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RESEARCH ARTICLE **ARAŞTIRMA MAKALESİ**

Depth-gradient biometrics of the invasive seaweed *Caulerpa taxifolia* spreading northward along the Turkish Aegean coast

Türkiye Ege kıyılarında kuzeye doğru yayılan istilacı deniz yosunu *Caulerpa taxifolia*'nın derinlik-meyilli biyometrisi

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Abstract: The presence of the invasive green alga *Caulerpa taxifolia* has been documented in the Turkish Aegean Sea, prompting a comprehensive investigation into its depth biometry and ecological interactions. This study sought to assess the distribution, density, and morphological characteristics of *C. taxifolia* at four distinct depths (10, 15, 20, and 30 m) in Dikili Bay, İzmir, during the summer of 2024. A total of 321 sampling stations were surveyed, and *C. taxifolia* specimens were identified at four locations. Sampling was performed by SCUBA divers using a 0.4 x 0.4 m quadrat. Biometric measurements included shoot density, stolon length, frond length, and number of pinnae per frond. Environmental parameters such as temperature, salinity, pH, and light intensity were simultaneously recorded to evaluate their influence on algal growth. The internodal distance (frond) on stolon exhibited a range from 18.4 mm at the 15-m depth to 38.4 mm at the 30-m depth. The maximum shoot density (1397 shoots/m^2) was recorded at the deepest sampling depth. The minimum density of 343 shoots/m^2 was observed at 15 m. The number of fronds (shoots) per stolon showed a gradual decrease with depth up to 20 m. The length of the stolons ranged from 178 mm to 355 mm, with the shortest stolon occurring in the shallowest water, followed by a gradual increase with increasing bottom depth. Frond length exhibited a range from 49.9 mm at 10 m to 87 mm at 20 m, followed by 71 mm at 30 m. Frond width remained within a narrow range of 0.855 cm to 1.1139 cm across the bottom depth. The widest frond was observed at 30 m, while the narrowest frond was recorded at 10 m. A total of 35% of the specimens examined at 10 m were found to be budded, 12% at 15 m, and 7% at 20 m, and 20% at 30 m. The number of branchlets ranged from 6-18 to 156-210, with an average of 76 to 94 and 10-12 per 1 cm frond length.

Keywords: *Caulerpa taxifolia*, invasive species, biometric, depth distribution, Turkish Aegean Sea

Öz: İstilacı yeşil alg *Caulerpa taxifolia*'nın varlığı Türkiye Ege Denizi'nde belgelenmiş olup, bu durum derinlik biyometrisi ve ekolojik etkileşimleri hakkında kapsamlı bir araştırma yapılmasını sağlamıştır. Bu çalışma, 2024 yazında İzmir, Dikili Körfezi'nde dört farklı derinlikte (10, 15, 20 ve 30 m) *C. taxifolia*'nın dağılımını, yoğunluğunu ve morfolojik özelliklerini değerlendirmeyi amaçlamıştır. Toplam 321 örnekleme istasyonu araştırılmış ve *C. taxifolia* örnekleri dört lokasyonda tanımlanmıştır. Örnekleme, 0,4 x 0,4 m'lik bir kuadrat kullanılarak SCUBA dalgıçları tarafından gerçekleştirilmiştir. Biyometrik ölçümler sürgün yoğunluğu, stolon uzunluğu, yaprak uzunluğu ve yaprak başına pinna sayısını içermiştir. Sıcaklık, tuzluluk, pH ve ışık yoğunluğu gibi çevresel parametreler, alg büyümesi üzerindeki etkilerini değerlendirmek için eş zamanlı olarak kaydedilmiştir. Stolon üzerindeki sürgün arası mesafe (frond) 15 m derinlikte 18,4 mm'den 30 m derinlikte 38,4 mm'ye kadar bir aralık gösterdi. Maksimum sürgün yoğunluğu (1397 sürgün/m^2) en derin örnekleme derinliğinde kaydedildi. Minimum yoğunluk 343 sürgün/m^2 olarak 15 m'de gözlendi. Stolon başına düşen frond (sürgün) sayısı, 20 m'ye kadar derinlikle kademeli bir azalma gösterdi. Stolonların uzunluğu 178 mm ile 355 mm arasında değişti; en kısa stolon en sığ suda meydana geldi, ardından artan dip derinliğiyle kademeli bir artış izledi. Frond uzunluğu 10 m'de 49,9 mm'den 20 m'de 87 mm'ye kadar bir aralık gösterdi, ardından 30 m'de 71 mm oldu. Frond genişliği dip derinliği boyunca 0,855 cm ile 1,1139 cm arasında dar bir aralıkta kalmıştır. En geniş frond 30 m'de gözlenirken, en dar frond 10 m'de kaydedilmiştir. 10 m'de incelenen örneklerin toplam %35'inin tomurcuklu, %12'sinin 15 m'de, %7'sinin 20 m'de ve %20'sinin 30 m'de olduğu bulunmuştur. Pinna sayısı 6-18 ile 156-210 arasında değişmiş olup, ortalama 76 ila 94 ve 1 cm'lik frond uzunluğu başına 10-12 pinna bulunmaktadır.

Anahtar kelimeler: *Caulerpa taxifolia*, istilacı türler, biyometrik, derinlik dağılımı, Türk Ege Denizi

INTRODUCTION

The Mediterranean basin, particularly the eastern basin and seas such as the Levant and Aegean, has become a notable location for the introduction and invasion of exotic species. Biological invasions have the potential to pose a significant threat to the conservation of endangered species in natural communities of plants and animals. Researchers have found that these invasions can facilitate a deeper understanding of the biometric interactions and effects of seagrasses on submerged algal communities (Ceccherelli and Cinelli, 1998). Fish, benthic fauna, and macrophytes comprise the majority of intentionally and accidentally introduced species in the eastern Mediterranean (Ceccherelli and Cinelli, 1998). The invaders are predominantly Indo-Pacific and temperate and tropical species, and they affect ecosystems already established in the Mediterranean, causing an extension of their succession and spatial changes in the ecosystem. The abundance and population growth rate of seaweeds serve as indicators of theoretical and applied processes, as they facilitate the understanding of how variations in their life history interact in isolated and mixed populations (Schemske et al., 1994). Clonal vegetative growth is a prevalent phenomenon in areas with high-density aggregations, where seaweeds forage and move to suitable adjacent spaces, undergo rapid expansion, and face a reduced risk of mortality (Wright, 2005).

A total of 143 species of marine algae have been introduced into the Mediterranean, including nine species previously (*Caulerpa taxifolia* (M. Vahl) C. Agardh; *Caulerpa racemosa* (Forsskal) J. Agardh; *Sargassum muticum* (Yendo) Fensholt; *Saccharina japonica* (Areschoug) C.E.Lane, C.Mayes, Druehl & G.W.Saunders; *Asparagopsis armata* Harvey; and *Undaria pinnatifida* (Harvey) Suringar; and *Womersleyella setacea* (Hollenberg) R. E. Norris; *Acrothamnion preissii* (Sonder) E.M. Wollaston; *Lophocladia trichoclados* (C.Agardh) F.Schmitz) and additionally *Caulerpa cylindracea* Sonder; and *Rugulopteryx okamurae* (E.Y.Dawson) I.K.Hwang, W.J.Lee & H.S.Kim and *Caulerpa taxifolia* var. *distichophylla* (Sonder) Verlaque, Huisman & Procaccini have been found to have invasive and economic impacts (Siguan and Ribera, 2002; Galanidi et al., 2023). The density of fifty species has increased in the last two decades. Nevertheless, the western Mediterranean basin contains approximately 90 nonindigenous species (of Japanese or Pacific origin) (Galanidi et al., 2023). The eastern basin, on the other hand, contains increased 72 nonindigenous species, predominantly of Red Sea or Indian Ocean origin, as updated following the inclusion of nonindigenous macrophyte species in the Mediterranean Sea (Zenetos and Galanidi, 2020; Galanidi et al., 2023) and the Turkish waters of the eastern Mediterranean (Cinar et al., 2021; Galanidi et al., 2023).

Caulerpa taxifolia (Vahl) C. Agardh (Ulvophyceae, Caulerpales) is a coenocytic (siphonous) green alga. Members of the genus *Caulerpa* are typically found in warm tropical and subtropical waters. Recently, *C. taxifolia* was reported from the northern Mediterranean Sea (Meinesz and Boudouresque, 1996). The first documented instance of *C. taxifolia* in the Mediterranean occurred in 1984, and it is believed that this species may have escaped from the tropical display aquaria of the Oceanographic Museum in Monaco (Meinesz and Boudouresque, 1996; Meinesz and Hesse, 1991). The alga has become established and is found in abundance in the northern Mediterranean, with no previous reports of its presence in tropical native regions. The invasive nature of the alga was demonstrated by its remarkable spread: by the end of 1996, an area of 3096 ha had been colonized by *C. taxifolia*, most of which was recorded off the coasts of France and Italy (between Toulon, France and Alassio, Italy) (Meinesz et al., 1997). Numerous isolated occurrences have been documented in Italy (Liguria, Elba, Sicily), Croatia (Isle of Hvar, Isle of Krk), Spain (Balearic Islands) (Meinesz and Boudouresque, 1996), and Tunisia (Meinesz et al., 2001), and Türkiye (Gulf of İskenderun) (Cevik et al., 2007) (Gulf of İzmir) (Turan et al., 2011). *C. taxifolia* in the Mediterranean is regarded as a significant threat to native flora (and fauna) due to its rapid growth rate and production of secondary metabolites, many of which are toxic (Lemée et al., 1993; Meinesz et al., 1993).

