Seasonal and depth effects on growth and agar yield of *Gracilaria gracilis* cultivated at Sidi Rahal, Moroccan Atlantic coast

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Abstract. *Gracilaria gracilis* farming was developed at Sidi Rahal on the Atlantic Coast. Experimental trials aimed to shed light on the link between the *G. gracilis* farming performance and environmental conditions. The study was conducted between September 2022 and August 2023. The algae were cultivated using the rope culture technique for four periods of 90 days each to identify the most suitable season. Farming was then carried out at three clump spacing intervals (20 cm, 30 cm, and 40 cm) for 90 days. Finally, two zones were selected (coastal and deep zones, 0.5 m and 1 m, respectively) for a culture period of 75 days. Maximum growth rates were observed in spring, with 14.39% day^{-1} and 14.67% day^{-1} for 40 cm spacing between clumps, and finally 14.22% day^{-1} for the deep zone. Overall, the best period for cultivating *G. gracilis* in the Sidi Rahal intertidal zone is from spring to midsummer. An apparent effect of the culture period was observed on agar yield, and thus, the spacing between clumps and the depth had a remarkable impact on agar production.

Key Words: depth, *Gracilaria gracilis*, rope culture, season, seeding density.

Introduction. Macroalgae have been used for decades in medicine, agriculture, and animal feed (Buchholz et al 2012; Mouritsen et al 2019), also constituting an important resource for the pharmaceutical industry (Dhargalkar & Verlecar 2009). Their cultivation offers ecological and socio-economic benefits, as well as potentially having positive impacts on the environment (Cabral et al 2016). Cultivated algae can provide habitat for numerous commercially important species such as nematodes, polychaetes and molluscs (Walls et al 2016; Walls et al 2019). Global seaweed production reached a total of 36 billion tons in 2021, with Asian countries accounting for almost 97% of this production, setting a new record of 218 million tons for the fisheries and aquaculture sector, including seaweed production, of which around 58% comes from aquaculture (FAO 2023).

Gracilaria is a genus of agarophytes that holds significant commercial value and is the most common and promising source of agar. It includes over 150 species found in temperate and subtropical regions (Vuai 2022). According to McHugh (2003), *Gracilaria*, the main industrially exploited genus of agarophyte worldwide, accounts for 65% of total agar-producing species production, primarily sourced from countries in America and Asia. Contributions from Africa and Europe are marginal. The leading producing countries are Chile, China, Indonesia, Vietnam, and Argentina.

Gracilaria species are utilized across various sectors, such as direct human consumption (Jensen 2004; Dillehay et al 2008; Gordon 2017), and in medicine for treating conditions including intestinal constipation, dysentery, enteritis, thyroid diseases, urinary disorders, respiratory diseases, and diarrhea (Costa et al 2016; Fu et al 2016; Leódido et al 2017). *Gracilaria gracilis* is a benthic, intertidal red macroalga (Rhodophyta) belonging to the commercially valuable *Gracilaria* genus, Gracilariales order, and Gracilariaceae family. It is esteemed in scientific research for its capability to produce high-quality agar and various essential organic components, including proteins, lipids, fatty acids, phenols, sterols, and carbohydrates. Due to market demand and inadequate crop management practices, natural stands of *G. gracilis* have been overharvested in multiple locations, leading to scarcity, price increases, and a demand for a stable supply and quality. Consequently, there has been significant interest in farming this species, leading to the development of numerous cultivation techniques to enhance the yield and quality of farmed *Gracilaria* compared to wild populations.

Gracilaria production primarily comes from cuttings propagation in many tropical countries, where good sunlight is available; however, seeding from reproductive elements is also feasible. The genus *Gracilaria*, widely distributed worldwide, comprises nearly 160 species and is characterized by the diversity of its habitats (Santelices & Doty 1989). According to Pérez (1997), the propagation of species within this genus through cutting can be carried out in marshes, ponds, or in the sea, employing techniques as specific and varied as dictated by biological differences among species. Distinct cultivation methods are observed in China and Taiwan (McLachlan & Bird 1986), Chile (Kim 1970; Santelices & Doty 1989; Westermeier et al 1993; Troell et al 1997), India (Kaladharan et al 1996), Hawaii (Glenn et al 1998; Nelson et al 2001), and the USA (Rosenberg & Ramus 1982).

Morocco’s coastline is home to an exceptional variety of marine algae, with more than 500 species recorded, encompassing green, brown, and red groups (Grina et al 2020). Within this diversity, red algae such as *Gelidium sesquipedale* represent the primary species harvested for commercial use (Ouahid et al 2021). Thanks to the favorable salinity levels and hydro-climatic conditions along the Moroccan shores, the seaweed valorization industry began to take shape in the 1950s (Ouahid et al 2021). Today, this industry provides steady employment to over 500 workers, creates seasonal jobs for approximately 9,000 individuals, and generates nearly 170 million MAD in annual revenue (Ouahid et al 2021).

