically refers to initiatives aimed at enhancing the well-being and productivity of marine ecosystems through various methods, such as the introduction of nutrients to support the growth of phytoplankton or the rehabilitation of degraded habitats. In general, algae and seagrass are known for their ability to absorb and accumulate nutrients from the water, particularly nitrogen and phosphorus, which are essential for their growth. Various studies have focused on the use of algae as agents for purifying domestic wastewater, agricultural effluents, and intensive fishpond systems for several decades (Kindig and Littler 1980; Chan et al. 1982; Neori et al. 1991, 1996; Haglund and Pedersén 1993). These research efforts, conducted on various species, have highlighted the role of marine macroalgae as living biofilters for water nutrients (especially phosphorus and nitrogen) and certain heavy metals, although at varying levels depending on taxa and environmental conditions. For instance, studies have demonstrated that the filtering performance of *Ulva* is higher compared to that of *Gracilaria* and *Fucus* (Martinez-Aragón et al. 2002; Ben-Ari et al. 2014; Shpigel et al. 2018; Marcelo Costa et al. 2020).

*Zostera noltei* like other marine seagrasses play a key role in plant-sediment interactions through several biogeochemical processes (Delgard et al. 2013): it assimilate high concentrations of nutrients available in the interstitial water of sediments through its aboveground and underground plant tissues; vegetated sediments are often enriched in organic matter resulting from the decomposition of plant material; This seagrass facilitate the efficient transport of oxygen to underground tissues buried in anoxic sediments.

### Life cycle maintenance

*Gracilaria*, *Ulva*, *Fucus*, *Cystoseira* and *Zostera* provide a structural foundation for numerous lagoonal ecosystems habitats and associated trophic networks. These habitats nourish native and migratory birds and serve as nurseries for fish, particularly for fry and juveniles. They provide exceptional sites for bird migration, nesting, and feeding. Their high productivity promotes fishing and shellfish farming, especially for commercially valuable species such as mollusks and fish (MNHN and OFB 2003–2024; Salomidi et al. 2012).

Seagrass meadows provide a crucial role as habitat and nursery grounds for a diverse range of marine species, including commercially significant fish like snapper and grouper. Juvenile fish often seek refuge in seagrass beds, using them as shelter from predators, which significantly boosts their chances of survival (Heck et al. 2003). These seagrass meadows support a rich biodiversity, offering food and shelter to various organisms, from small invertebrates to large fish and sea turtles. Many species depend on seagrass ecosystems for either a part or the entirety of their life cycles (Duarte and Chiscano 1999). Research on *Zostera noltei* has revealed that this seagrass variety provides shelter for various animals such as shrimp, seahorses, and sea urchins, promoting significant biological diversity (Hily 2006; Bouma et al. 2009). This species causes a shift from endobenthic to epibenthic macroinvertebrate species, as the vegetation offers habitat and protection to epibenthic animals from predation.

According to Mackenzie et al. (2000), experimental and observational studies in Europe and the USA have shown that algal mats, particularly *Ulva lactuca*, reduce the abundance of bivalves and other animals buried in sediments. This negative impact is closely correlated with the algae's coverage rate, which varies seasonally (Mackenzie and Clyde 2000). While the upper part of these algae can form habitats for shrimp, crabs, and small fish (Wilson et al. 1990; Sogard and Able 1991; Kolbe et al. 1995; Mackenzie and Clyde 2000). As an invasive species, *Sargassum muticum* competes with native marine seagrasses and algae, thereby leading to the degradation of habitats for these indigenous species and consequently disrupting the life cycle of associated species.

**Biological regulation**

Macroalgae are of great importance as a potential source of bioactive compounds, such as antibacterials, antifungals, antioxidants, and others (Kim et al. 2008; Belattmania et al. 2016; Zerrifi et al. 2018; Passos et al. 2021). The genus *Gracilaria* is one of the most attractive algae, as several research experiments have demonstrated its ability to serve as a complementary food source for mitigating fish stress in their environment, combating bacterial infections, and enhancing antioxidant capacity, immune response, and resistance to pathogens (Capillo et al. 2018; Hoseinifar et al. 2018; Passos et al. 2021). Additionally, numerous research studies have shown promising antimicrobial activity in the *Ulva* and *Fucus* genera against human bacterial and fungal pathogens (Kolanjinathan and Stella 2011; Deveau et al. 2016).