The species *C. taxifolia* is grazed by certain species of grazers, including *Oxynoe olivacea* (Gianguzza et al., 2007) and *Elysia subornata* (Thibaut et al., 2001) and the sea urchin *Paracentrotus lividus* and the fish *Sarpa salpa*, as previously documented by Lemée et al. (1996) and Boudouresque (1997). It is a poor substrate for epiphytes for most of the year. The alga has been observed to cover up to 100% of the substrate across a range of depths, primarily between 0 and 50 meters (although it has been recorded at 100 meters), and on diverse substrate types (Meinesz et al., 1993; Belsher and Meinesz, 1995; Meinesz et al., 1995). Komatsu et al. (1997) demonstrated that *C. taxifolia* from the northern Mediterranean Sea exhibited survival capacity across a temperature range of 10 to 31.5 °C, with optimal irradiance levels ranging from 88 to 332 μmol $m^{-2}.s^{-1}$. The authors of the study posited that the Mediterranean strain of *C. taxifolia* possesses considerable potential for expansion throughout the Mediterranean region and for invasion into adjacent tropical and temperate seas (Gillespie et al., 1997). However, following its initial proliferation, *C. taxifolia* has undergone a shift in its kinetic phase, resulting in a substantial decrease or stabilization of its distribution across most regions of the Mediterranean Sea. Consequently, it is no longer regarded as a threat to the same extent as previously observed (Montefalcone et al., 2015).

In addition to aquaria, ships and fishing gear have been identified as significant vectors for the dissemination of *C. taxifolia* through fragments of the species destroyed by anchoring within and between localities (West et al., 2007; Relini et al., 2000). A notable distinction between the life cycle of *C. taxifolia* and that of other Mediterranean macrophytes pertains to the timing of its peak biomass, which occurs in the autumn, a season coinciding with the decline in productivity of autochthonous algae (Ballesteros, 1989). This phenomenon, characterized by the reduction in photophilic algal communities, has been shown to facilitate competition (Verlaque and Fritayre, 1994). During the winter months, the minimum biomass consists of a dense network of thick stolons with short, highly branched primary axes (Meinesz et al., 1995), which still completely cover the substrate and ensure algal regrowth in spring (Komatsu et al., 1997).These characteristics lead to a modification of habitat structure with various direct or indirect consequences for flora and fauna (Boudouresque et al., 1995).

In the ecosystem, the species has a role, effect, and impact; *C. taxifolia* changes the shoot density and orthotropic/plagiotropic rhizomes ratio of *P. oceanica* (Molenaar et al., 2009). When *P. oceanica* coexists with *C. taxifolia*, it reduces leaf length and biomass, while *C. taxifolia* increases frond length (Pergent et al., 2008). However, the presence of *C. taxifolia* did not significantly affect *Cymodocea nodosa* shoot density, and an increase in nutrient availability in the sediment did not alter this pattern (Ceccherelli and Sechi, 2002). A slightly insignificant effect on fish fauna biomass occurred only in a colonized *C. taxifolia* sample (Francour et al., 1995). The invasion of *C. taxifolia* did not cause significant changes in the density of the main taxa forming the macrobenthic community (Caronni, 2011). However, *C. racemosa* affects macroalgal communities more than does *C. taxifolia* when cooccurring with *C. racemosa* (Piazzi et al., 2003; Balata et al., 2004). Furthermore, *C. taxifolia* has been observed to impact the invertebrate fauna inhabiting *Posidonia* beds following its invasion (Francour et al., 2009) and within soft-bottomed environments (McKinnon et al., 2009).

A variety species of *C. taxifolia*, *Caulerpa taxifolia* var. *distichophylla* has been documented along the Turkish coastline, with occurrences reported in İskenderun Bay (Cevik et al., 2007) and Antalya Bay (Mutlu et al., 2022), Alanya Bay, Kaş Bay, Sea of Marmara (Taşkın et al., 2023), and the Aegean coast (Mutlu et al., 2025a). Cevik et al. (2007) reported the occurrence of *C. taxifolia* from İskenderun Gulf, located in the eastern Mediterranean waters of Türkiye. However, this species was subsequently corrected by Jongma et al. (2013) to be *C. taxifolia* var. *distichophylla*. The initial documentation of *C. taxifolia* in Turkish Aegean waters was reported from Uzunada Island with a special permission to study at one bottom depth from Turkish Republic Navy Forces Command, in İzmir Gulf (Turan et al., 2011). Subsequent to the initial documentation of *C. taxifolia* in the Aegean Sea by Turan et al. (2011), the present study, which examines a subsequent occurrence of the species extending northward in the Turkish Aegean Sea, has yielded substantial insights into the morphological and biometric characteristics of this invasive species. The species occurred second times in the Aegean Sea as well as the eastern Mediterranean basin. Of the 321 SCUBA sampling stations deployed during the present study, however, the species occurred only at four different bottom depths of one site, Dikili Bay. Therefore, the present study was designed to provide an exhaustive biometric analysis of *C. taxifolia* across the depth gradient and to compare distinguished biometrics with congeneric species, *C. taxifolia* var. *distichophylla*.

MATERIALS AND METHODS

Specimen and environment sampling

A research cruise was conducted to ascertain the distribution and species composition of seagrasses and seaweeds as submerged vegetation along the Turkish coast of the Aegean Sea from May to August of 2024 (Figure 1). During the survey, which was conducted during daylight hours, 321 stations were sampled. In August of 2024, four stations recorded the presence of *Caulerpa taxifolia*. The stations were located in Dikili Bay, İzmir, Aegean Sea, Türkiye (Figure 1).

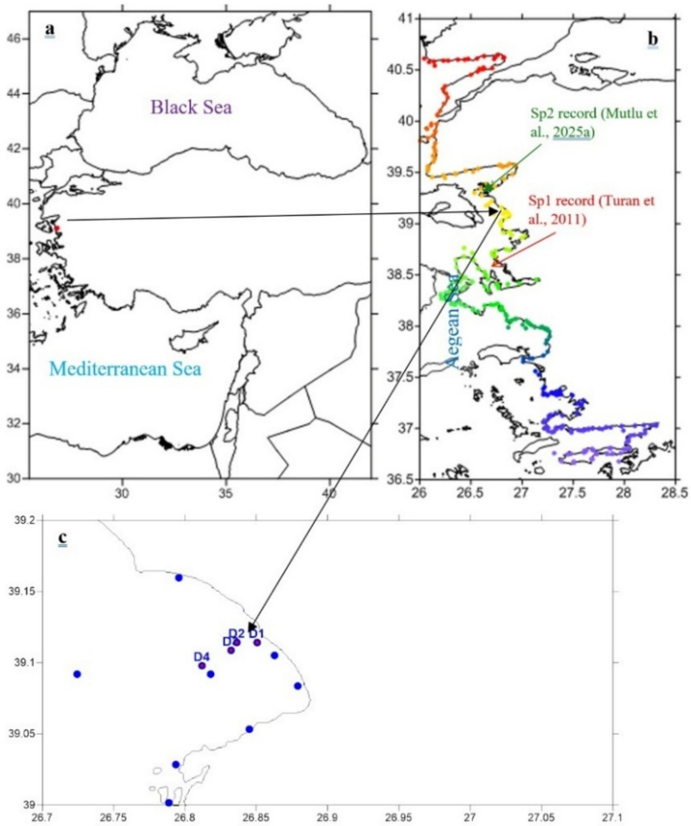

Figure 1. Study area (a, b), sampling stations (b) colored basing the geographic latitude and stations in Dikili Bay where *Caulerpa taxifolia* occurred (D1-D4 in red circle) (c). Red arrow denotes the first occurrence of Sp1: *C. taxifolia* in the Aegean Sea (Turan et al., 2011), and dark green Sp2: *C. taxifolia* var. *distichophylla* (Mutlu et al., 2025a) during the present survey (Appendix Figure A1)

A transect was meticulously established from the shore to the seaward side at four different bottom depths (10, 15, 20, and 30 m at stations D1, D2, D3, and D4, respectively). At these stations, runner stolons of specimens were triply replicated and collected by SCUBA divers in a 0.4 m × 0.4 m quadrat. On board the *R/V Akdeniz Su,* the tangled fronds, stolons, and rhizoids were untangled and prepared for biometric measurements (Figure 2). Measurements were taken from fresh, unpreserved specimens.

Figure 2. *Caulerpa taxifolia* appearance on entire specimens (a and b) and close-up view of fronds (c and d). F: frond, St: stolon, Rh: rhizoid, FL: frond length, FW: frond width, P: pinnae, R1: rachis 1, and R2: rachis 2. Specimen in Figure 2c could be scaled from same specimen indicated by a arrow in Figure 2e

During the shipboard sampling, physicochemical parameters (temperature, salinity, pH, oxygen, and total suspended solids) and optical parameters (Secchi disk depth and photosynthetically active radiation, PAR) were measured from surface and near-bottom waters. Water samples were collected on board using a 5-liter Niskin bottle, and the physicochemical parameters were measured using multiparameter probes (AZ Combo, model 84051). The PAR was measured using an ampoule (Spherical SPQA-4671 model, LI-COR, Inc.) and a multiparameter recorder (LI-1400 model). The D1 sample was collected at 12:40, the D2 sample at 12:13, the D3 sample at 11:40, and the D4 sample at 09:07. The ampoule was casted with the cable from the surface to the near-bottom depth, and the profiled PAR values were subsequently converted to percent values with respect to the sea surface value as 100% throughout the water depth.