In Morocco, maritime activities are deeply rooted in culture and traditions, as reflected in the widespread presence of fishing communities along the coast. Coastal spatial planning, launched in 2000, aims to integrate and promote the development of aquaculture at the national level. The upwelling systems along the Atlantic coast create favorable conditions for algal growth. This natural abundance has supported the establishment of algae-processing industries since the 1950s. Preliminary assessments of Morocco's coastal environment have identified potential sites for algae farming. Nevertheless, mastering cultivation techniques and understanding the interactions between macroalgal performance and environmental factors remain significant challenges that require further scientific research.

Morocco has adopted a new strategy to develop the seaweed sector, given its importance to the blue economy. National seaweed production was 24,672 tons in 2017 and reached 11,768 tons in 2022. The decline in wild seaweed exploitation was attributed to the development of aquaculture, which produced 1439 tons in 2022, compared to 596 tons in 2017 (Ministère de l’Agriculture, de la Pêche Maritime, du Développement Rural et des Eaux et Forêts 2022). Seaweed production was 72 tons in 2017 and increased to 174 tons in 2022 (Ministère de l’Agriculture, de la Pêche Maritime, du Développement Rural et des Eaux et Forêts 2022). The seaweed industry in Morocco relies mainly on agar extraction from wild *Gelidium sesquipedale* to supplement natural resources for agar production, and the National Aquaculture Development Agency has recently identified suitable sites for Gracilaria cultivation. Seaweed farming units in Morocco include four units in the Oriental region, two units in the Souss-Massa region, and 96 units in the Dakhla-Oued Eddahab region. The study site is located in the Casablanca-Settat region, an area under study for seaweed farming projects. Therefore, it is necessary to fully understand the essential elements to consider for the success of such projects. Site identification for seaweed farming is based on the evaluation of environmental factors. This study aims to understand: i) the seasonal effect (temperature, salinity, nutrient levels - nitrogen and phosphorus) on the growth performance of the red algae *G. gracilis* and on the quantity of agar produced, ii) the effect of seeding density on the growth of *G. gracilis*, and iii) the impact of depth on the production of *G. gracilis*.

Material and Method

Description of the study sites. The study was carried out in Sidi Rahal, on the Atlantic coast of Morocco (Figure 1), from September 2022 to August 2023. The site's geomorphology, characterized by a double rocky band -an offshore band that protects the farming area from waves and a coastal band that serves as a barrier against sand movement - formed an effective farming tank measuring 100 meters in width, 500 meters in length, and 80 centimeters in depth.

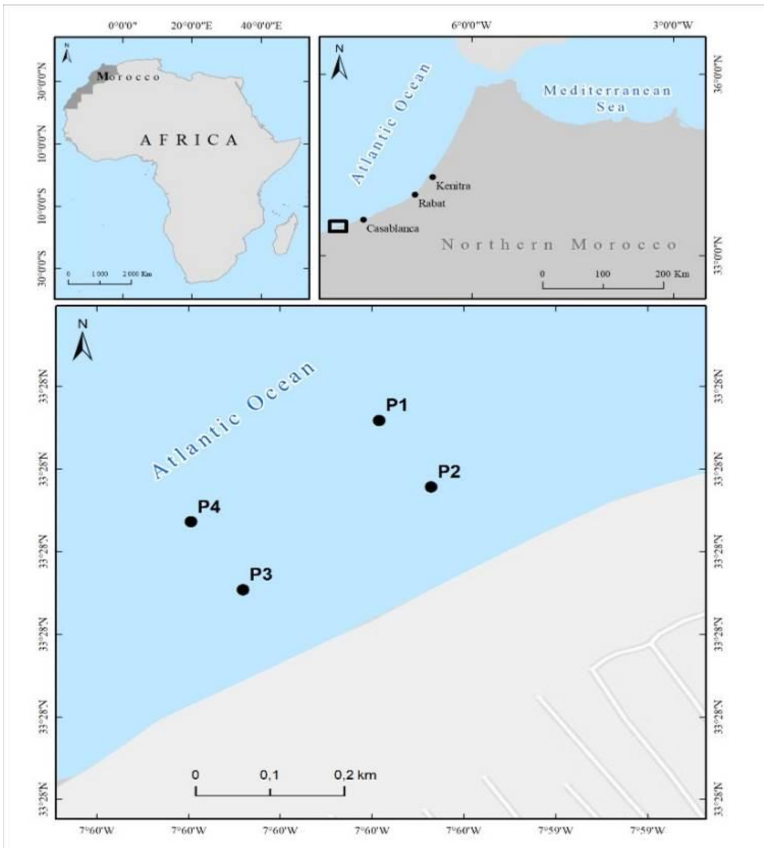

Figure 1. Map showing the geographical location of the study site in Sidi Rahal, located on the Atlantic coast of Morocco.

