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Research Article.

Phenological and lepidochronological study of *Posidonia oceanica* along the coast of Tipaza, Algeria

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ABSTRACT

An investigation into the phenological parameters of the leaves and rhizome growth of Posidonia oceanica was carried out at a depth of 18 meters in Bou Ismail Bay (central coast of Algeria) between March and May 2024. The seawater in the study area was characterized by a suspended particulate matter of approximately 37.35 ± 6.49 mg/L and a relative abundance of particulate organic matter of around 38.5% with statistically significant spatial variation ($p < 0.05$). The mean leaf length is 419.57 ± 186.52 mm ($n = 60$; $p < 0.0001$), indicating the good health of the P. oceanica meadows. Leaves increase in width as they move outwards from the rhizome. Overall leaf area and total leaf biomass are 519.63 ± 219.90 cm^2 and 1.21 ± 0.80 g d.w., respectively, with local differences strongly linked to sampling periods. Additionally, 55.24±19.68% of leaves have lost their apex due to herbivore grazing. Furthermore, 0.74±1.61 mg of epiphyte per cm^2 of leaf is recorded. A higher number of sheaths per cycle (12) was found at Kouali in 2016, corresponding to the highest growth rate recorded (9.25 mm/year).

KEYWORDS

Magnoliophyte;
Leaf morphometry;
Epiphytic Index;
Growth of rhizomes;
Southwestern Mediterranean.

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1. INTRODUCTION

Posidonia oceanica, an endemic plant of the Mediterranean, plays a major ecological and economic role by forming underwater meadows that modify and stabilize the coastal environment. These meadows, considered as key ecosystems, are sensitive to pollution, urban and industrial discharges, and human activities such as aquaculture and trawling (Boudouresque *et al.,* 2006). They also serve as bioindicators of marine water quality due to their longevity and ability to concentrate chemical pollutants *(*Boudouresque *et al.,* 2006).

In Algeria, *Posidonia oceanica* covers a large part of the infralittoral zone, notably in the Gulf of Annaba, the Bay of Bou-Ismail, and the Gulf of Arzew, although concerning declines have been observed, particularly near urban areas (Vaissière and Fredj, 1963). This decline is mainly due to physical impacts, eutrophication, and competition with invasive algae (Marbà *et al.,* 2014). Environmental factors such as light, nutrients, and sediments also influence the state of these meadows (Boudouresque *et al.,* 2006).

The assessment of *Posidonia oceanica* meadow health and the quality of the surrounding marine environment relies heavily on the analysis of phenological parameters, which serve as sensitive indicators of the plant's physiological status and its response to environmental fluctuations. As a long-lived, slow-growing seagrass endemic to the Mediterranean, *P. oceanica* integrates the effects of both natural and anthropogenic stressors over time, making its phenological traits—such as leaf length, width, surface area, biomass, rhizome growth rates, and the number of sheaths per cycle—particularly valuable for detecting early signs of environmental degradation (Pergent *et al.,* 1994). These biometric descriptors reflect key physiological processes, including photosynthetic capacity, nutrient availability, and mechanical stress exposure, while additional indicators such as epiphyte load and herbivore grazing pressure (Coefficient A: an indicator of leaf integrity) provide insights into ecosystem functioning and trophic interactions (Leoni *et al.,* 2006). By integrating these phenological parameters, researchers can establish baseline conditions, monitor temporal trends, and evaluate the effectiveness of conservation measures. Consequently, the characterization of *P. oceanica* phenology constitutes an essential tool for assessing seagrass meadow health and, by extension, the ecological quality of coastal waters, particularly in regions where anthropogenic pressures such as sedimentation, nutrient inputs, and coastal development are prevalent.

In the environmental study of *P. oceanica*, lepidochronology provides a powerful means of assessing long-term meadow dynamics. Based on the analysis of persistent leaf sheaths preserved on the rhizome, this technique enables the reconstruction of historical growth patterns and the detection of past environmental disturbances, making it particularly valuable for evaluating the cumulative effects of anthropogenic pressures in coastal ecosystems (Rico and Pergent, 1990).

The proposed study aims to (1) evaluate the influence of changing environmental conditions, such as suspended particulate matter ‘SPM’ and particulate

organic matter 'POM' content, on the health of the *Posidonia oceanica* meadow, i.e., length, width, leaf area, dry biomass, and rhizome growth. (2) Evaluate results by calculating the A coefficient and the epiphytic index. (3) Establish the correlation between the species' biological parameters and the environmental conditions taken into consideration.

2. Materials and Methods

2.1. Study Area

A total of four sites reflecting a gradient of anthropogenic pressure were selected along Bou Ismail Bay: Tipaza Harbor (36.60° N, 2.45° E), Kouali (36.59° N, 2.49° E), Bou Ismail (36.65° N, 2.69° E), and Fouka (36.68° N, 2.72° E) (Figure 1). All samples were collected at a depth of 18 m, with Tipaza Harbor and Kouali sampled during March 2024 and Bou Ismail and Fouka during May 2024.