Biometrical measurements

The material examined included unpreserved specimens, with eight stolons and 88 fronds at D1, six stolons and 75 fronds at D2, five stolons and 76 fronds at D3, and five stolons and 95 fronds at D4. The total frond count at D1, D2, D3, and D4 was 63, 67, and 87, respectively. The fronds were collected at locations specified by geographical coordinates: 39.1142° N and 26.85061° E, 39.11427° N and 26.83638° E, and 39.10874° N and 26. 83232 E, and 39.09793 N and 26.81195 E from depths of 10, 15, 20, and 30 m by SCUBA diving, respectively, on August 8, 2024, by Yaşar Özvarol and Barış Akçalı.

The biometry was characterized by the following parameters: density (number of shoots/m^2 and per quadrat; TS, buds: leaf or frond growing from main frond; BNo, internodal distance: the distance between two fronds along a stolon; IND, number of fronds per stolon; FNo, number of stolons; #S, number of paired rachises or pinnae (ramuli) per rachis and per 1 cm rachis; #F, leaf area: frond width x length; LA) and morphometry (stolon length; SL, frond length: FL, and frond width: FW) of the samples (Figure 2). The morphometric parameters were measured with an accuracy of µm using a caliper. Additionally, the buds on the fronds were enumerated, and the biometric parameters were measured.

Statistical interpretation of biometrics

In order to ascertain the biometric characteristics of the species, the relationships between frond length-width and frond length-number were established using Pearson correlation and regression models. Subsequently, differences in the frond length-number of pinnae relationships among the bottom depths were tested using analysis of co-variance (ANOCOVA). Following the testing of normality (dispersion index, randomness test, FAO, 1991), all the biometric variables were subjected to an analysis of variance (ANOVA) to determine differences among the four sampling depths and a post-hoc test (Least Significant Difference, LSD) was then applied. Spearman's correlation coefficient was employed to assess the relationship between biometric data and environmental variables. The confidence level established for the statistical significance of the tests was $p < 0.05$. All analyses were conducted using the statistical software MATLAB (version 20221a, MathWorks, Inc.).

RESULTS

Study environment

A total of 321 sampling stations were surveyed, and four of these stations (D1 at 10 m, D2 at 15 m, D3 at 20 m, and D4 at 30 m; Table 1) were located in coastal waters around the town of Dikili in the city of İzmir. The study area was frequently visited by recreational boats, vacationers and tourists.

Table 1. Minimum, maximum, mean and standard deviation values of the morphometrical variables of *C. taxifolia* at the depths three times replicated (Rx) for the sampling. S#: number of stolons per quadrat, SL: stolon length in mm, FNo: number of fronds per stolon, FL: frond length in mm, FW: frond width in mm and IND: internodal distance in mm. nd is not detected in the specimens

		SL	FNo	FL	FW	IND	SL	F#	FL	FW	IND	SL	F#	FL	FW	IND
				R1					R2					R3		
S#	D1	33														
Min		35	1	5	2.45	4	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Max		570	19	181	18.5	74	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
S#	D2	5					3									
Min		130	3	8	2.4	1	130	8	14	3.44	3	nd	nd	nd	nd	nd
Max		557	28	170	17.6	54	350	17	142	15.13	67	nd	nd	nd	nd	nd
S#	D3	28					2									
Min		178	1	7	2	1	493	30	12	2.8	3	nd	nd	nd	nd	nd
Max		533	21	166	13.3	64	493	39	250	18.1	53	nd	nd	nd	nd	nd
S#	D4	95					13					36				
Min		150	1	7	2.9	3	45.3	1	4.2	3	3	45.3	1	5.9	2.9	7
Max		908	46	171	17.8	134	740	13	174	107.4	122	740	14	164	16	103

Mutlu et al. (2025a) provided a comprehensive overview of the physical properties of the waters throughout the study area. These properties included sea surface temperature variations ranging from 20.5 to 28.5°C and near-bottom water temperatures fluctuating between 18 and 28°C. The presence of cold water in the Black Sea and the Sea of Marmara was observed in the Dardanelles Strait exit in the Aegean Sea, while warmer water was identified in the northern part of the Aegean Sea. The impact of the river Meriç was evident in this region, where less saline water was recorded (Figure 3).

The sea surface temperature of Dikili Bay was approximately 25.5 °C. However, a decrease in sea surface salinity was observed from the coast (34 PSU) to the open waters (32 PSU), with the exception of the Black Sea water in the northernmost Aegean Sea (Figure 3). The pH of the sea surface ranged from 8.35 to 8.4, while the pH of the near-bottom water varied from 8.4 to 8.45. Within Dikili Bay, the dissolved oxygen levels in surface waters exhibited moderate values ranging from 7.4 to 11.2 mg/L, and the total suspended solids levels varied from 23 to 27 mg/L (Figure 4). These measurements were obtained across the entire study area.

The salinity exhibited a gradient of decreasing values from south to north within the study area, a trend that was more pronounced in the near-bottom waters. Conversely, the oxygen content and pH levels exhibited a slight increase from south to north, contrasting with the variation in total suspended solids (Figure 4).

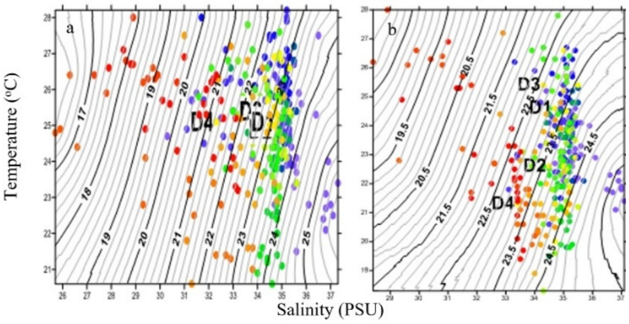

Figure 3. Sea surface (a) and near-bottom water (b) T-S diagram with isoclines of density, σ_t, at the stations colored according to geographical latitude (see Figure 1b for the station locations)

With respect to the sea surface water, the TS diagram revealed that the temperatures at stations in Dikili Bay were comparable, yet D4 (σt=21.5) exhibited a divergence from D1, D2, and D3 with respect to water density (σt=23). In contrast to the surface waters, the near-bottom waters at the four stations exhibited distinct salinity and temperature values, yet shared the same temperature value of σt=23.2 (Figure 3).

Along the transect with D1-D2, which exhibited a vertical distribution of water temperature, the warmest water body was located within the first 10 meters, followed by the seasonal thermocline in the second layer from 10-15 meters to 20 meters, and the coldest water body started after a water depth of 20 meters (Figure 4).

The open station (D4) exhibited lower levels of saline surface water, with a gradual increase in salinity toward the coastal waters. In the initial five meters of the bottom, the salinity exhibited a decrease from the surface, followed by a slight increase up to fifteen meters and a subsequent gradual decrease up to thirty meters (Figure 4). The total suspended solids (24-25.6 mg/l) and pH (8.3-8.5) exhibited analogous vertical profiles to those of the salinity, while the oxygen profile exhibited contrast with that of temperature (Figure 4). The coastal water had a lower irradiance value (PAR) than did the open waters of Dikili Bay. The Secchi disk depth exhibited a strong correlation with an irradiance value of 4.6 mol photons/cm²/s, indicating the presence of an euphotic zone extending from 5 to 2.5 m from D1 to D4. The lowest percentage value (99.64%) was observed at a water depth of 20 m, as depicted in Figure 4.

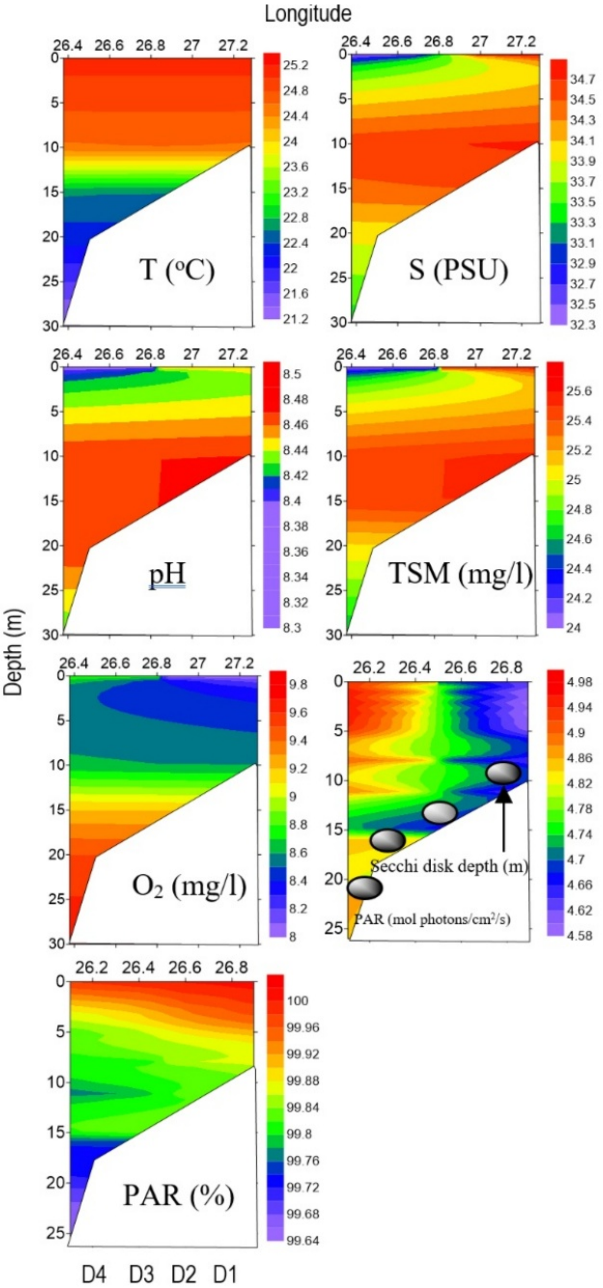

Figure 4. Profiles of water temperature in °C, salinity in PSU, pH, dissolved oxygen in mg/l, total suspended matter in mg/l, PAR in mol photons/cm²/s and percent across D1 to D4 across geographical longitudes

Plan traits

Caulerpa taxifolia (M.Vahl) C.Agardh is a green macroalga belonging to the class Ulvophyceae (subkingdom Viridiplantae, kingdom Plantae).