Preparation of vegetative material and farming technique. The farming method employed was "horizontal rope culture" (Smith et al 1984), a method favored worldwide for its ease of installation, maintenance, and moderate cost. For this project, the National Institute of Fisheries Research set up eight ropes in the intertidal zone of Sidi Rahal. Each rope, with a diameter of 12 mm and a length of 100 meters, was equipped with seine floats every 10 meters and supported by two mooring posts at each end, as well as a galvanized steel hanging post in the middle. The ropes were spaced one meter apart. The farming involved attaching whole thalli to these linear ropes, which were suspended and stretched between posts driven into the ground.

After the ropes were installed, harvested algae/seaweed were weighed using a precision balance to determine their initial weight. For the study on zone effects, 70 g of algae were seeded in each zone (333 tufts per rope) and subsequently weighed. For the seasonal effect study, each rope was seeded with 333 tufts of algae, totaling an initial weight of 100 g under humid conditions. To assess the impact of the stocking density (tuft spacing), an initial weight of 100 g was used with three different spacings: 20 cm (500 tufts/rope), 30 cm (333 tufts/rope), and 40 cm (250 tufts/rope). To avoid physical contact between the ropes, a 1-meter gap was maintained. The ropes remained horizontal and submerged at a depth of 50 cm during low tide, and at least one meter (with a variation of ±0.50 cm) during high tide. Depth affects the growth of *G. gracilis*, so two depths were tested: 1 meter at low tide (deep zone) and 0.5 m at low tide (coastal zone). Seasonal effects were explored over four distinct periods, each lasting 9 weeks: autumn 2022 (starting September 15), winter 2022 (starting December 15), spring (starting March 15), and summer (starting June 15). The effects of stocking density (tuft spacing) and depth on growth efficiency and agar production were also assessed over 9 weeks, starting March 15. The objective was to identify optimal seasonal conditions, specific zones, and suitable spacings for *G. gracilis* farming. Three ropes were used for each experiment, and algae were harvested after 2, 4, 6, and 8 weeks of growth, irrespective of the period. To measure the wet weight of each sample, it was placed on absorbent paper to remove any residual moisture. This paper acts as a desiccant, minimizing the risk of trapped water and ensuring more accurate measurements.

Physicochemical parameters. Every two weeks during the algae farming period, various environmental parameters were assessed. Water temperature, salinity, and dissolved oxygen levels were measured at a depth of 30 cm using a portable multi-parameter probe (HANNA HI 9829) with multiple electrodes, enabling simultaneous readings of these variables. Water samples for nutrient analysis (PO_4^- and NO_3^-) were collected in triplicate. Immediately after collection, these seawater samples were transported to the laboratory. Dissolved inorganic nutrients were quantified from 10 mL water samples, which were first filtered through Whatman GF/F filters and then analyzed using an auto-analyzer in the oceanology laboratory.

Daily growth rate. For each study, three fronds were harvested at each interval. The thalli were collected, carefully cleaned, and weighed to determine the algal growth rate. The collected data were then used to calculate the daily growth rate (DGR), which estimates algae production over time, using the formula provided by Loureiro et al (2010):

$$\text{DGR } (\%\ \text{day}^{-1}) = \frac{(\text{Ln(final weight} - \text{initial weight))}}{\text{Growth duration}} \times 100$$

Agar extraction. After drying the collected samples at 70°C in an oven, the dried material was processed according to the method outlined by Hayashi & Okasaki (1970), with some modifications. Triplicate samples, each weighing 4 grams, were boiled for 2 hours in 100 mL of distilled water to perform an alkaline-free extraction. The agar extracted was then filtered using a vacuum pump and left to gel at room temperature. Once the gel had formed, it was frozen overnight at -10°C for 12 hours, thawed in tap water, soaked in ethyl alcohol, air-dried, and finally oven-dried at 50°C. This procedure allowed for the determination of the agar yield.

Statistical analysis. The data were subjected to a normality test (Shapiro-Wilk test), with a significance threshold set at 5%. Analysis of variance (ANOVA) was used to detect differences in biomass yield and DGR among the various experimental sets. In case of significant differences, Tukey's HSD method was employed for post hoc comparisons. Furthermore, Pearson correlation analysis was conducted to explore relationships between seasons, depth, tuft spacing, environmental factors, and DGR and yield. All statistical analyses were performed using SPSS 25.0 software.