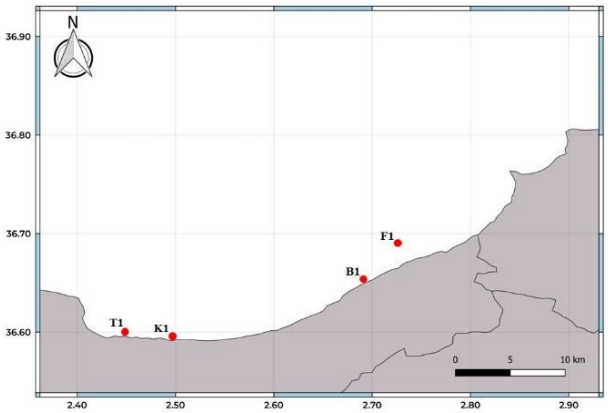

Figure 1. Sampling station of P. oceanica from the Bou Ismail Bay, Algeria. (T1: Tipaza, K1: Kouali, B1: Bou Ismail, and F1: Fouka)

2.2. Sampling

At each station, 500 mL of seawater were collected from the seagrass meadows to analyze suspended particulate matter (SPM) and particulate organic matter (POM) (Rodier, 2009).

Twenty (20) orthotropic bundles of *P. oceanica* were collected per site at 18 m depth, maintaining a one-meter distance between rhizomes to avoid duplicate sampling (Guendouzi *et al.,* 2015). Stored in a refrigerator, they were used for phenological, lepidochronological, and biomass analyses.

2.3. Suspended Particulate Matter 'SPM' and Particulate Organic Matter 'POM'

Seawater was collected at each station using a Niskin bottle, with three replicate 0.5 L samples transferred into polyethylene bottles and immediately refrigerated at 4 °C until analysis. In the laboratory, samples were filtered through 0.45 µm 'Whatman GF/F' filters; the filters were subsequently dried at 105 °C for 2 h and weighed to determine suspended particulate matter (SPM). Particulate organic matter (POM) was calculated as the mass lost upon ashing at 450 °C for 2 h, representing the difference between the dry weight and the ashed weight of the filters (Rodier, 2009).

2.4. Phenology of *P. oceanica* Leaf

Biometric and phenological studies of leaves can be used to assess the vigor of *Posidonia oceanica* seagrass beds. In the laboratory, immediately the length, width, and base of the leaves were measured using a ruler. To account for positional variations in

leaf morphology and age, leaf bundles should be kept in the same order as they were inserted following extraction from the rhizome and sheath removal. This basal portion—referred to by previous authors as the "basal part," "scale," "basal part of leaves," or "basal dead part"—is essential for accurate phenological assessments.

As leaves mature centrifugally from the rhizome center, they progressively develop a petiole. Based on the classification system of Gmnum (1977) in Giraud (1979), leaves were classified into adult (petiole ≥ 2 mm, length > 50 mm), intermediate (no petiole or petiole ≤ 2 mm), and juvenile (no petiole, length ≤ 50 mm) categories, with juvenile leaves excluded from this study.

2.4.1. Morphological Parameters of Leaf

Number of leaves per bundle: The number of leaves per bundle was determined after dissecting the rhizome and classifying adult and intermediate leaves based on their petiole. The total number of leaves was then counted for each rhizome bundle.

Leaf length and leaf width per bundle: for adult and intermediate leaves, length and width were measured in mm using a ruler.

Leaf surface area per bundle: this parameter is calculated using the following formula (Drew and Jupp, 1976):

$$LSA\ [cm^2/bundle] = mean\ leaf\ length \times mean\ leaf\ width \times number\ of\ leaves\ per\ bundle.$$

2.4.2. Leaf Biomass

Epiphytes were removed by gently scraping each leaf with a glass slide. Following cleaning, mature and intermediate leaves from each bundle were weighed individually on a precision balance (accuracy: 0.01 mg). The leaves were subsequently dried in an oven at 70 °C for 72 h and weighed again. Biomass was determined as the difference between fresh and dry weights and is reported in grams of dry weight per bundle (Giraud, 1977).

2.4.3. Coefficient A%

Coefficient A is the percentage of leaves that have lost their apex (Giraud, 1977).

$$Coefficient\ A\ [\%] = \frac{Leaves\ lost\ their\ apex}{Total\ number\ of\ leaves} \times 100$$

2.4.4. Epiphytic Index

The epiphytic index, calculated for each leaf type (adult and intermediate), is the ratio between the biomass of epiphyte and the surface of the leaf (Martínez-Crego *et al.,* 2010).

$$Epiphytic\ index\ [mg/cm^2] = \frac{Epiphyte\ biomass}{Leaf\ surface}$$

2.4.5. Sheath Length

Only adult leaves were used to measure the length of the sheath in mm using a ruler.

2.5. Lepidochronological of *P. oceanica*

The number of sheaths per cycle was determined by detaching the sheaths from each rhizome in the order

in which they appeared, from oldest to most recent (Pergent, 1987). The thickness of the sheath was assessed by touching it with the fingers (Rico and Pergent, 1990). The growth of the rhizomes was assessed by obtaining a series of segments, each one delimited by two successive thickness minima sheaths corresponding to one year. The length of each segment was measured, and the number of associated sheaths was recorded (Pergent, 1993).

2.6. Statistical Analysis

The results are presented as mean value ± s.d. (standard deviation). Data were tested for normality using the Shapiro-Wilk test and Levene's test to verify the homogeneity of variance. Since the data are not normally distributed, nonparametric tests (Kruskal-Wallis and Mann-Whitney) were used. All measured biological parameters were compared between stations using one-way analyses of variance (ANOVA). When significant differences were present, Duncan's post hoc test was performed to assess differences between treatment levels. A hierarchical clustering analysis (HCA) was conducted to better understand the similarities in the biometric parameters and morphometric indices of various bundles of *P. oceanica* collected from different locations. The correlation analysis was performed using the statistical software package STATISTICA version 13.5.0.17 for Windows, with a significance level of $p < 0.05$.