Recent research studies (Lamb et al. 2017; Tasdemir et al. 2024) have demonstrated the role of seagrass beds in suppressing pathogenic bacteria in the water column. They effectively reduce the abundance of human fecal bacteria and a variety of marine pathogens harmful to fish, marine invertebrates, and marine mammals (Lamb et al. 2017). Previous studies have also confirmed lower levels of pathogens near seagrass beds, including Escherichia coli (Palazón et al. 2018), *Salmonella* spp. (Deng et al. 2021), and *Vibrio* spp. (Reusch et al. 2021). According to these authors, these antimicrobial effects can be explained by the phenolic compounds found in seagrass beds (Tasdemir et al. 2024).

The chloroformic and ethanolic extracts of *Sargassum muticum* demonstrate antimicrobial activity against various bacterial, fungal, and microalgal strains involved in marine biofilm formation and could serve as the basis for an antifouling product (Hellio et al. 2001; Silkina et al. 2009; Plouguerne et al. 2010a, 2010b; Milledge et al. 2016).

## Cultural services (Symbolic and aesthetic values/Recreation and tourism/Cognitive benefits)

Algae and seagrass play a multifunctional role in the preservation of lagoon ecosystems as primary producers, substrate stabilizers, water purifiers, oxygenators, and participants in nutrient cycling. They, also provide habitats for benthic fauna, which in turn serve as food for migratory birds, thereby contributing to the preservation of its cultural services: its symbolic, aesthetic, and touristic values. Furthermore, these algae and seagrass constitute an important ecosystem for scientific research and industrial development (Pellegrini et

al. 1997; Bennouna et al. 2000; Farid et al. 2009, 2012, 2020; Rezzoum et al. 2022). According to Dirhamsyah (2007), Pugh and Skinner (2002), the value of the knowledge contribution can be estimated through the cost of research projects (Campagne 2015).

The invasive algae *Sargassum muticum* poses a threat to the balance of coastal habitats, leading to serious economic and environmental impacts, thereby negatively affecting the symbolic and aesthetic values of the attacked ecosystem. It is imperative to find strategies to control their spread and success. For this reason, scientific research projects have focused more on their use as possible sources of valuable new natural compounds.

### Assessment of the potential MCES provided by the Oualidia lagoon and comparison with currently exploited ecosystem services

The explored research indicates that the potential MCES provided by native algae and seagrasses in the Oualidia lagoon present a positive impact on 81% of the evaluated ES. The remainder primarily corresponds to highly limited research findings or a lack of information. Invasive algae have a negative impact on 43% of ecosystem services compared to 50% with a positive impact. Seagrasses play the most significant role in regulating and maintaining ecosystem services, while native algae predominantly contribute positively to provisioning services. Various native algae and seagrasses contribute positively to cultural services, whereas invasive algae have a negative impact, except in certain regulating and maintenance services, research and educational contexts (Table 4).

The information available on the current actual exploitation of ecosystem services provided by algae and seagrass beds in the Oualidia lagoon indicates that, with the exception of agar-agar extraction from *Gracilaria*, none of the species studied are used for human consumption or in the medical, cosmetic, or other industries. Therefore, provisioning services, as assessed above (Table 4), can be considered negligible. In contrast, the lagoon's rich biodiversity, the presence of pollution-sensitive species, its role as a refuge for juvenile fish, and its frequent use by birds for feeding clearly highlight the importance of its regulating and maintenance services (El Hamoumi et al. 2022; Jawhari 2022; Rezzoum et al. 2022; Zidane et al. 2022). Regarding cultural services, only cognitive benefits are recognized as significant, due to the numerous research studies conducted in the lagoon. The comparison between potential (Provisioning services + Regulating and maintenance services + Cultural services, Table 4) and current marine coastal ecosystem services (Regulating and maintenance services + Cognitive effects) provided by algae and seagrass beds shows that these resources are underutilized, with 25–30% of services remaining unused (Fig. 3). This aligns with the objectives of the site's RAMSAR status, which promotes the sustainable use of its natural resources.

## Discussion

*Gracilaria gracilis*, *Ulva lactuca*, *Ulva fasciata*, *Ulva intestinalis*, *Fucus spiralis*, *Cystoseira humilis*, *Zostera noltei* and surely other species of seaweed and seagrasses of the lagoon ecosystems and marine environment of the Moroccan coast can play significant roles in lagoon water nourishment, aiding in the restoration

**Table 4.** Assessment Matrix of MCES for Algae and Seagrass Species in the Oualidia Lagoon: positive impact (+1), negative impact (-1), and Restricted information or lack of information (0).