Description

The plants were characterized by a green, prostrate axis (stolon) with downward-growing colorless rhizophores, which were attached to a hard substrate or anchored in the unconsolidated substrate (Figure 2).The stolons were smooth (glabrous) and produced erect photosynthetic fronds (assimilators). The assimilators constituted a central axis (rachis) bearing lateral branches (ramuli or pinnae) in a distichous configuration and a sickle shape (falcate) on a pedicel (Figure 2). The rachises exhibited regular constrictions (annulations). The basal part of the ramuli attached to the rachis was constricted and contracted (Figure 2). The maximum frond length ranged from 16.6 to 18.1 cm, and the frond width ranged from 13.3 to 18.5 mm. The number of branchlets varied between 6-18 and 156-210, with an average of 76 to 94 and 10-12 per 1 cm frond length, respectively. The relationship between frond length and the number of branchlets was found to be best fit by a slope of less than 1 (Figure A2).

Remarks

It has a similar structure to *Caulerpa mexicana,* and both *C. mexicana* and *C. taxifolia* have distichous fronds, but *C. mexicana* has a type between clavate and club-shaped (wider than tip parts of ramuli) falcate ramuli, and *C. taxifolia* has a variant of falcate, sickle-shaped ramuli. The basal part of the ramuli of both species contracts, but it is not contracted in *C. taxifolia* var. *distichophylla* (Verlaque et al., 2015). For *C. taxifolia*, the maximum frond length ranged from 16.6 to 18.1 cm, and the width ranged from 13.3 to 18.5 mm. The number of branchlets varied from 6-18 to 156-210, with an average of 76 to 94 and 10-12 per 1 cm frond length. The slope of the relationship between frond length and the number of branchlets was estimated to be 2.15 greater than 2 for *C. taxifolia* var. *distichophylla* (Mutlu et al., 2025a). The slope of the relationship between frond length and number of branchlets was estimated to be less (0.81-0.97) than 1 for *C. taxifolia* (Table A1, Figure A2).

Distribution

In addition to the previous record in the Gulf of İzmir, Aegean Sea (Figure 1), *Caulerpa taxifolia* was collected from four different locations in the shallow and coastal waters of the Aegean Sea (Dikili Bay, Türkiye). The distribution ranged from 10 m to 30 m.

Biometrics

The biometric parameters of the species were recognized as density and morphometric variables to characterize the recent measurements made from the live specimens that occurred for the second time in the Aegean Sea. Basic descriptive statistics of the biometric variables of *C. taxifolia* are presented in Table 1. The number of stolons recorded at each depth interval is listed in Table 1. At 10 m (D1), the number of stolons was 33; at 15 m (D2), it was 3–5; at 20 m (D3), it was 2–28; and at 30 m (D4), it was 13–95 stolons per quadrat.

Density

The internodal distance (IND) is indicative of the rarefaction and densification of shoot density. The IND exhibited a range of values between 18.4 mm, measured at the 15-m depth, and 38.4 mm, measured at the 30-m depth (Table 2). A positive correlation was observed between the IND and depth, with an increase in IND with decreasing depth after 10 m (Figure 5). The first two depths exhibited slightly greater variations in the IND measurements compared to the deeper depths. The IND exhibited a significant and negative correlation with the sea surface total suspended solids and near-bottom pH (Table 3).

The LSD test revealed that the internodal (shoot) distance (IND) was minimal at bottom depths of 15 and 20 m, where a significant difference in IND was observed compared to bottom depths of 10 m and 30 m (Figure 5). The IND was found to be significantly differentiated by bottom depth (Figure 5).

Table 2. Depthwise distribution of density variables for *C. taxifolia* (mean±SD). IND: internodal distance (mm), LA: leaf area per quadrat (cm^2), TS: shoot density (fronds/m^2), LAI: leaf area index (m^2/m^2, and FNo; number of fronds per stolon

Depth	IND	LA	TS	LAI	FNo
10	23.1±1.1	5.56*10^{-4}±3.09*10^{-5}	560±330	3.43±4.82	11.0±0.6
15	18.4±1.2	8.17*10^{-4}±3.91*10^{-5}	343±330	3.89±4.82	10.5±1.1
20	19.9±0.9	9.78*10^{-4}±3.39*10^{-5}	431±572	25.38±8.36	10.2±1.0
30	38.4±0.9	9.01*10^{-4}±3.33*10^{-5}	1397±330	16.83±4.82	7.4±0.6

Leaf area (LA): In contrast to the actual leaf area of seagrass leaves, *Caulerpa* species, except for *C. prolifera*, had fronds and ramuli that did not reflect the total leaf area. LA exhibited an increase with depth, ranging from an estimated 5.56*10^{-4} m^2 at 10 m to 9.78*10^{-4} m2 at 20 m, followed by 9.01*10^{-4} m^2 at 30 m (Table 2, Figure 5). However, LA and leaf area index (LAI) were not correlated with any of the other environmental parameters (Table 3). LA per quadrat is a function of frond length and width and was a minimum of 5 m. LA was significantly different among the bottom depths (Figure 5). The maximum LA was found at 20 m, followed by a depth of 30 m (Figure 5).

Shoot density (TS): In contrast to the IND treatment, the maximum shoot density (1397 shoots/m^2) was found at the deepest sampling depth (Table 2), while the minimum density of 343 shoots/m^2 occurred at 15 m. The TS exhibited a tendency to increase seaward by 15 m (Figure 5). Furthermore, a negative correlation was observed between TS and sea surface salinity, total suspended solids, and near-bottom pH at a significance level of $p < 0.05$ (Table 3). However, no significant differences in TS were detected among the different bottom depths. Notably, TS at 30 m showed a significant increase compared to 15 m (Figure 5).

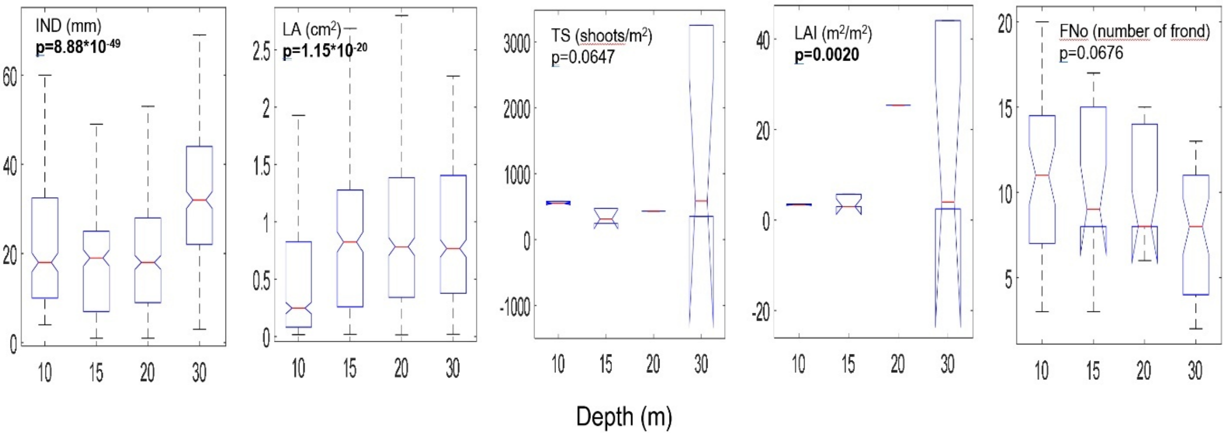

Figure 5. Notch plots of density variables of *C. taxifolia* at the sampling depths. TS: number of shoots per sampler, LAI: single-sided leaf area index (cm^2/m^2), and FNo: number of fronds per stolon. The bold p value denotes a significant difference in the variable among the bottom depths, in other words, from station D1 to D4

The leaf area index (LAI) exhibited a significant increase in the deeper layers of the water column, reaching a maximum at 20 m and then decreasing at 30 m (Table 2, Figure 5). This increase in LAI at 20 m was notably higher compared to the values at 10 and 15 m (Figure 5).

The number of fronds per runner (FNo) also showed a distinct pattern. The number of fronds (shoots) per stolon exhibited a gradual decrease with depth up to 20 m, with the lowest recorded number of fronds per stolon observed at 30 m within the study area. FNo demonstrated a positive correlation with salinity, pH, total suspended solids in surface waters, and pH in near-bottom waters, and a negative correlation with bottom depth (Table 3). However, FNo exhibited no significant change with bottom depth, although a notable difference in FNo was observed between 5 and 30 m (Figure 5).

Number of stolons (#S): The number of stolons per quadrat exhibited a tendency to increase with depth greater than 10 m, reaching a maximum of 95 stolons per quadrat at 30 m.