3. Results and Discussion

3.1. Environmental Parameters

Given the importance of suspended particulate matter (SPM) and particulate organic matter (POM) in regulating the growth rate of rhizomes and the abundance of epiphytes, respectively, it is crucial to measure these parameters in biomonitoring programs that use *Posidonia oceanica* as a bioindicator species.

3.1.1. Suspended Particulate Matter (SPM)

The spatial distribution of suspended particulate matter (SPM) is illustrated in Figure **2**. Concentrations ranged from 31.6 to 45.4 mg/L, with a mean of 37.35 ± 6.49 mg/L. Lower SPM values were observed at Tipaza Harbor and Kouali, likely attributable to a two-month sampling offset and the relative distance of these stations from industrial discharge sources. In the case of Kouali, weak hydrodynamics may further contribute to reduced resuspension. Elevated SPM concentrations recorded at Bou Ismail and Fouka are likely linked to multiple anthropogenic inputs, including discharges from the Tonic Emballage facility, industrial effluents from the Bou Ismail and Kolea industrial zones, runoff from the Blida watershed, and brine discharge from the Fouka desalination plant. High SPM levels prevent light penetration and reduce photosynthesis, impacting the growth of *Posidonia oceanica* meadows. Variation in SPM content is influenced by climatic conditions, the intensity of hydrodynamics, particle diameter, and continental inputs (Benhalima *et al.,* 2022).

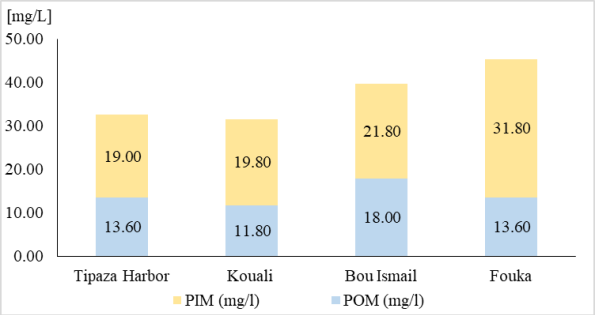

Figure 2. Content of particulate organic matter "POM" and particulate inorganic matter "PIM" in seawater surrounding the *Posidonia oceanica* meadows. Suspended particulate matter (SPM) is the sum of POM and PIM

3.1.2. Particulate Organic Matter (POM)

Particulate organic matter (POM) concentrations in seawater ranged from 11.80 to 18.00 mg/L, with a mean value of 14.25 ± 2.64 mg/L (Figure 2). The proportion of POM relative to SPM varied significantly among stations ($p < 0.05$), decreasing in the following order: Bou Ismail (45%) > Tipaza (42%) > Kouali (37%) > Fouka (30%). The highest POM content was recorded at Bou Ismail, likely attributable to intensive agriculture and urbanization, which enhance organic matter runoff into the marine environment, as well as industrial and domestic discharges from the city of Bou Ismail.

3.2. Phenology of *P. oceanica*

3.2.1. Morphological Parameters of Leaves

- **Number of leaves per bundle**

The number of adult leaves per bundle varied between stations (Figure 3.A), ranging from 1 to 4 adult leaves per bundle (n=60; $p<0.0001$). The averages are close to 3 adult leaves per bundle for the sites of Bou Ismail, Kouali, and Fouka. The number of intermediate leaves per bundle varied from 2 to 4 depending on the station (n=60; $p<0.0001$). The averages are close to 3 intermediate leaves per bundle for all sites. An equal number of adult and intermediate leaves per bundle was observed, *i.e.,* 3 leaves of each category per bundle. This could perhaps be a characteristic of the area, such as low hydrodynamics and water quality (*e.g.,* transparency). In addition, a low concentration of certain nutrients (Benhalima *et al.,* 2024) may reduce the development of epiphytic algae, which accelerates leaf weakening and fall (Wittmann *et al.,* 1981). Our results concur with those of Boudefoua and Kada (2007). In Bou Ismail Bay, the number of overall leaves per bundle varied between 4 and 8 leaves/bundle, depending on the station (n=60; $p<0.0001$). Globally, each bundle of *P. oceanica* contains 6 leaves (Figure 3.A).

- **Leaf length per bundle**

Adult leaf length values ranged from 33.66 to 791.66 mm (Figure 3.B), with a mean of 427.65±159.31 mm (n=60; $p<0.0001$). These values show a continuous upward trend in descending order as follows: Tipaza Harbor (301.02±61.35 mm) < Kouali (346.00±90.66 mm) < Bou Ismail (464.58±160.02 mm) < Fouka (598.46±111.46 mm). For intermediate leaves, total length values ranged between 125.00 and 816.5 mm (Figure 3.B), with a mean of 391.86±188.99 mm (n=60; $p<0.0001$). The mean total length of intermediate leaves decreases as ($p<0.0001$): Kouali (223.07±42.03 mm) > Tipaza Harbor (227.47±57.06 mm) > Fouka (528.71±98.26 mm) > Bou Ismail (588.20±122.47 mm). The overall leaf length ranges

from 166.67 to 1177.50 mm, with a mean of 419.57±186.52 mm (n=60; p<0.0001). The results indicate a progressive trend in leaf length, with the following order: Tipaza Harbor (264.24±96.55 mm) < Kouali (284.82±125.35 mm) < Fouka (563.58±159.60 mm) < Bou Ismail (565.64±246.93 mm). The large difference in the overall leaf length measured at the four stations is strongly linked to the sampling period. Stations sampled in March (Tipaza Harbour and Kouali) had the shortest leaves. Indeed, several studies have demonstrated seasonal fluctuations in leaf length (Panayotidis and Giraud, 1981; Pergent and Pergent-Martini, 1988).