| Ecosystem services | Native algal species | | | | Seagrass species | invasive algal species |
|---|---|---|---|---|---|---|
| | *Gracilaria gracilis* | *Ulva (U. lactuca, U. fasciata & U. intestinalis)* | *Fucus spiralis* | *Cystoseira humilis* | *Zostera noltei* | *Sargassum muticum* |
| Food provision | 1 | 1 | 0 | 0 | 0 | -1 |
| Water storage and provision | 0 | 0 | 0 | 0 | 0 | -1 |
| Biotic materials and Biofuels | 1 | 1 | 1 | 1 | 1 | 1 |
| **Total** | **2** | **2** | **1** | **1** | **1** | **-1** |
| Water purification | 1 | 1 | 1 | 0 | 1 | 1 |
| Air quality regulation | 1 | 1 | 1 | 1 | 1 | 1 |
| Coastal protection | 0 | 0 | 0 | 0 | 1 | -1 |
| Climate regulation | 1 | 1 | 1 | 1 | 1 | 1 |
| Weather regulation | 1 | 1 | 1 | 1 | 1 | 1 |
| Ocean nourishment | 1 | 1 | 1 | 1 | 1 | 0 |
| Lifecycle maintenance | 1 | 1 | 1 | 1 | 1 | -1 |
| Biological regulation | 1 | 1 | 1 | 1 | 1 | 1 |
| **Total** | **7** | **7** | **7** | **6** | **8** | **3** |
| Symbolic and aesthetic values | 1 | 1 | 1 | 1 | 1 | -1 |
| Recreation and tourism | 1 | 1 | 1 | 1 | 1 | -1 |
| Cognitive effects | 1 | 1 | 1 | 1 | 1 | 1 |
| **Total** | **3** | **3** | **3** | **3** | **3** | **1** |
| **by species** | **12** | **12** | **11** | **10** | **12** | **3** |
| Weighting factor (see table 3) | 5 | 3 | 2 | 2 | 2 | 2 |
| **by spatial cover by species** | **60** | **36** | **22** | **20** | **24** | **6** |

and maintenance of the lagoon's ecosystem health while providing economic benefits to coastal communities. Nevertheless, advanced scientific research and outreach activities to local managers and decision-makers is needed on this subject, taking into account local environmental conditions and specific objectives.

Literature review carried out shows the lack of information available on ES of natives seaweed and seagrasses identified in the countries of the North-West African region, including Moroccan coast, especially provisioning services. This finding is confirmed by Web et al. (2023). The majority of the works published concerns the checklist up-to-date, distribution mapping, biomass estimation, biologic cycle and the regulatory role of certain pollutants (Benhissoune et al. 2001, 2002, 2003; De Clerck et al. 2003; John et al. 2004; Givernaud et al. 2005; Gaudry et al. 2007; El Ati-Hellal et al. 2007; Rezzoum et al. 2022; Al Qoh et al. 2022). It is only in the last decade that researchers began to publish on the bioactive components of certain algae for medicinal and cosmetic applications. This research work was carried out particularly on the species *Gracilaria gracilis* wild or from seaweed farming and this because of the global demand for its agar-agar (Ben Said et al. 2019; Hmani et al. 2021; Belattmania et al. 2021; Yahyaoui et al. 2024) (Table 4).

There are also, in the North-West African region, other works of valorization of bioactive components on *Fucus spiralis* (Andrade et al. 2013; Samri et al. 2019; Grina et al. 2020; Boutjagualt et al. 2022; Baroud et al. 2023), *Cystoseira humilis* (Belattmania et al. 2016; Grina et al. 2020; Saidani et al. 2022; Farid 2024) and

*Ulva lactuca* (Andrade et al. 2013; Oucif et al. 2020; Bouzenad et al. 2024; Brahimi et al. 2024; Ouahabi et al. 2024) (see Table 4). All this research, mostly recent, is still at the analysis and testing stage, and has not yet reached the level of industrialization. Moreover, the introduction of algae into the culinary culture of these countries remains very rare or even completely absent in some countries.

The comparison with neighboring countries in Southern Europe as Spain, France and Portugal, shows that the species of *Gracilaria gracilis*, *Ulva lactuca* and *Fucus spiralis* constitute a vital raw material for the food and pharmaceutical industries because of their gelling properties. Agar extracted from *Gracilaria* is used in food as a thickener and stabilizer, as well as in microbiological and pharmaceutical contexts (Andrade et al. 2013; Filote et al. 2022). France was the first European country to establish a specific regulation concerning the use of seaweeds for human consumption as non-traditional food substances. Currently, 12 macroalgae among which *Ulva* sp., species of the genus *Fucus* and *Gracilaria* are authorized as vegetables and condiment (CEVA 2019). However, the use of algae in the culinary traditions of these Europeen countries is still marginal, often confined to specialized restaurants or regional gastronomic initiatives.