Table 3. Spearman correlation coefficients between the biometrical variables and sea surface and near-bottom water environmental variables (T: temperature, S: salinity: S, TSM: total suspended matter, DOx: Dissolved oxygen, Depth: bottom depth). Bold coefficients denote significant correlations between the variables at $p < 0.05$ (sample size, n = 4)

	Sea surface water					Near-bottom water					
	T	S	Ph	TSM	DOx	Depth	T	S	Ph	TSM	DOx
SL	0.3913	-0.6662	-0.7685	-0.6518	0.3617	0.871	**-0.9552**	-0.8644	-0.5335	-0.7824	**0.9908**
FL	0.6047	-0.2917	-0.421	-0.2788	-0.0877	0.5788	-0.7449	-0.5949	-0.1187	-0.4927	0.8301
FW	-0.2631	-0.7383	-0.8061	-0.7142	0.7658	0.8243	-0.9267	-0.7496	-0.7121	-0.6732	0.8475
IND	-0.0361	-0.9449	-0.8845	**-0.9519**	0.8792	0.79	-0.5164	-0.7911	**-0.9769**	-0.8573	0.4786
LA	0.4291	-0.4702	-0.5953	-0.4529	0.1606	0.7296	-0.8902	-0.7222	-0.3197	-0.6174	0.9381
TS	-0.0253	**-0.956**	-0.9006	**-0.9622**	0.882	0.8113	-0.5464	-0.8116	**-0.9829**	-0.8732	0.5097
LAI	0.849	-0.4481	-0.5253	-0.4513	-0.0536	0.6461	-0.6235	-0.7103	-0.2781	-0.6735	0.7494
FNo	-0.0175	**0.9956**	**0.9933**	**0.9917**	-0.8777	**-0.9564**	0.8061	0.9395	**0.979**	0.9492	-0.7714

Morphometry

The morphometry of *C. taxifolia* included stolon length (SL), frond length (FL), and frond width (FW).

Stolon length (SL): The length of the stolons ranged between 178 mm and 355 mm, with the shortest stolon occurring in the shallowest water. A gradual increase with increasing bottom depth was observed (Table 4, Figure 6). However, a negative correlation between SL and the near-bottom water temperature was observed at a significance level of $p < 0.05$ (Table 3). The stolon length exhibited significant variation across different bottom depths. The shortest length was recorded at 10 m, and at greater depths, the stolon length did not differ significantly. The length of the stolons gradually increased with increasing bottom depth (Figure 6).

Frond length (FL): A similar trend was observed in frond length along the bottom gradient (Table 4, Figure 6), ranging from 49.9 mm at 10 m to 87 mm at 20 m, followed by 71 mm at 30 m. However, none of the environmental parameters exhibited a significant correlation with variations in FL (Table 3). A significant relationship was identified between frond length and bottom depth (Figure 6). FL exhibited an increasing trend up to a depth of 20 m, followed by a decrease at 30 m. The minimum length was recorded at 10 meters. Notably, the FL exhibited no significant variation between 15 m and 30 m (Figure 6).

Table 4. Depthwise distribution of morphometrical variables of *C. taxifolia* (mean±SD). SL: stolon length in mm, FL: frond length in mm and FW: frond width in mm

Depth	SL	FL	FW
10	178.5±26.3	49.9±2.0	0.855±0.021
15	277.2±37.2	67.5±2.5	1.063±0.025
20	347.4±34.4	87.1±2.2	0.979±0.022
30	355.1±25.7	71.8±2.1	1.139±0.021

Frond width (FW): In a manner analogous to FL, frond width exhibited no significant correlation with any of the other environmental parameters (Table 3). Furthermore, it remained within a narrow range of 0.855 cm to 1.1139 cm (Table 4). The frond with the greatest width was observed at a depth of 30 m, while the narrowest frond was measured at 10 m (Table 4, Figure 6). A significant decrease in FW was observed at 5 m compared to the other depths (Figure 6). FW exhibited an increase from 10 m to 15 m, followed by a decrease at 20 m and an increase at 30 m. The variation in FW among the different depths was found to be statistically significant (Figure 6).

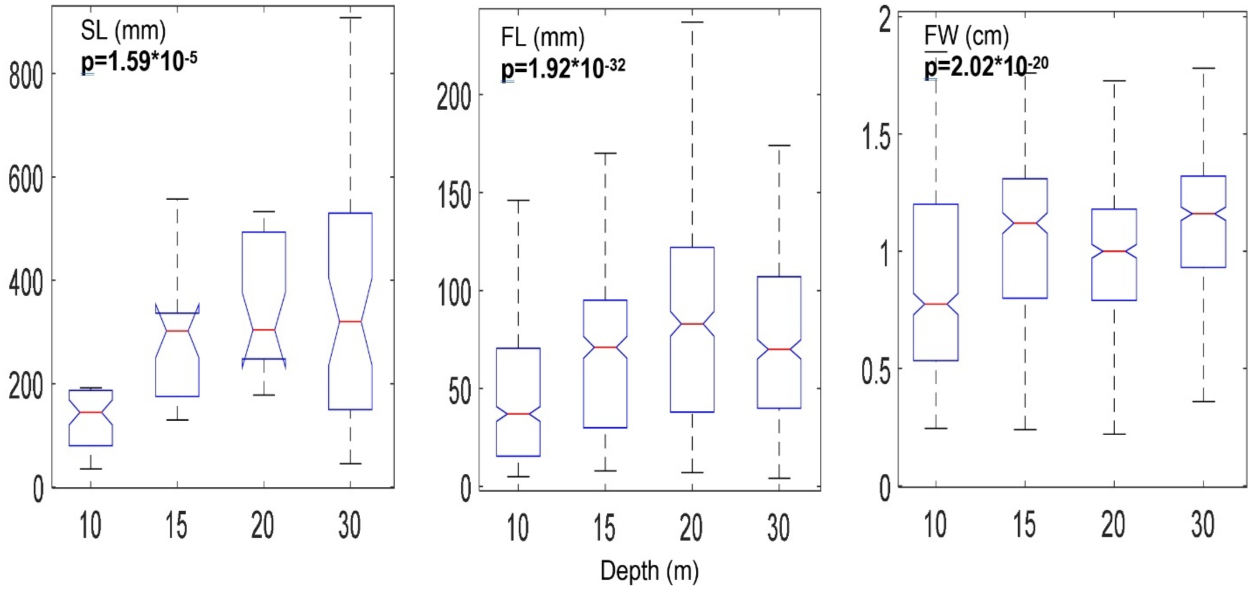

Figure 6. Notch plots of morphometrical variables of *C. taxifolia* at the sampling depths. SL: stolon length in mm, FL: frond length in mm, and FW: frond width in mm. The bold p value denotes a significant difference in the variable among the bottom depths, in other words, from station D1 to D4

Budding

The stolons of the species manifested as a continuous line formed by the buds (Figure 2). A total of 1 stolon, 31 shoots, 11 buds at 10 m, 6 stolons, 63 shoots, 8 buds at 15 m, 6 stolons, 67 shoots, 5 buds at 20 m, 8 stolons, 84 shoots, and 17 buds at 30 m were identified among the total specimens examined in the present study area (Figure 7). The frequency of budding was as follows: 35% of the total numbers of specimens examined at 10 m were found to be budded, 12% at 15 m, 7% at 20 m, and 20% at 30 m. Multiple buds rarely occurred on one main shoot of the specimens (Figure 7).

Interbiometric relationship

The interbiometric relationship was characterized by the number of pinnae vs. frond length and frond length vs. frond width (Figures 8, 9). This relationship could be useful for the identification of congeneric species of *Caulerpa*.

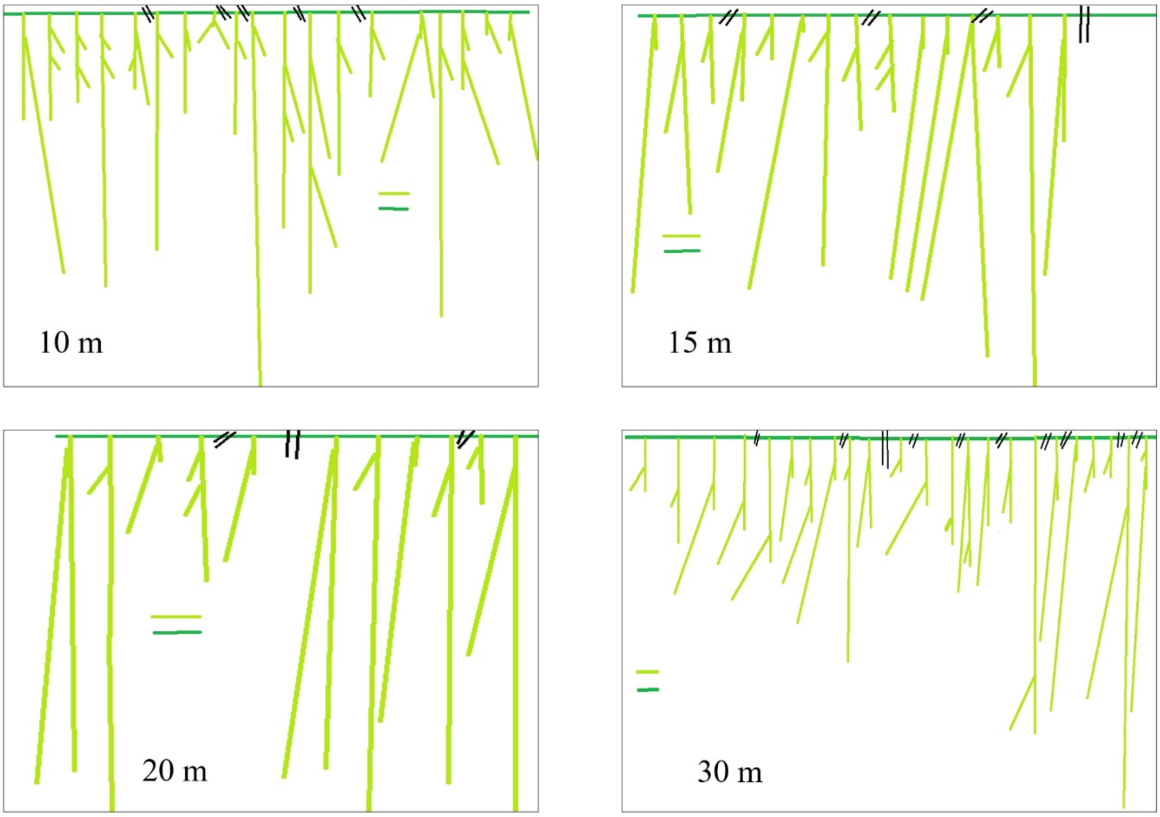

Figure 7. Schematized frond buds (see Figure 2 for the real appearance of budding reticulated with branches) of *C. taxifolia* were found at 10-30 m, in other words, from station D1 to D4. The light green represents fronds (scale: 2 cm), and the dark green represents unscaled stolons. The diagonal line denotes fronds at each stolon, and the perpendicular line represents the separation of replicate samples

The number of ramuli (pinnae) was significantly correlated with frond length at $p < 0.05$ (Figure 8). The estimated slope of this relationship was approximately 1, indicating that a 1-unit increase in frond length corresponds to a 1-unit increase in pinnae number. The minimum and maximum number of pinnae per 1 cm frond length are documented in Table 5, and the average number of fronds ranged from 9.6 to 11.8 pinnae per 1 cm frond length (Table 5). The relationship at each bottom depth was found to be significant at $p < 0.05$ (t-test). However, a significant difference in the relationships between the bottom depths was observed (ANOCOVA, $p = 3.16*10^{-6}$) (Figure 8).