Leaf length is one of the main parameters studied in the analysis of *P. oceanica* meadows, and it is important to consider this when assessing the health of these meadows (Leoni *et al.,* 2006; Pergent-Martini *et al.,* 2005). Average values for lengths of adult and intermediate leaves show significant variations at all stations (p<0.0001). Adult leaves are longer than intermediate leaves at Tipaza Harbor, Kouali, and Fouka stations. However, at the Bou Ismail station, the intermediate leaves are longer; this is perhaps due to the pressure exerted by or the strong hydrodynamics that characterize the area (see below the results obtained for Coefficient A). A significant correlation was observed between adult and overall leaf length (p<0.05, R=90%).

The mean values for intermediate leaf lengths at the Bou Ismail station align with those reported by Misraoui and Sengouga (2011). However, the mean values for adult leaves are lower. The mean length of adult and intermediate leaves at the Kouali station is comparable to the value obtained by Boudefoua (2011).

- **Leaf width per bundle**

The local variation in the width of the two types of leaves (adult and intermediate) is statistically significant (p<0.0001). The total width of adult leaves ranges between 9.25 and 13.00 mm with a mean of 10.95±0.76 mm (n=60; p<0.0001; Figure 3.C). The mean value of leaf width decreases as Tipaza Harbor (10.24±0.57 mm) < Fouka (11.12±0.73 mm) < Kouali (11.19±0.74 mm) < Bou Ismail (11.25±0.60 mm). For the intermediate leaves, values of width ranged from 8.83 to 11.50 mm, with a mean of 10.23±0.69 mm (n=60, p<0.0001). The results highlight a progressive trend, with a decrease in values in the following order (Figure 3.C): Bou Ismail (10.57±0.56 mm) > Kouali (10.54±0.47 mm) > Fouka (10.19±0.69 mm) > Tipaza Harbor (9.64±0.64 mm).

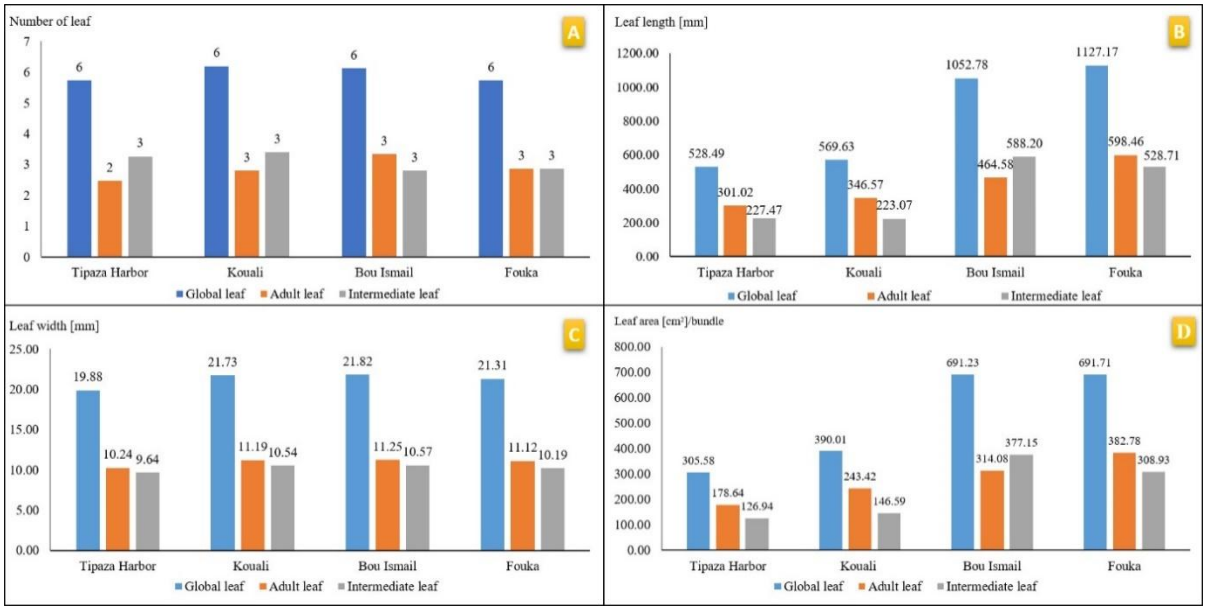

Figure 3. Morphological parameters of leaves of *P. oceanica* sampled between March and May 2024 in Bou Ismail Bay, Algeria. (**A**) Average number of leaves per bundle, (**B**) Average leaf length (mm) per bundle, (**C**) Average leaf width (mm) per bundle, and (**D**) Average leaf area per bundle (cm^2/bundle)

The average width of adult leaves is greater than that of intermediate leaves (p<0.0001), meaning that adult leaves are wider than intermediate ones. In fact, leaves increase in width as they move outwards: the oldest leaves are generally the widest, irrespective of location or season (Thelin and Giorgi, 1984). According to Dalla Via *et al.* (1998); Pergent-Martini (1994), this increase may be an adaptation to specific environmental conditions, such as nutrient enrichment or high turbidity.