Regarding the seagrass species *Zostera noltei*, all research in Morocco and other countries of the North-West African region has focused on its support and provisioning services (Clavier et al. 2011; Boutahar et al. 2019; El-Hacen et al. 2020; Mosbahi et al. 2020; Bououarour et al. 2021; Sidi Cheikh et al. 2022; Hamza et al. 2024). A similar pattern is observed in Southern European countries (Cabaço et al. 2008; Román et al. 2018; Garmendia et al. 2021), with some rare publications on the valorisation of proactive products, the example of the work of Achamlale et al. (2009), which highlighted the potential of this seagrass as a novel source of zosteric acid (Table 4). This overview of the current consideration of algae and seagrasses in the North-West African region is well illustrated by the case study of the Oualidia Lagoon (Morocco), where the estimation of the potential Marine and Coastal Ecosystem services (MCES) demonstrated a partial exploitation of its ecosystem services, primarily dominated by regulating and maintenance services, while provisioning and cultural services remain almost unexploited (Table 4, Fig. 3).

*Sargassum muticum*, as an invasive species, has negative impacts on the invaded ecosystem by competing with native species. Its assessment in the Oualidia Lagoon shows that this species has a negative impact of 50% of MCES. To mitigate its proliferation and reverse this trend, various research projects have recently been initiated in the North-West African region to explore its potential uses (Ould Abdellahi et al. 2017; Bouzenad et al. 2024; Brahimi et al. 2024), similar to efforts in neighbouring Southern European countries having explored this area several years in advance (Silva et al. 2013, 2019, 2023; Puspita et al. 2017) (Table 5).

The World Bank, in its report "Global Seaweed New and Emerging Markets 2023" indicated that in the natural world, the field of seaweed is still untapped, while it could stimulate economic growth and promote greater social equality, while addressing environmental issues. According to the same report, the ecosystem services of seaweed could contribute to the achievement of at least nine of the 17 UN Sustainable Development Goals. They can indeed help eliminate hunger, improve health, mitigate climate change, conserve biodiversity and marine life, promote economic growth and create decent jobs.

**Table 5.** Examples of efforts to valorise seaweeds and seagrasses in the North-western African region, along with a comparison to studies conducted in neighboring Western European countries at later dates.

| Marine and Coastal Ecosystem Services | Species | Countries | References |
|---|---|---|---|
| Provisioning services (Bioactive components) | *Gracilaria gracilis* | Tunisia | Yahyaoui et al. 2024; Hmani et al. 2021; Ben Said et al. 2019 |
| | | Morocco | Belattmania et al. 2021 |
| | *Ulva lactuca* | Algeria | Bouzenad et al. 2024; Oucif et al. 2020 |
| | | Morocco | Ouahabi et al. 2024; Brahimi et al. 2024 |
| | | Portugal | Andrade et al. 2013. |
| | *Fucus spiralis* | Morocco | Baroud et al. 2023; Boutjagualt et al. 2022; Grina et al. 2020; Samri et al. 2019 |
| | | Portugal | Filote et al. 2022; Andrade et al. 2013 |
| | *Cystoseira humilis* | Algeria | Saidani et al. 2022 |
| | | Morocco | Farid 2024; Grina et al. 2020; Belattmania et al. 2016 |
| | *Sargassum muticum* | Algeria | Bouzenad et al. 2024 |
| | | Morocco | Brahimi et al. 2024 |
| | | Mauritania | Ould Abdellahi et al. 2017 |
| | | France | Puspita et al. 2017 |
| | | Spain | Baltrusch et al. 2023; Carro et al. 2015; Silva et al. 2023 |
| | | Portugal | Silva et al. 2013; Silva et al. 2019. |
| | *Zostera noltei* | France | Achamlale et al. 2009a |
| Regulating and maintenance services | *Zostera noltei* | Tunisia | Mosbahi et al. 2020 |
| | | Algeria | Hamza et al. 2024 |
| | | Morocco | Bououarour et al. 2021; Boutahar et al. 2019 |
| | | Mauritania | Sidi Cheikh et al. 2022; El-Hacen et al. 2020; Clavier et al. 2011 |
| | | Senegal | Sidi Cheikh et al. 2022 |
| | | Portugal | Cabaço et al. 2008 |