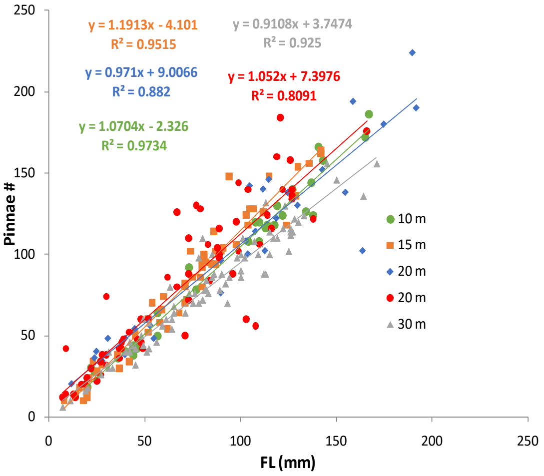

Figure 8. Relationships between frond length and the number of pinnae (#P) at 10-30 m, in other words, from station D1 to D4

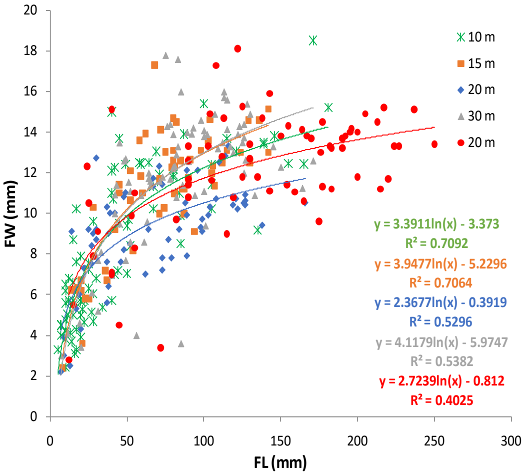

Figure 9. Relationships between frond length (FL) and frond width (FW) at 10-30 m depth, in other words, from station D1 to D4

Table 5. Minimum, maximum, mean and standard deviation values of the number of pinnae per 1 cm long frond

Pno/FL	D1	D2	D3	D4
Min	8.64	5.6	5.2	7.1
Max	13.64	15.7	24.7	13.8
Mean	10.40	11.1	11.8	9.6
SD	1.10	1.7	3.0	1.2

However, the frond length-width relationship was significantly estimated with a curved linear (logarithmic) model as opposed to a linear model (Figure 9). The relationship exhibited considerable variability in the scatter plot (Figure 9). Nevertheless, there were significant differences in the relationships between bottom depths (ANOCOVA, p = 0.0046) (Figure 9).

DISCUSSION

Caulerpa species were identified as target species of interest due to their distinctive characteristics (e.g., unique siphonous thallus composed of a single multinucleate cell, utilization as food, and invasive characteristics) (Paul and Fenical, 1987; Ceccherelli et al., 2002). The invasive nature of these organisms is attributable to their remarkable flexibility and capacity to thrive under a broad spectrum of temperatures and irradiances (Uchimura et al., 2000; Ljiljana et al., 2006). Consequently, these plants have developed vegetative reproduction, fragmentation, and morphological plasticity in a variety of marine environments (Ceccherelli and Cinelli, 1999a, b; Ceccherelli and Piazzi, 2001; Wright, 2005). It has been documented that certain species within this group exhibit remarkably high levels of morphological plasticity, a phenomenon that has contributed to significant taxonomic confusion and the description of nearly 400 species, varieties, forms, and ecads (i.e., environmentally modified morphologies) (Zubia et al., 2020). Consequently, the collection of morphometrics from diverse locations and seas has become imperative for effective species identification.

It shares a structural resemblance to *Caulerpa mexicana*, and both *C. mexicana* and *C. taxifolia* possess distichous fronds. However, a distinguishing characteristic of *C. mexicana* is the presence of a type of frond that exhibits an intermediate form between clavate and club-shaped (wider than the tip parts of ramuli) falcate ramuli, while *C. taxifolia* manifests a variant of falcate, sickle-shaped ramuli (Verlaque et al., 2015). The basal part of the ramuli of both species was contracted, but this was not observed in *C. taxifolia* var. *distichophylla* (Verlaque et al., 2015) (Figure A1).

In the Mediterranean basin, *Caulerpa taxifolia* is an invasive alga that was introduced into the ecosystem from an aquarium in France (Meinesz and Hesse, 1991). In Turkish waters, the species was observed in İskenderun Bay (Mediterranean Sea), followed by the Gulf of İzmir and Dikili Bay (Aegean Sea). However, its biometry was not extensively detailed because of its previous occurrence along the bottom depth gradient. Following the sporadic introduction of specimens to the Mediterranean Sea in 1991 (Meinesz and Hesse, 1991), the species proliferated at depths ranging from 45 to 100 m. Along the French coast, the species was found to consist of a stolon measuring approximately 20 cm, bearing a cluster of approximately ten living fronds, each ranging from 5 to 15 cm in length (Belsher and Meinesz, 1995). In areas where *Posidonia oceanica* was present, the positive impact of *P. oceanica* on *C. taxifolia* was more pronounced at the deepest edge of the seagrass stand, where shoot density was lower. This phenomenon was partially explained by the observation that the algal leaves were larger where they occurred at the edge of the mimic transparent plants. This suggests that protection comes at a cost. Therefore, dense *P. oceanica* meadows are likely to be less vulnerable to algal invasion, while sparse meadows represent an optimal compromise between protection and shading (Villele and Verlaque, 1995; Ceccherelli and Cinelli, 1999b).

Biometric parameters are critical variants that are identical to species or congeneric species, as evidenced by the analysis of seaweeds and seagrasses. In addition, the environment can modify biometric measurements, thereby creating measurements specific to the location and broad-scale space. Furthermore, depth-dependent environments are very effective for the flora and fauna of bottom ecosystems. At a depth of 20 m, where *C. taxifolia* colonized the lake, Molenaar et al. (2006) observed that the density remained within normal parameters, measuring 311 to 515 ± 32 shoots/m^2 (Cap Martin, France). This finding aligns closely with our own measurements at a similar depth (431 ± 572 shoots/m^2). The photosynthetic capacity of *C. taxifolia* exhibited a positive or null trend within the temperature range of 5-35 °C, yet demonstrated a negative response at 40 °C (Gacia et al., 1996). The maximum photosynthetic capacity was observed in November, followed by a slight but significant decline in July, and an approximate twofold reduction in April, September, and January (Gacia et al., 1996). Consequently, *C. taxifolia* demonstrated pronounced seasonal patterns in terms of light-saturated photosynthetic rates, which exhibited no correlation with the environmental parameters that predominantly influence the productivity of Mediterranean seaweeds, namely light availability, water temperature, and nutrient availability (Ballesteros, 1989).

Extreme salt loading, defined as a concentration of more than 50 kg per square meter, has been observed to significantly reduce the abundance of *C. taxifolia*. A study conducted by Glasby et al. (2005) reported a 75-90% decrease in salt loading at the *C. taxifolia* site compared to the control site. The study also noted that shoot density and the number of fronds per stolon remained constant for *C. taxifolia*, irrespective of bottom depth. However, the analysis revealed significant variations in other biometric variables with changes in bottom depth. The findings suggest that *C. taxifolia* may be nutrient limited, as evidenced by the positive correlation between leaf density and nutrient addition (Ceccherelli and Cinelli, 1997). Moreover, the removal of *C. taxifolia* has been shown to result in the sustained presence of high nutrient concentrations in fertilized sediments during competition with *Cymodocea nodosa* (Ceccherelli and Cinelli, 1997). At a depth of 9 m (Cap Martin, Alpes-Maritimes, France), the length of *C. taxifolia* stolons exhibited a range from 150 to 352 mm throughout the year. The rhizoid columns were regularly spaced and demonstrated no seasonal variation, with an average of one column every 1.63 ± 4.3 cm along the stolon. The density of primary fronds exhibited a range from 5100 to 13920 m^{-2}, with the maximum number of branches recorded in spring, at 25000 m^{-2} (Meinesz et al., 1995).