- **Leaf area per bundle**

Leaf area, which integrates the length, width, and number of leaves per bundle for each leaf type (adult and intermediate), is a synthetic parameter of plant physiognomy. Values for adult leaf area ranged from 22.72 to 646.52 cm^2 with a mean of 279.72±115.50 cm^2 (n=60; p<0.0001). The data show a progressive increase between stations as Tipaza Harbor (178.64±52.95 cm^2) < Kouali (243.42±79.46 cm^2) < Bou Ismail (314.08±97.30 cm^2) < Fouka (382.78±112.39 cm^2). In addition, the leaf area of intermediate leaves ranges from 66.60 to 538.89 cm^2, with a mean of 239.90±124.91 cm^2 (n=60; p<0.0001). This parameter decreases locally as follows (Figure 3.D): Tipaza Harbor (126.94±39.25 cm^2) < Kouali (146.59±37.24 cm^2) < Fouka (308.93±86.69 cm^2) < Bou Ismail (377.15±83.75 cm^2). The area of the adult leaves was greater than that of the intermediate leaves at all stations, except at the Bou Ismail station, where the opposite was observed. Furthermore, if the nutrient supply is excessive, the proliferation of epiphytes generally leads to a decrease in leaf area per bundle of *P. oceanica* (Pergent-Martini, 1994).

For **overall leaf area**, the values ranged from 186.80 to 997.74 cm^2 with a mean of 519.63±219.90 cm^2 (n=60; p<0.0001). These results demonstrate a progressive trend, with an increase observed in the following order (Figure 3): Tipaza Harbor (305.58±83.73 cm^2) < Kouali (390.01±112.74 cm^2) < Bou Ismail (691.23±169.90 cm^2) < Fouka (691.71±157.56 cm^2). Local differences are strongly linked to sampling periods. May is usually characterized by the longest leaves and therefore the largest leaf lengths and areas. The difference in the number of leaves is linked to the rhythm of leaf formation and leaf fall, which also contribute to this result. Several authors have highlighted this trend in leaf area between seasons (Boumaza, 1995; Semroud, 1993).

The total length of intermediate/adult leaves is highly significantly correlated with the overall leaf area, with respective correlations of 82% and 78% (p < 0.05). This makes sense because the intermediate leaves are protected by the adult leaves at the tip, which are exposed to hydrodynamics and herbivores.

3.2.2. Leaf Biomass

The mean value of adult leaf biomass is 0.76±0.60 g (0.18 - 2.87 g) with (n = 60; p < 0.0001). The local variation of this parameter increases as (Figure. 4): Tipaza Harbor (0.38±0.25 g) < Kouali (0.44±0.12 g) < Bou Ismail (0.91±0.28 g) < Fouka (1.29±0.88 g). The intermediate leaf biomass values ranged from 0.06 to 1.50 g with a mean of 0.45±0.26 g (n=60; p < 0.0001). A local decrease in this parameter is as follows: Bou Ismail (0.69±0.69 g) < Fouka (0.36±0.62 g) < Tipaza Harbor (0.27±0.12 g) < Kouali (0.24±0.23 g).

The mean biomass of adult leaves is significantly higher than that of intermediate leaves at all stations (n = 60; p < 0.0001). This difference in leaf biomass is determined by the number, width, and length of the leaves. The highest values observed at the Bou Ismail and Fouka stations can be explained by the sampling period, which took place in May. Bay (1984) demonstrated that high leaf biomass values are consistently observed in summer in the Bay of Calvi.

Total leaf biomass ranged from 0.32 g to 4.38 g, with a mean of 1.21±0.80 g (n = 60; p < 0.0001). The high value was measured at Fouka (1.60±0.35 g). Although the lowest value was observed at Tipaza Harbor (0.65±0.28 g). As with leaf length and area, this trend is strongly linked to the sampling period.

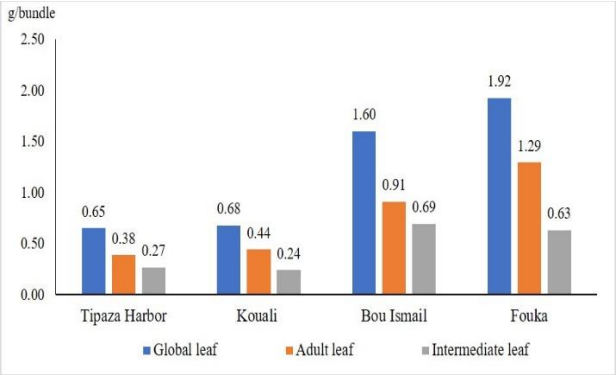

Figure 4. Global, adult, and intermediate leaf biomass of *P. oceanica* collected from the Bou Ismail Bay

3.2.3. COEFFICIENT A%

The coefficient A% is the percentage of leaves that have lost their apex. The average value of the coefficient A (%) of adult leaves is 88.47±19.05% (range: 33.33 to 100%; n=60; p<0.0001). The local A coefficient values decrease in the following order: Bou Ismail (92%) < Tipaza Harbor (89%) < Fouka (88%) < Kouali (84%). The high A% value at Bou Ismail Station may be explained by the short length of the adult leaves found at this site. The average A% coefficient for intermediate leaves is 24.17±29.06% (range: 0–100%; n = 60; p < 0.0001). These coefficient values show a decrease as follows: Fouka (15%) < Tipaza Harbor (18%) < Kouali (23%) < Bou Ismail (41%). The overall A coefficient represents all the adult leaves grazed and intermediate leaves in our study area. Its value varies between 14.29 and 100%, with an average of 55.24±19.68% (n=60; p<0.0001).