Results

Environmental parameters. The monthly variations in the key environmental parameters at the study site are presented in Table 1. Sea water temperatures ranged from 16.41 to 23.35°C, with the highest average recorded in July and the lowest in March. Salinity levels fluctuated between 30.2 and 38.2 PSU, reaching a winter low of 30.2 PSU. Dissolved oxygen levels exhibited significant variation, reaching a minimum of 2.22 ppm in July and peaking at 6.82 ppm in spring. Turbidity also showed notable seasonal variation, with a peak of 0.97 NTU in winter. The analysis of nutrient concentrations indicated marked variations in phosphate (PO_4^{3-}) and nitrate (NO_3^{-}) levels. Phosphate values ranged from a minimum of 0.89 µM to a maximum of 4.21 µM, while nitrate concentrations varied between 1.83 and 20.38 µM.

Table 1

Environmental parameters (mean±SD) recorded at the study site (Sidi Rahal) in the morning between 09:00 and 10:00 during the years 2022-2023

Date	*Temperature (°C)*	*Salinity (PSU)*	*Turbidity (NTU)*	*PO_4^{3-} (µM)*	*NO_3^- (µM)*	*Dissolved oxygen (ppm)*
15 Sep 2022	22.65±0.12	36.40±6.53	0.50±0.04	2.51±0.52	17.07±2.16	2.31±0.87
15 Oct 2022	21.14±0.10	37.17±5.43	0.66±0.05	3.63±0.43	4.76±1.23	3.04±1.23
15 Nov 2022	19.13±0.34	36.54±6.01	0.51±0.03	3.51±0.36	3.88±0.5	3.03±1.50
15 Dec 2022	17.27±0.1	36.2±5.22	0.68±0.07	1.34±0.14	10.72±2.03	2.7±0.56
15 Jan 2023	17.22±0.23	36.37±7.32	0.41±0.03	0.90±0.06	19.24±3.58	2.31±0.23
15 Feb 2023	17.28±0.15	30.2±5.67	0.97±0.1	2.11±0.65	6.86±1.70	5.78±1.45
15 Mar 2023	16.41±0.30	37.34±4.89	0.42±0.02	4.21±0.98	4.14±0.98	6.82±1.34
15 Apr 2023	17.97±0.13	37.6±6.43	0.77±0.05	0.89±0.09	4.49±1.65	5.22±1.43
15 May 2023	20.35±0.25	38.2±7.21	0.28±0.01	1.65±0.17	20.38±5.26	4.16±1.98
15 June 2023	21.77±0.18	37.57±6.10	0.40±0.02	2.11±0.52	6.86±1.76	2.51±0.63
15 July 2023	23.35±0.29	37.23±5.13	0.40±0.01	1.04±0.12	4.49±1.20	2.22±0.54
15 Aug 2023	21.9±0.21	36.65±7.34	0.50±0.03	0.91±0.07	1.83±0.12	2.27±0.12

Seasonal effects. Fronds wet weight fluctuations were significant across the four seasons (Figure 2). After 45 days of cultivation, the maximum wet weight recorded was 749.65±15.28 g in spring, followed by summer with 603.69±11.90 g. After 60 days, the wet weight measured was 364.26±6.37 g in autumn and 485.37±18.01 g in winter. The ANOVA test indicated a significant difference in wet weight across seasons (F3,24 = 4.99, $p < 0.05$), with Tukey's post hoc test revealing a particularly notable difference between spring and autumn.

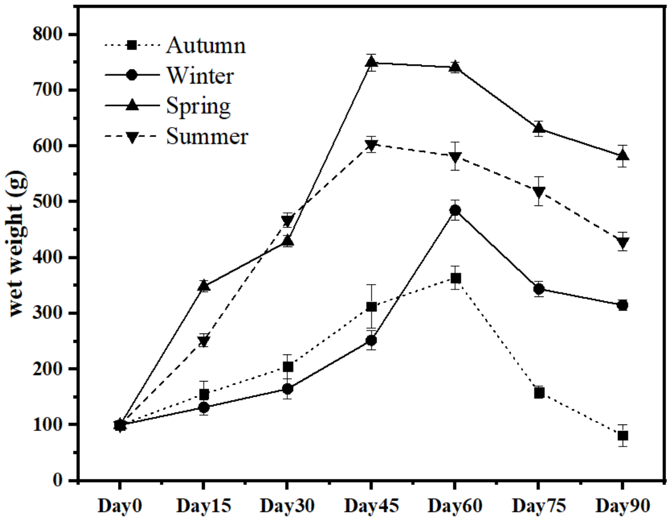

Figure 2. Seasonal variation in the wet weight of *G. gracilis* clumps.