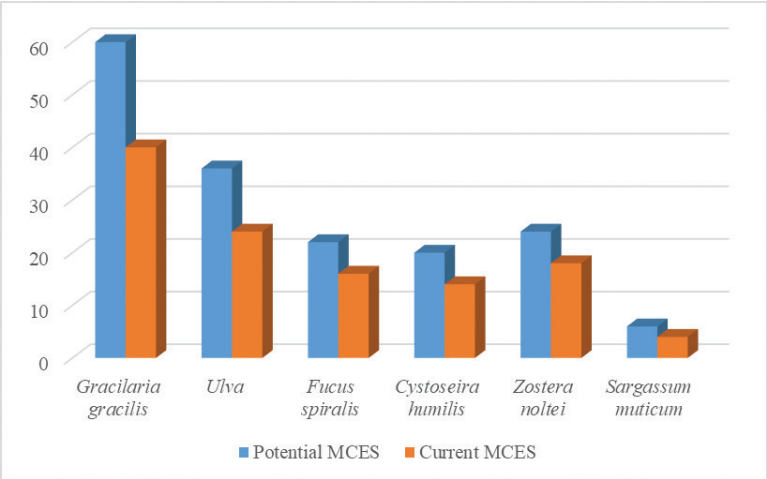



**Figure 3.** Comparison between potential and current MCES provided by algae and seagrass beds in the Oualidia lagoon.

## Conclusion

In this study, we examined the ecosystem services provided by algae and seagrass species that dominate the lagoonal ecosystems along the Moroccan Atlantic coast, in northwestern Africa—a region where local research remains limited. Based on a comprehensive literature review, we assessed the contribution of key native species (Gracilaria gracilis, Ulva spp., Cystoseira humilis, Fucus spiralis, and Zostera noltei), as well as the invasive species Sargassum muticum, to Marine and Coastal Ecosystem Services (MCES). A semi-quantitative

approach was then applied to integrate the functional and spatial value of each species into the overall evaluation of MCES, while accounting for their relative importance in the structure and functioning of the lagoon ecosystem.

The results from the Oualidia Lagoon indicate that 70–85% of potential ecosystem services are documented, with native algae and seagrass species contributing primarily to regulating and supporting services. In contrast, S. muticum exerts a negative impact on approximately 43% of these services, particularly those related to water retention, coastal protection, and cultural value.

An assessment of the current use of ecosystem services shows that, except for the extraction of agar-agar from Gracilaria, none of the studied species are currently exploited for food, medical, cosmetic, or industrial purposes, suggesting minimal provisioning value. Conversely, the lagoon's high biodiversity, the presence of pollution-sensitive bioindicator species, its role as a nursery for juvenile fish, and its importance as a feeding ground for migratory birds all highlight the dominance of regulating and supporting services. Regarding cultural services, only cognitive benefits were identified as significant, mainly due to the extensive scientific research conducted on the site. A comparison between the theoretical potential and the actual MCES currently utilized reveals an underuse of approximately 25–30% of their potential. This finding aligns with the lagoon's Ramsar designation, which promotes the sustainable use of natural resources rather than intensive exploitation.

In conclusion, strengthening applied research and awareness-raising initiatives is essential to maximize the potential of native species while mitigating the impacts of invasive species such as Sargassum muticum. Bridging current knowledge gaps will not only help reduce ecological pressures but also contribute to the achievement of several United Nations Sustainable Development Goals (SDGs), particularly those related to food security, health, climate action, and biodiversity conservation. Promoting the sustainable use of native species and developing pilot algal aquaculture projects in lagoonal environments could ultimately transform these ecosystems into drivers of blue growth and ecological resilience at the regional scale.

## Additional information

### Conflict of interest

The authors have declared that no competing interests exist.

### Ethical statement

No ethical statement was reported.

### Use of AI

No use of AI was reported.

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## Author contributions

Rachida HOUSSA, Nor-Eddine REZZOUM and Hakima ZIDANE contributed to the study conception and design. Material preparation, data collection and analysis were performed by Nor-Eddine REZZOUM, Hakima ZIDANE, Sara el Mouttaqui, Fatima EL ASRI and Rachida HOUSSA. The first draft of the manuscript was written by Rachida HOUSSA. Ouafa CHRIFI, Nor-Eddine REZZOUM and Hakima ZIDANE commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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## Data availability

Data used in this article were published in 2022 by Rezzoum et al. (https://doi.org/10.34874/IMIST.PRSM/fsejournal-v12i1.30614). Fig. 1 satellite image of Oualidia lagoon was generated using open access data from https://earthexplorer.usgs.gov/.

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