We observe that mature leaves have a higher A coefficient than intermediate leaves (p < 0.0001), which can be attributed to their position at the periphery of the bundle. Here, they are more exposed to grazing by herbivores, a factor that is further exacerbated by the presence of epiphytes (Mazzella and Russo, 1989). The A coefficient may reflect prevailing hydrodynamic conditions, particularly at shallow sites (Pergent-Martini *et al.,* 2005). For example, it can provide information on the pressure exerted by herbivores on the environment. The fish *Sarpa salpa* and the sea urchin *Paracentrotus lividus*, for instance, leave grazing marks on leaves(Pergent *et al.,* 1994). Our results show significantly higher values at the Bou Ismail and Kouali stations than those reported by Boudefoua (2011).

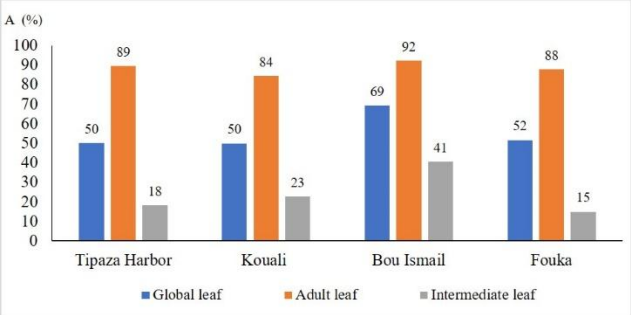

Figure 5. Coefficient A% calculate for global, adult, and intermediate leaves of *P. oceanica* collected from the Bou Ismail Bay

3.2.4. EPIPHYTIC INDEX

The average epiphytic index of adult leaves ranged from 0.04 to 12.13 mg/cm^2, with a mean of 0.62±1.55 mg/cm^2 (n=60; p<0.0001). The values of this index are similar at the Tipaza Harbour and Kouali stations, at 0.21 ± 0.13 mg/cm^2 (Figure 6). The highest value was recorded at Bou Ismail station (1.62 ± 2.92 mg/cm^2). The average epiphytic index measured for intermediate leaves ranged from 0 to 0.78 mg/cm^2, with a mean of 0.12 ± 0.15 mg/cm^2 (n = 60; p<0.0001; ANOVA). The maximum value of this index (0.28±0.13 mg/cm^2) was recorded in the intermediate leaves of the Bou Ismail station. Conversely, the lowest value (0.05±0.03 mg/cm^2) was recorded in leaves sampled at the Fouka station. The overall epiphytic index ranged from 0.06 to 12.55 mg/cm^2, with a mean of 0.74±1.61 mg/cm^2 (n=60; p<0.0001).

On average, the epiphytic index of adult leaves is higher than that of intermediate leaves, *i.e.,* epiphytes are more numerous on the oldest leaves (p<0.0001). In fact, intermediate leaves are less exposed than adult leaves (Peirano *et al.,* 2001)

because they are located inside the bundle, are more recent, and have less extensive epidermal coverage, resulting in fewer epiphytes. Epiphytic biomass is greater in areas with high levels of nutrients and/or organic matter (Pergent-Martini *et al.,* 1999). The development of epiphytes is influenced by environmental factors: temperature and light, and chemical factors such as nutrient content and organic pollution (Piazzi *et al.,* 2016).

The maximum overall epiphytic index value obtained at Bou Ismail (1.91±2.97 mg/cm^2) may be due to either the sampling period (Cancemi *et al.,* 2003) or the enrichment of the environment by organic matter (45% of SPM is POM; see Figure 2).

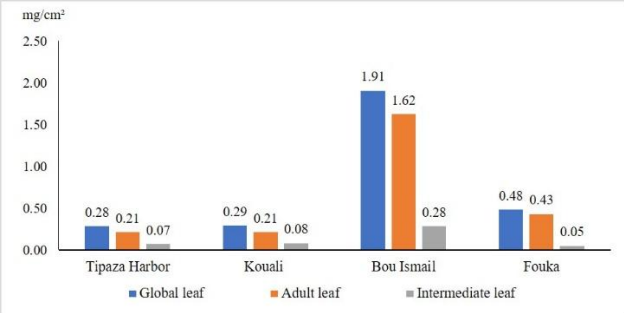

Figure 6. Epiphytic index of global, adult, and intermediate leaves of *P. oceanica* collected from the Bou Ismail

3.2.5. Sheath Length

The length of the adult leaf sheath ranged from 15.33 to 52.00 mm, with an overall mean of 35.15 ± 7.74 mm (n = 60; p<0.0001). The length of the adult leaf sheath was particularly high at the Fouka station compared to the other stations. The order from smallest to largest is as follows (Figure 7): Tipaza Harbour (30.19 ± 8.31 mm) < Kouali (34.36 ± 6.79 mm) < Bou Ismail (35.83 ± 5.89 mm) < Fouka (40.23 ± 6.87 mm). The length of the adult leaf sheath varies according to leaf rank, with the maximum length observed in the oldest leaves (Pergent and Pergent-Martini, 1988).