The highest DGR was observed in spring at 14.39% day^{-1}, with summer close behind at 13.83% day^{-1}. Growth rates in winter and autumn did not exceed 10% day^{-1} (Figure 3). Statistical analyses showed a significant difference in DGRs among seasons ($p < 0.05$).

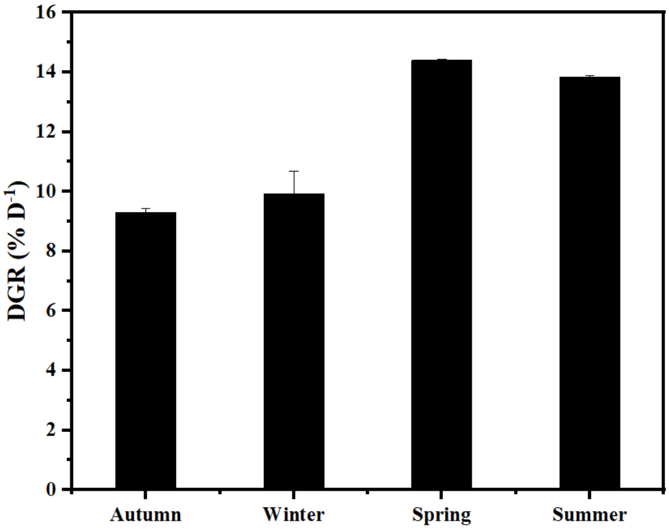

Figure 3. Seasonal variation in the daily growth rate of *G. gracilis*.

There was no significant positive correlation between biomass yield and DGR (r = 0.98, $p < 0.05$). Spring also showed the highest agar production relative to dry weight at 42.29%, followed by summer at 38.89% and winter at 35.39% (Figure 4). ANOVA confirmed a significant difference in agar quantities among seasons ($p < 0.05$). A significant positive correlation was found between the DGR and the quantity of agar produced relative to dry weight (r = 0.88, $p > 0.05$). Pearson correlation analysis revealed no significant correlation between biomass yield and environmental factors: temperature (r = 0.18, $p > 0.05$), salinity (r = 0.07, $p > 0.05$), dissolved oxygen (r =

0.21, $p > 0.05$), nitrate ($r = 0.10$, $p > 0.05$), phosphate ($r = 0.44$, $p > 0.05$), and turbidity ($r = 0.02$, $p > 0.05$).

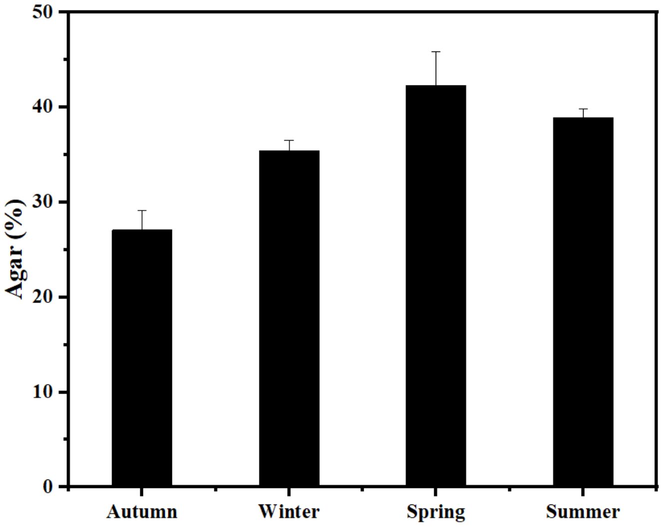

Figure 4. Seasonal variation in the quantity of agar produced in relation to the dry weight.

Effects of stocking density. After 45 days of cultivation, the wet weight of tufts spaced 40 cm apart was 835.36±13.04 g. For tufts spaced 30 cm apart, the wet weight was 749.82±11.35 g. In contrast, at 20 cm spacing, the maximum wet weight recorded after 60 days was 588±17.90 g (Figure 5). ANOVA test showed no significant differences in wet weights at these distances ($F_{2,18} = 1.79$, $p = 0.19$).

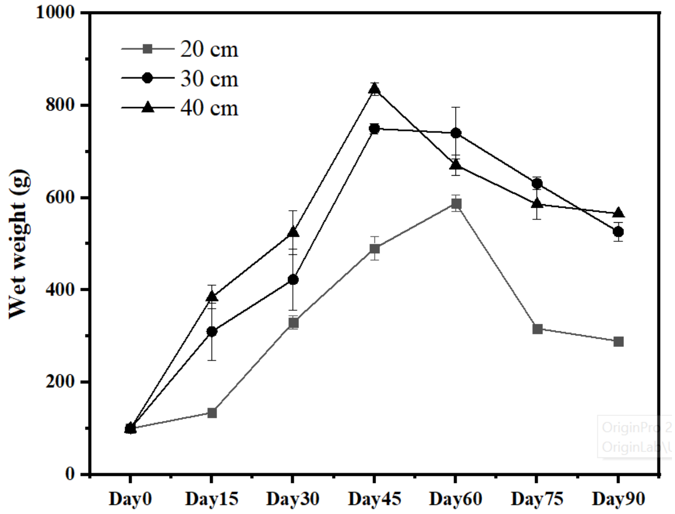

Figure 5. Variation in the wet weight of a clump of *G. gracilis* between each distance studied.