The variables that demonstrated a tendency to increase or decrease with depth included stolon length, frond length and width, leaf area, internodal distance, and the number of fronds per stolon. The leaf size of *C. taxifolia* was found to be greater at 10 m than at 2 m depth, while controlling for the presence of *P. oceanica* (Ceccherelli and Cinelli, 1999b). The greatest blade length of *C. taxifolia* was found in individuals at the edge of *P. oceanica*, while the blade length was intermediate within *C. nodosa* beds (Ceccherelli and Cinelli, 1998). A reduction in blade density was observed in spring in sandy and *C. nodosa* habitats but not in *P. oceanica* habitats (Ceccherelli and Cinelli 1998). However, the mean biomass of *C. taxifolia* at 5 m depth was greater than that at 20 m depth on the French Mediterranean coast (Thibaut et al., 2004), which contrasts with our estimates of the density variables. The biomass changes in exposed areas are abrupt due to frequent thermal fluctuations, while biomass changes progress in sheltered areas (Thibaut et al., 2004). The optimal temperature for maximum stolon and assimilator elongation was determined to be 25 °C, with growth observed up to 30 °C and slight growth at 15 °C. The growth patterns of *C. taxifolia* remained consistent across the range of irradiances studied. The maximum mean stolon and assimilator elongation was recorded at an irradiance of 75 µmol photons m^{-2} s^{-1} (Gillespie et al., 1997). The number of fronds was 10-12 per 10 cm of stolon, and the fronds were 2.0-10.0 cm high and 1.9-3.5 mm wide. A comparison of the Turkish Levantine coast (Cevik et al., 2007) with the Turkish Aegean coast revealed that the former had a higher number of fronds, though these were longer and narrower than those measured in the present study. The Turkish Aegean coast had an average photosynthetic photon flux (PAR) of approximately 4.8 mol photons/cm^2/s, which is indicative of higher levels of photosynthesis (Burfeind and Udy, 2009). It has been established that light and nutrients play a pivotal role in the growth of *C. taxifolia* (Burfeind and Udy, 2009).

Interbiometric relationships can be used to characterize species, and in the present study, these relationships were differentiated by bottom depth for *C. taxifolia* as well as *C. mexicana* and *C. taxifolia* var. *distichophylla*. Two congeneric species were identified, and they exhibited significant differences in their relationships with each other (Figure A2). The relationship between frond length and the number of lateral branches exhibited a slope greater than 2 for *Caulerpa taxifolia* var. *distichophylla* and a slope less than 1 for *C. taxifolia* (Figure A2) (Mutlu et al., 2025a). The length-width relationship of the frond of *C. taxifolia* var. *distichophylla* specimens collected from Antalya Gulf of the Turkish Mediterranean coast (Mutlu et al., 2022) exhibited a comparable relationship with specimens of the Aegean Sea (Mutlu et al., 2025a) (Figure A2). The relationships between the seas were not significantly different at $p < 0.05$ (ANOCOVA, p: 0.457). Consequently, the plasticity of the specimens due to the different marine environment could not be valid for *C. taxifolia* var. *distichophylla* in terms of the biometrical relationship (Figure A2). This is further supported by the observation that the sampling dates of both seas were highly different (Mutlu et al., 2022, 2025a).

However, the basal part of ramuli of the specimens published by Erduğan et al. (2009) exhibited no contraction, and the frond blade was sickle-shaped (Verlaque et al., 2015). The species could be identified as *C. taxifolia* var. *distichophyla*. In contrast, the specimen reported from the Turkish coast of the Aegean Sea by Turan et al. (2011) is *C. taxifolia*, as the basal part of the ramuli was contracted (Verlaque et al., 2015). Turan et al. (2011) characterized the biometry of the pinnules of *C. taxifolia* collected from the İzmir Gulf, Aegean Sea, as follows: The mean stolon diameter, frond width, maximal length of pinnules, and width of pinnules of a total of 50 *C. taxifolia* samples were 1.6 ± 0.5 mm, 9.9 ± 2.3 mm, 5.4 ± 1.3 mm, and 1.1 ± 0.1 mm, respectively. Cevik et al. (2007) described the fronds of the putative species *C. taxifolia* isolated from İskenderun Bay as green, simple to 1-2 times laterally branched, 2.0-10.0 cm long, and 1.9-3.5 mm wide. In a similar study along the Turkish coast of the Aegean Sea, Mutlu et al. (2025a) reported that the frond length of *C. taxifolia* var. *distichophylla* ranged from 2.10 mm to 105 mm, with a mean of 46.51 ± 1.4 mm. Similarly, the frond width varied between 1.30 and 4.10 mm, with a mean of 2.68 ± 0.003 mm. The specimens isolated from the aquarium were characterized by green fronds ranging in length from 1.5 to 15.0 cm and in width from 10.0 to 13.0 mm (Cevik et al., 2007). Based on these observations, it was estimated that the FL of *C. taxifolia* ranged from 2 mm. to 250 mm, with 49.9 mm at 10 m to 87 mm at 20 m, followed by 71 mm at 30 m on average, and frond width remained within a narrow range of 8.55 mm to 11.139 mm. However, Erduğan et al. (2009) measured frond length overall in a range of 1-15 cm (0.4-23 cm) and frond width in a range of 6-9 mm (3-13 mm) of a putative species *C. mexicana* (most probably, *Caulerpa taxifolia* var. *distichophylla* according to our description in Table A1 and Mutlu et al. 2025a, b) collected from İskenderun Bay. However, three studies (Cevik et al., 2007; Erduğan et al., 2009; Turan et al., 2011) did not establish the biometric relationship. Molecular data has corroborated these morphological similarities and suggests that *C. distichophylla* is a brittle form of *C. taxifolia* (Famà et al., 2002; Stam et al., 2006).

Cevik et al. (2007) conducted a molecular analysis to identify specimens found in İskenderun Bay (Türkiye) by comparing them to specimens from other world seas and an aquarium in İzmir. They recognized the İskenderun specimens as *C. taxifolia*. Notably, the İskenderun specimens exhibited an absence of contracted structure at the basal part of the ramuli attached to the rachis (Verlaque et al., 2015), which suggests that this species differs from *C. taxifolia* collected from the aquarium (Turan et al., 2011). Indeed, both locus specimens (İskenderun and İzmir) exhibited biometric differences at the time of description performed by Cevik et al. (2007). The specimens inhabiting İskenderun Bay were subsequently corrected for genetically misidentification by Jongma et al. (2013). The following abstract was prepared to emphasize the significance and challenges encountered in both genetic and morphological studies: "On the basis of morphological and molecular studies, we identified the Australian endemic green alga known as *Caulerpa distichophylla* along the coasts of Sicily (Italy, Mediterranean Sea). The slender *Caulerpa* previously reported as *C. taxifolia* from southeastern Türkiye (Gulf of İskenderun) also belongs to *C. distichophylla*. Morphologically, *C. distichophylla* clearly differs from *C. taxifolia* in its slender thallus and the lack of large rhizoidal pillars. However, genetic data do not provide undisputed evidence that the species are distinct. Sequences of the tufA cpDNA gene and of the cp16S rDNA intron-2 sequences separated the two taxa by only one single nucleotide mutation, whereas ITS rDNA sequences did not clearly distinguish them". Specimens of *C. taxifolia* var. *distichophylla* from Rhodes and Cyprus Islands do not exhibit the usual morphologies of *C. mexicana* or *C. taxifolia*, or the typically robust morphology of the invasive *C. taxifolia* in the aquarium strain, but was found in range of plant traits of specimens from the eastern Levant coasts, İskenderun and Antalya bay, Türkiye (Aplikioti et al., 2016; Cevik et al., 2007; Mutlu et al., 2022). We listed their biometry in detail (Table A1) including the Levant specimens (Mutlu et al., 2022) since we observed these two species of *Caulerpa* during the present study (Mutlu et al., 2025a) in addition to *C. mexicana* (Mutlu et al., 2025a, b). Verlaque et al (2015) described the species for their featured traits.

The bud and stolon structure of *C. taxifolia* (Figure 2) was also found to be comparatively simple when compared to those of *C. taxifolia* var. *distichophylla* (Mutlu et al., 2025a).

In conclusion, this study provides valuable insights into the depth biometry of the invasive species *Caulerpa taxifolia* in the Turkish Aegean Sea. The biometry and biometrical relationship could be specific to similar species of the *Caulerpa* genus. These results demonstrated the ability of *C. taxifolia* to adapt to and thrive under a range of environmental conditions in the Aegean Sea, and the biometric plasticity of the species likely contributes to its invasive success by allowing it to exploit different niches. This study establishes a foundation for the region's invasive alga monitoring and ecological impact assessment. Subsequent studies will prioritize the analysis of seasonal depth-wise population and biometric dynamics to inform ecosystem management.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare that are relevant to the content of this article.

AUTHOR CONTRIBUTIONS

All the authors contributed to the study conception and design. Material preparation and measurements, data collection, scripting, and analysis were performed by Erhan Mutlu, Barış Akçalı, Yaşar Özvarol, Zeynep Zabun, Zeynep Narlı and Berivan Elif Alsan. The first draft of the manuscript was written by Erhan Mutlu and reviewed by Barış Akçalı, and all the authors commented on previous versions of the manuscript. All the authors read and approved the final manuscript.

ETHICAL APPROVAL STATEMENT

The authors declare that all applicable guidelines for sampling, care, and experimental use of animals in the study have been followed.

DATA AVAILABILITY STATEMENT

Not applicable.