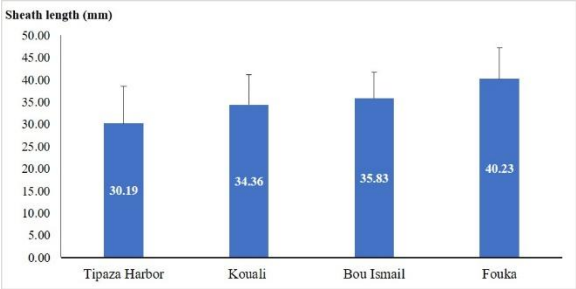

Figure 7. Length of adult leaf sheath (mm) of *P. oceanica* collected from the Bou Ismail Bay, Algeria

3.3. Lepidochronological of *P. oceanica*

3.3.1. Number of Sheaths Per Cycle

A statistically significant variation was found in the local variation of the number of sheaths per cycle (p<0.05). The average number of sheaths per cycle is ranged between 6 and 12, which corresponds to the values observed in the literature (Pergent and Pergent-Martini, 1988). The higher number of sheaths per cycle (12) was found at Kouali in 2016. While the lower (6) was recorded at Bou Ismail in 2018. The extreme values of the number of sheaths per cycle can be associated with various internal factors (physiological state or morphogenetic situation of rhizomes) or external factors (climatic conditions) (Pergent *et al.,* 1982).

Tipaza Harbor and Kouali stations show the same cycle of years, which spreads out from 2018 to 2024. Although Bou Ismail and Fouka share the same cycle

of years, which spreads out from 2016 to 2024 (Figure 8).

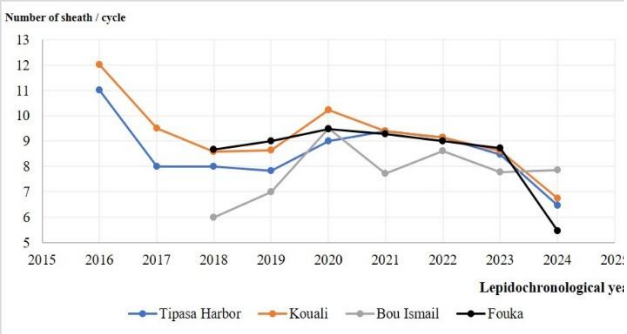

Figure 8. Average number of sheaths per cycle of *P. oceanica* collected from the Bou Ismail Bay, Algeria

3.3.2. Growth of Rhizomes

Sections of rhizome corresponding to a given year's lepidochronological cycle were obtained and used to accurately assess growth during that year (Figure 9). There were significant differences in the average growth rates of the rhizomes between the stations (p<0.05). The highest growth rates were recorded at Kouali in 2016 (9.25 mm/year) and at Fouka in 2020 (9.19 mm/year). On the other hand, the lowest average was recorded at Tipaza Harbor in 2016 (3.5 mm/year).

A rhizome growth rate of less than 7 mm/year is considered to be endogenous, meaning it is not significantly affected by sedimentary input (an external factor) that could bury the vegetative tip of the rhizome (Boudouresque *et al.,* 1984). This is the case for the Tipaza Harbor and Bou Ismail station. It may be the grain size of the sediments that influences rhizome growth at these sites. An in-depth study of grain size is strongly recommended to inform this discussion more precisely.

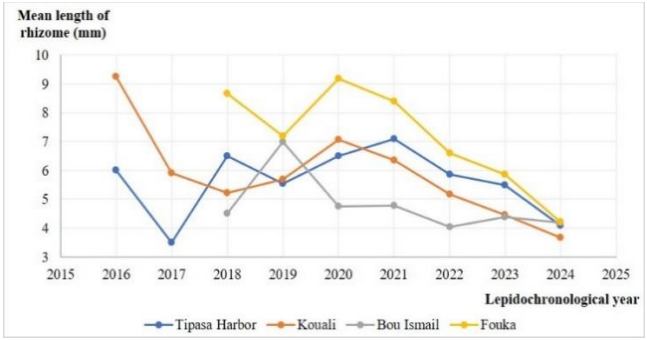

Figure 9. Average length of rhizome sections per lepidochronological year of *P. oceanica* collected from the Bou Ismail Bay, Algeria

3.4. Statistical Analysis

3.4.1. Cluster Analysis

Cluster analysis reveals two main groups (Figure 10), each of which contains several sub-groups. The first group, cluster A, comprises six phenological parameters of the leaves of *P. oceanica*: the leaf area of intermediate and adult leaves, the global leaf area, and the length of adult, intermediate and global leaves. The second group, cluster B, comprises twenty parameters, principally including leaf width, sheath length, the A% coefficient, the epiphyte index, and grazed leaves.

Cluster A is divided into two sub-clusters: sub-cluster C and sub-cluster D. Sub-cluster C comprises four parameters: adult leaf length, intermediate leaf length, global leaf length, and global leaf area. The global leaf area is linked to that of the adult and intermediate leaves, since it is the sum of them. There is also a direct correlation with the average length of each leaf type.