The DGR varied significantly, with a peak of 14.67±0.04% day^{-1} observed at 40 cm (Figure 6). The ANOVA test revealed significant differences in growth rates at different distances ($p < 0.05$). Pearson correlation analysis indicated no significant positive correlation between biomass yield and daily growth rate ($r = 0.99$, $p < 0.05$). The maximum agar quantity was also observed at 40 cm, followed by 30 cm (Figure 6). The ANOVA test confirmed a significant difference in agar production among the distances ($F_{2,12} = 8.92$, $p < 0.05$), with Tukey's post hoc test showing a significant correlation between the distance and the amount of agar produced ($r = 0.98$, $p > 0.05$).

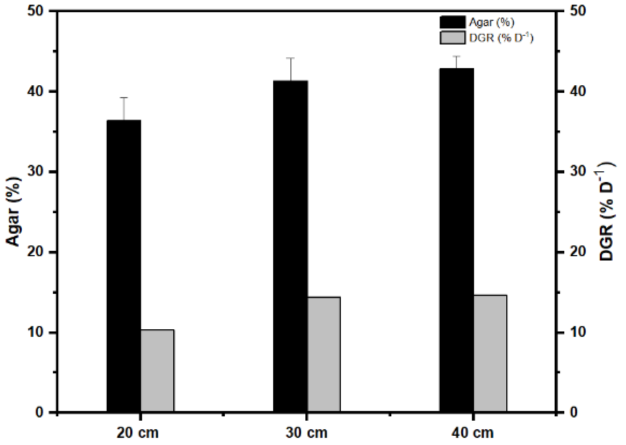

Figure 6. The quantity of agar produced and the daily growth rate of *G. gracilis* at each distance studied.

Effect of water depths. The effects of water depth on DGR and agar production are shown in Figure 7. After 45 days of cultivation, the wet weight in the deep zone (1 m at low tide) was 677.22±21.45 g, whereas after 60 days, it was 585.30±19.66 g in the coastal zone (0.5 m at low tide) (Figure 8). An ANOVA test revealed no significant difference in wet weight between the two depths (F1,10 = 0.31, p = 0.58). Similarly, no significant variation was observed in the agar yield, with percentages of 41.35±3.43% in the deep zone and 39.32±5.24% in the coastal zone. The ANOVA test confirmed no significant difference in agar percentages between the two depths (F1,12 = 0.73, p = 0.40). However, the DGR of *G. gracilis* was significantly higher in the deep zone compared to the coastal zone. An ANOVA test confirmed a significant difference in performance indices between the two depths ($p < 0.05$).

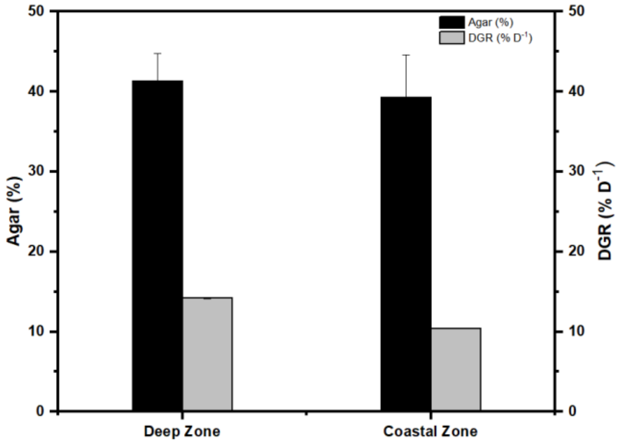

Figure 7. The quantity of agar produced and the daily growth rate of *G. gracilis* in each zone studied.