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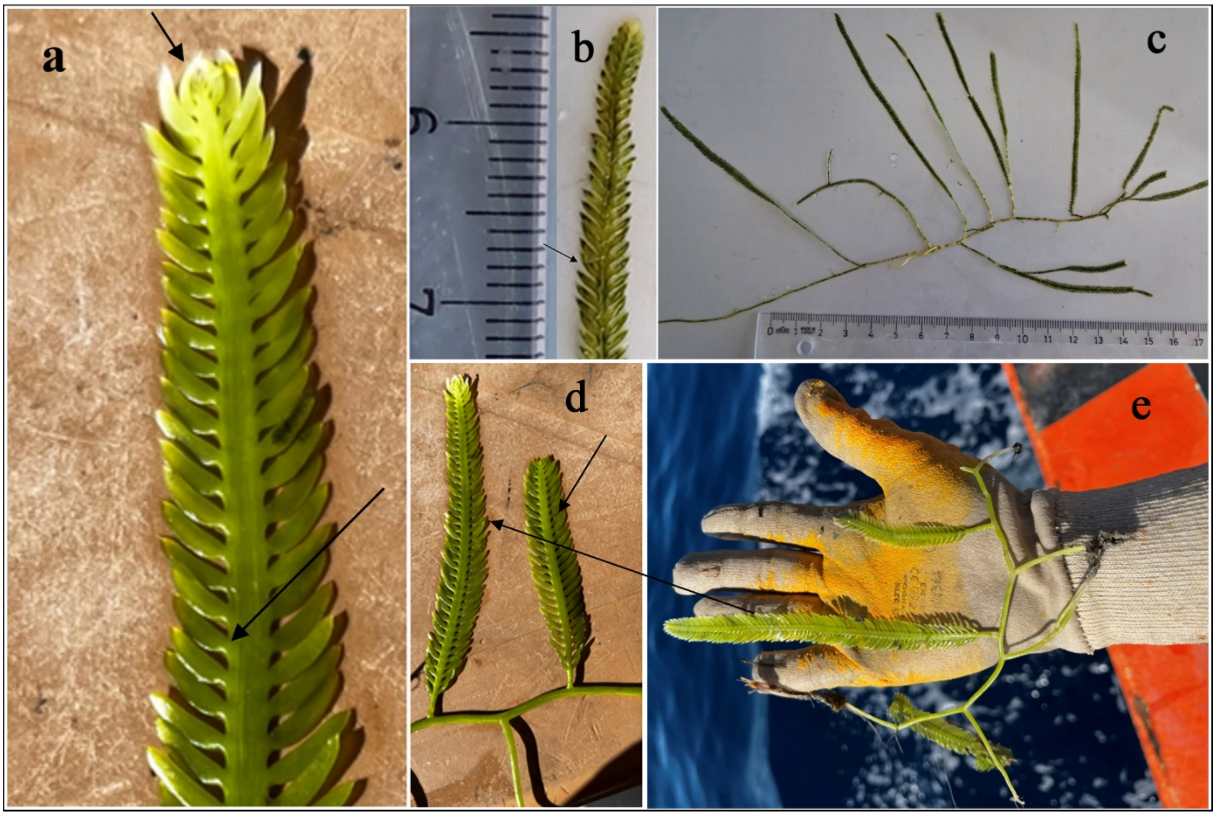

Figure A1. Fronds, rachises and pinnae of *C. taxifolia* (a, d, e) and *C. taxifolia* var. *distichophylla* (b, c, Mutlu et al., 2025a) from the Turkish Aegean waters. Specimen in Fig. A1a could be scaled regarding to same specimen in Fig. A1d, e (a hand of SCUBA diver, Barış Akçalı)

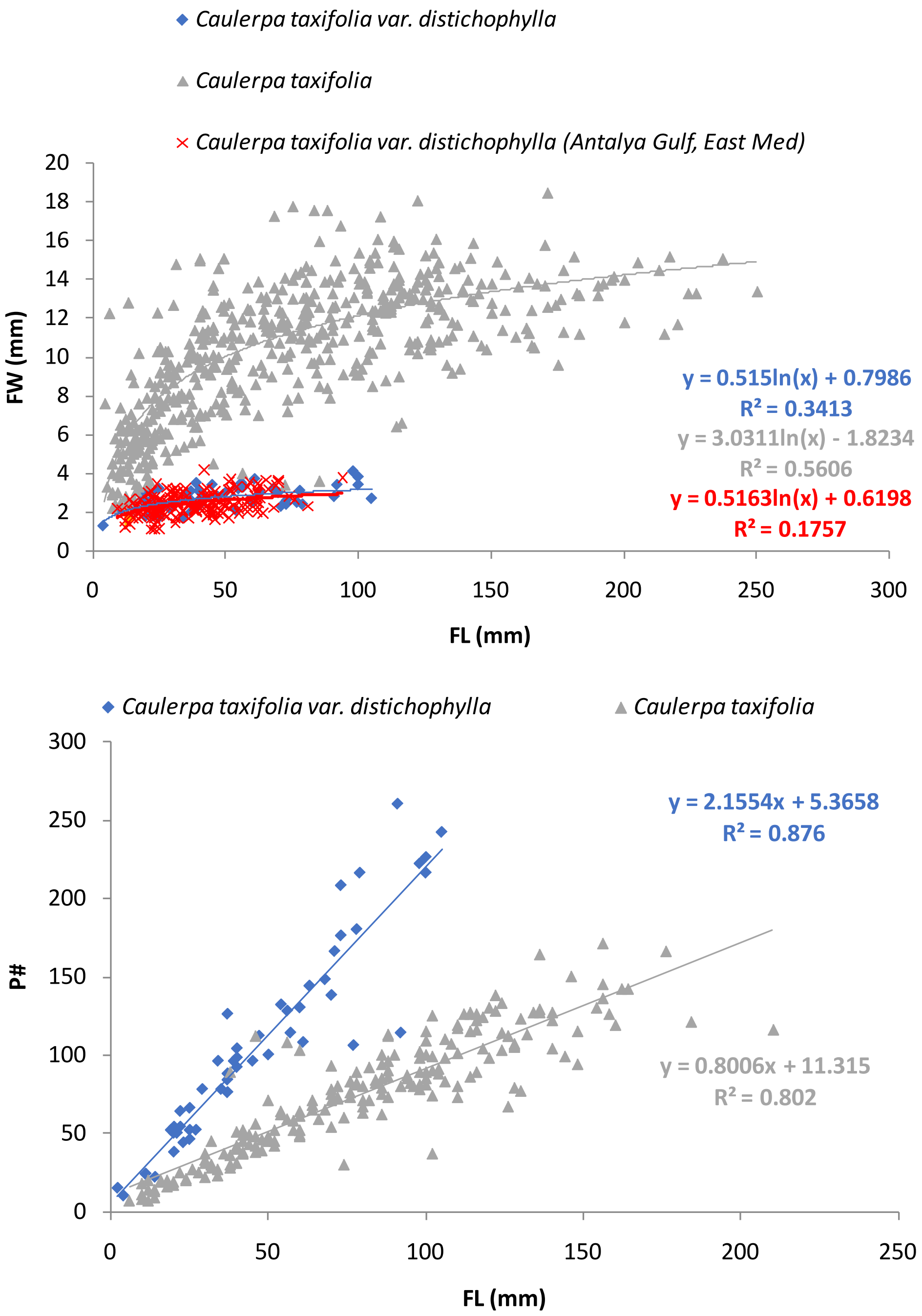

Figure A2. Frond length (FL)-width (FW) and frond length (FL)-number of pinnae (P#) of *Caulerpa taxifolia* and *C. taxifolia* var. *distichophylla* specimens collected during the present study conducted in the Turkish coast of the Aegean Sea (Mutlu et al. 2025a) and *C. taxifolia* var. *distichophylla* from Antalya Gulf, Eastern Mediterranean Sea for FL-FW, regardless of bottom depth and season (data from Mutlu et al. 2022)

Figure A3. *Caulerpa taxifolia* var. *distichophylla* at sea and air from the Antalya bay of the Mediterranean Sea (Mutlu et al. 2022)

Table A1. Plant trait comparison between *Caulerpa taxifolia* in the Aegean Sea (the present study) and *Caulerpa taxifolia* var. *distichophylla* (*C. t.* var. *distichophylla*) in the Mediterranean Sea (Mutlu et al. 2022) (see Fig. A3) and Aegean Sea (Mutlu et al. 2025a). * Additional data from Antalya Bay. +: identical characters for difference between two species. Variable coded below with [1] denoted excluding both ends of the frond. Variable coded below with [2] was given for the number per 1 cm frond length with the related table in a publication by Mutlu et al. (2025a), but the number was indeed per 1 mm frond length

Variable	*Caulerpa taxifolia*	*C. t.* var. *distichophylla*
+Frond shape [1]	ellipsoid	rectangular
Frond length (mm)	49.9-87, 69.1	2.1-105, 46.5 up to 100, 27-48*
+Frond width (mm)	8.55-11.14, 10.1	1.3-4.1, 2.6 up-to 4.8, 2.6-4.8*
+Widest frond	in mid-frond	all through frond
Ramuli shape	sickle	sickle
+Ramuli base	contracted	not contracted
Ramuli tip	knife-shape	knife-shape
+Ramuli tip color	green	blackish
+frond color	green	green in sea, dark green in air
+Rhizoid color	green	cream
+Rhizoid hairs (thallus)	available	almost rudimental
+Thallus aggregation shape	ball-shape	almost rudimental
Stolon shape	slender	slender
+Stolon color	green	dark green-creamy
Budding structure	simple	little complex
Frond apex	similar	similar
Ramuli per 1 cm frond		
+Min-max	3.6-24.3	7.1-34.1 [2]
+Average	9.8	22.7 [2]
+Slope for FL-FW	greater than 2 (>2.4)	less than 1* (~0.5)
+for FL-P#	less than 1 (<1.1)	greater than 2
Rachis shape	similar	similar
+Rachis color	green	dark green
+Rachis midrib	apparent	not-apparent
+Thallus	much hairy	few hairy