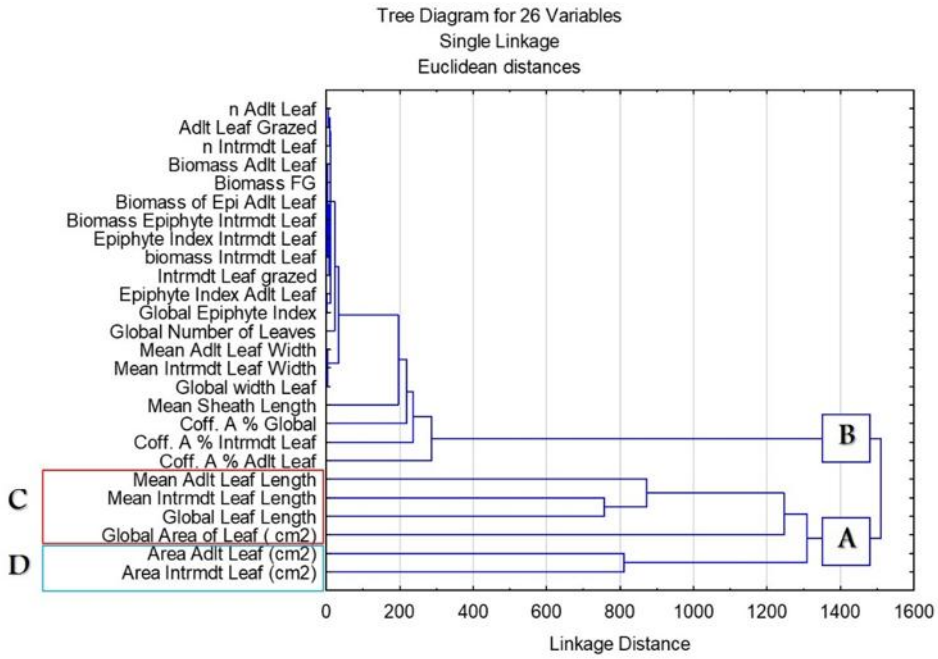

Figure 10. Cluster of phonologic parameters and indices of *P. oceanica* collected from the Bou Ismail Bay, Algeria

Leaf area integrates length, width, and number of leaves per cluster, thus constituting a synthetic parameter of plant physiognomy. Sub-cluster D comprises two parameters: adult leaf area and intermediate leaf area. These parameters demonstrate the close relationship between the areas of adult and intermediate leaves (Figure 10).

In Group B, the close proximity of the parameters mainly suggests a direct correlation, for example between the overall A% coefficient and the number of grazed adult leaves and the epiphytic index. This indicates that adult leaves are directly exposed to suspended matter. As previously observed, the A coefficient is directly linked to leaves that have lost their apex in this group. This confirms that mature leaves are particularly at risk of detachment. Hydrodynamics play a crucial role in this process. The forces exerted by ocean currents and waves are often sufficient to tear leaves off. Additionally, the pressure exerted by herbivores contributes to weakening the leaves, rendering them more susceptible to hydrodynamic forces. Therefore, the interaction between hydrodynamics and herbivore activity can explain why mature leaves are most likely to lose their apexes and be torn off.

4. Conclusion

This study investigated the phenological parameters of *Posidonia oceanica* leaves and rhizome growth at 18 m depth in Bou Ismail Bay (central coast of Algeria) between March and May 2024. The seawater in the study area was characterized by suspended particulate matter (SPM) concentrations averaging 37.35 ± 6.49 mg/L, with particulate organic matter (POM) representing approximately 38.5% of SPM and exhibiting statistically significant spatial variation ($p < 0.05$). The integration of environmental parameters SPM and POM with

phenological descriptors of *P. oceanica* (including number of leaves per bundle, leaf length, sheath length, proportion of grazed leaves, Coefficient A, and epiphytic index) confirmed a significant influence of environmental conditions on seagrass growth, supported by statistically significant correlations (p<0.05). Mean leaf length was recorded at 419.57 ± 186.52 mm (n = 60; p<0.0001), indicating the generally good health of the meadows, while overall leaf area and total leaf biomass averaged 519.63 ± 219.90 cm^2 and 1.21 ± 0.80 g d.w., respectively, with local differences strongly linked to sampling periods. Additionally, 55.24 ± 19.68% of leaves exhibited apex loss attributable to herbivore grazing, and epiphyte biomass reached 0.74 ± 1.61 mg per cm^2 of leaf.

Phenological parameters revealed clear differences between stations sampled in March (Tipaza Harbor and Kouali) and those sampled in May (Bou Ismail and Fouka). Despite this temporal variability, the Bou Ismail station was distinguished by vitality indicators suggesting an imbalance in meadow health relative to the other sites. This condition was reflected by pronounced organic enrichment, with POM accounting for 45% of SPM and a correspondingly high epiphytic load. Lepidochronological analysis indicated that the maximum number of sheaths per cycle (12) was observed at Kouali in 2016, corresponding to the highest recorded growth rate (9.25 mm/year) and coinciding with the lowest pollution levels. Conversely, the minimum sheath number was recorded at Bou Ismail, where high anthropogenic pressure—including untreated discharges, coastal development, and proximity to effluents from Tonic Emballage and the desalination plant—combined with intense hydrodynamics likely contributed to reduced growth performance. Notably, despite the various pressures documented at Bou Ismail and Fouka, the meadows exhibited robust leaf area development, suggesting favorable ecological quality. This seemingly paradoxical outcome may be explained by the configuration of the bay, which is open to waves and swell from the open sea, facilitating water renewal and mitigating the accumulation of stressors.

To accurately assess the impacts of pollution and the principal drivers of seagrass meadow decline in Bou Ismail Bay, future studies should broaden the spatial and temporal scope of investigation. Recommended measures include delineating the upper and lower limits of the meadows, extending the study area to encompass a wider range of environmental conditions, and further developing phenological and lepidochronological monitoring to establish long-term trends and inform conservation strategies.

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