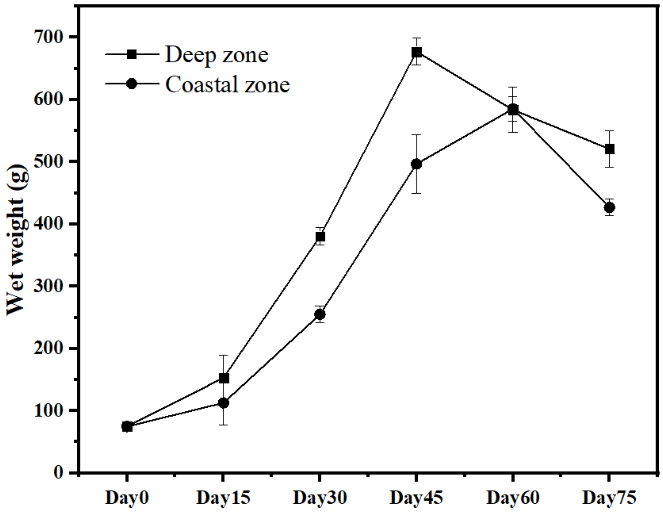

Figure 8. Variation in the wet weight of a clump of *G. gracilis* between the two areas studied.

Discussion. The increasing commercial interest in agar has prompted extensive studies on *Gracilaria* from biological, genetic, and ecological perspectives. Notably, these species are experiencing significant declines in their natural populations, making aquaculture essential to meet the rising demand for these resources. Consequently, understanding and developing *G. gracilis* farming within its environment presents challenges that could enhance production. Seaweeds live in a dynamic and complex ecological environment that can be classified as an extreme environment because abiotic (e.g., temperature, light intensity, salinity, and nutrients) and biotic (e.g., epiphytism) factors can fluctuate widely and rapidly, requiring seaweeds to adapt quickly (Cotas et al 2020). Therefore, understanding how these factors affect growth and production is essential in cultivating and managing this marine macroalgae (Njobeni 2006).

Water depth significantly impacts the growth and DGRs of *Gracilaria*, with optimal wet weight per tuft and DGR observed at a submerged depth of 1 meter. Our findings align with Mensi et al (2009), who studied *G. verrucosa* in Bizerte Lagoon (Tunisia), as well as Yang et al (2006), who reported maximum biomass production of *G. lemaneiformis* at depths of 0.5-1.5 meters in Jiaozhou Bay, China. Similarly, Buschman et al (2008) found that *Gracilaria* thrived best at 1 meter depth. Our study indicated that algae farmed in deeper zones exhibited higher wet weights per tuft and DGRs than those in coastal zones, contrary to Sobuj et al (2023), who found maximum yields of *G. verrucosa* at the surface on the coast of Cox’s Bazar in Bangladesh. This discrepancy may be attributed to light availability; deeper water likely allows for greater sunlight penetration than shallower depths. As algae require light for photosynthesis - an essential process for growth - 1 meter depth could provide optimal light intensity for *G. gracilis*, promoting its growth. Moreover, competition may be more intense at shallow depths (e.g., 0.5 m), leading to greater competition for light, nutrients, and space. In contrast, reduced competition at a depth of 1 m may enable *G. gracilis* to thrive more effectively.

Oliveira et al (2012) found that *Gracilaria birdiae* exhibited a higher daily growth rate (DGR) of 35.7% per day when grown submerged, compared to a DGR of 25.4% per day under surface farming conditions. This suggests that *G. birdiae* prefers moderate light exposure. The study also indicated that algae cultivated at the surface are more vulnerable to dehydration and excessive light stress. Veeragurunathan et al (2015) reported a slightly higher daily growth rate (2.31% day^{-1}) for submerged cultures compared to surface-grown algae, aligning with our maximum DGR of 14.22% day^{-1}. Kaladharan & Chennubhotla (1993) noted that *G. edulis* showed low biomass yields when cultured at the water's surface due to high illumination and frond desiccation. Additionally, increased UV radiation at the surface during low tide has been associated with decreased DGRs, as UV-B can damage DNA (Zacher et al 2007) and reduce photosynthetic efficiency (Hanelt et al 1997; Han et al 2003).

G. gracilis studied along the Moroccan Atlantic coast exhibited a daily growth rate of 14.39% day^{-1}, surpassing those of other *Gracilaria* species, such as *G. chilensis* (7% day^{-1}) and *G. gracilis* (5% day^{-1}) as reported by Troell et al (1997) and Anderson et al (1996). Variations in DGRs between *G. gracilis* from the Atlantic coast of Morocco and *G. chilensis* from the Pacific Ocean off Chile may be attributed to distinct environmental and ecological factors specific to each region. The quality and quantity of sunlight can also vary by geographical location and weather, influencing the light requirements for photosynthesis and growth. Genetic and ecological adaptations of algal populations to local conditions may further affect their growth potential.

G. parvispora cultured in Taiwan in floating cages from nursery-produced seedlings exhibited a DGR of 2.64% day^{-1} (Glenn et al 1998), which is significantly lower than our findings of over 14% day^{-1}. Likewise, *G. tenuistipitata* reared in ponds showed a DGR of 2.4% day^{-1} (Chaoyuan et al 1993), further emphasizing our higher growth rates. Pickering et al (1990) recorded 4-5% day^{-1} for *G. chilensis* cultivated in New Zealand. These differences can be attributed to variations in farming methods, which may vary by region based on available resources, local farming practices, and production objectives.

Water temperature, salinity, and dissolved oxygen concentration are also critical factors for the growth and production of *Gracilaria*. Most species thrive at 20°C or higher and in well-aerated conditions (Bird 1988; Choi et al 2006). In our experiments, *G. gracilis* thrived under optimal growth conditions, with a temperature range between 16.41 and 23.35°C. In a study conducted at Klein Oesterwal, Langebaan Lagoon, South Africa, it was found that the growth of *G.gracilis* was positively affected by higher temperatures, with growth measurements increasing between 22 and 30°C, but decreasing at 18°C (Beltrand et al 2022). Mensi et al (2020) reported that the optimal growth has been observed in restricted temperature ranges, between 20 and 28°C.

The dissolved oxygen levels ranged from 2.22 to 6.82 ppm. High nutrient concentrations enabled *G. gracilis* from Sidi Rahal to achieve its growth potential, mirroring the findings of Mensi et al (2009). Anderson et al (1996) reported low growth rates in environments with poor ammonium levels (< 0.01 mg L^{-1}) and minimal water movement. Based on our experience, algae, including *G. gracilis*, require nutrients for growth by supplying essential elements. Additionally, temperature appears to play a vital role in algal growth; *G. gracilis* reared at 20°C tends to be more efficient in biological processes such as photosynthesis and respiration, which promotes growth.

Our results indicated that DGRs increased with tuft spacing, consistent with findings for *G. dura* along the southeast coast of India, where maximum growth rates were observed at a density of 50 fronds m^{-2} (Veeragurunathan et al 2015). This increase can be explained by reduced competition for resources; at higher densities, *Gracilaria* tufts compete for light, nutrients, and space. Lower population densities diminish this competition, enabling each individual to access necessary resources more effectively. Interactions among individuals within a population can also influence growth and survival, with high densities potentially causing negative effects. Msuya (2013) found significantly higher growth rates for *Eucheuma dentriculatum* and *Kappaphycus alvarezii* at lower seed densities. Xu & Gao (2008) demonstrated that high density negatively affected growth rates due to competition-induced stress. Seedling density impacts growth by influencing light intensity and UV exposure; our results indicated that a spacing of 20 cm between tufts, corresponding to a higher density, recorded a DGR of 10.32% day^{-1}. Increased population densities can lead to heightened environmental stress, including competition for resources and accumulation of metabolic wastes. By reducing population density, environmental stress is alleviated, allowing individuals to better meet their metabolic needs and grow more rapidly. Ksouri et al (2000) reported a growth rate of 2.20% day^{-1} at a tuft spacing of 50 cm after 90 days of cultivation, with higher DGRs observed at closer tuft spacings. This contrasts with our findings, which show that growth rates improve with increasing tuft distance.

Regarding agar production from *G. gracilis*, our results revealed seasonal variations, consistent with studies on *Gelidium spinosum* from Monastir (Ben Said et al 2009) and *Gelidium latifolium* from the west coast of France (Roscoff) (Mouradi-Givernaud et al 1992). Sousa-Pinto et al (1999) reported that *Gelidium pulchellum* harvested from natural environments along the Portuguese coast exhibited an agar yield close to 30%. Mouradi-Givernaud et al (1999) found that the agar yield of *Gelidium sesquipedale* from the Moroccan coast varied seasonally, decreasing from 40% in spring to 36% in autumn, which aligns with our findings. Environmental factors such as water temperature, nutrient availability, sunlight, and precipitation can fluctuate significantly with the seasons, influencing the growth and metabolism of *G. gracilis* and agar production. Additionally, the seasonal life cycle of *G. gracilis* can affect its growth and biomass production. Seasonal changes may impose environmental stress on algae, impacting their physiology and agar production.

Conclusions. This study shows that *G. gracilis* thrives better under submerged conditions with moderate light exposure. Growth is further enhanced in nutrient-rich environments and at an optimal temperature of 20°C, conditions that support essential biological processes such as photosynthesis and respiration. These findings emphasize the key factors for the efficient cultivation of *G. gracilis*. Future studies should investigate long-term growth performance under diverse environmental conditions to optimize large-scale production.

In conclusion, the highest yields of algae are observed in spring and summer, likely due to more favorable environmental conditions - particularly temperature and salinity - which influence agar production. By leveraging these optimal conditions for algae farming, Morocco can achieve sustainable economic benefits and enhance the livelihoods of coastal communities.

Conflict of interest. The authors declare that there is no conflict of interest.

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