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First Record of *Vaucheria litorea* C. Agardh in Spain: Morphological, Reproductive, and Ecological Features of Populations from the Mar Menor Hypersaline Coastal Lagoon

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Abstract

Vaucheria litorea C. Agardh has been reported for the first time in the hypersaline coastal lagoon of Mar Menor (Murcia, southeastern Spain). Sediment samples and surface and interstitial water samples were collected at 22 sites distributed throughout the lagoon, and the species was detected at eight, particularly in the western sector, in areas influenced by freshwater inputs from streams and groundwater discharge. The sites with the species present are characterized by a marked variability in salinity and elevated nutrient concentrations, especially ammonium in interstitial water. Specimens were found to have both monoecious and dioecious thalli, for a species traditionally defined as strictly dioecious, likely reflecting greater reproductive variability and taxonomic complexity. The occurrence of *V. litorea* may be associated with eutrophication and rising temperatures, both of which may favor opportunistic species, although its previous presence in the lagoon cannot be excluded. The species has been widely reported and seems to have a cosmopolitan distribution; however, there are considerable morphological discrepancies and limited knowledge of its ecological requirements. Despite the uncertainty about its origins, its ecological traits and environmental context suggest potential for expansion, highlighting the need for genomic studies and further monitoring.

Keywords: hypersaline coastal lagoons; Mediterranean Sea; mud; algae; *Vaucheria*; Xantophyceae

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1. Introduction

The Mar Menor is one of the largest hypersaline coastal lagoons in the Mediterranean Sea. It is of great environmental and conservation interest and is protected by several national and international regulations [1]. Nevertheless, the lagoon's macroalgal flora has scarcely been studied, though early contributions [2–5] were later complemented by floristic data from biomonitoring and ecological studies [6–8]. The dominant substrata of the lagoon are soft (mud and sand), where most algae cannot attach themselves and develop (except for *Caulerpa*). However, lithic substrata are found around five small islands (Mayor or Del Barón, Del Ciervo, Del Sujeto, Redondella, and Perdiguera) that have been more intensively sampled from a phycological perspective, and most available data refer to them.

Over recent decades, the lagoon has been subjected to intense eutrophication. Several watercourses drain into it, notably the Beal (an ephemeral low carrying mining-derived matter after torrential rainfall) and the Albujón (formerly an ephemeral watercourse, now a permanent flow sustained by agricultural drainage and irrigation water). In addition,

several eutrophicated groundwater discharges occur in shallow areas along the lagoon's western coast [9,10]. Groundwater from the Campo de Cartagena aquifer contains very high nitrate concentrations, far exceeding the 50 mg/l threshold established for groundwater bodies under European Union legislation [11], commonly ranging from 100 to 300 mg/l over recent decades and even exceeding 450 mg/l at some locations during the 1990s [10]. These high nitrate concentrations are primarily associated with diffuse agricultural and livestock inputs resulting from the long-term intensive use of nitrogen fertilizers and manure, which lead to nitrate leaching into the aquifer [10]. Furthermore, nutrient- and salt-rich agricultural drainage brines infiltrate the shallow aquifer, which hydraulically reaches the aquifer through direct or indirect infiltration. The expansion of irrigated agriculture and its associated increase in groundwater nitrate concentrations [12] raised groundwater levels in the Quaternary aquifer and boosted submarine groundwater discharge towards the Mar Menor [13]. Together, these diffuse and point inputs have increased nutrient availability in the lagoon and contributed to profound changes in its ecological functioning, causing an acute eutrophication crisis and mass fish mortalities in 2016 [14].

Until that crisis, the lagoon bottom was covered by monospecific or mixed meadows of *Caulerpa prolifera* (Forss.) Lamour. and *Cymodocea nodosa* (Ucria) Asch. However, the 2016 eutrophication event severely affected these communities, which nearly disappeared as the water turned green. A mapping survey of the lagoon's meadows documented the striking alteration and regression of submerged vegetation after that event [15]. This loss of benthic vegetation was accompanied by major changes in sediment functioning. The lagoon's sediments have been shown to play an active role in the internal dynamics of the system, acting as a potential source of nitrogen and phosphorus for the water column, especially when there are re-suspension events and elevated temperatures [16]. The presence of widespread reduction conditions and high sulfide concentrations further indicates a substantial alteration of the sediment's biogeochemistry after the 2016 crisis, with implications for internal nutrient loading and ecosystem recovery [16].

Shallow coastal systems such as the Mar Menor may become particularly susceptible to colonization by opportunistic or broadly tolerant species in the context of environmental alterations [17]. However, the appearance or expansion of taxa in these systems cannot always be unequivocally interpreted as a recent introduction, as it may also reflect the emergence of previously present but undetected species, favored by changes in environmental conditions [18]. This duality between cryptic presence and recent colonization is a key aspect when studying new records in highly dynamic environments.

The genus *Vaucheria* is characterized by its siphonous filaments of an intense green color forming very conspicuous mats and is common in both aquatic and terrestrial habitats, typically occurring on muddy substrates [19]. Some species prefer saline environments and are frequent in salt marshes, where they can tolerate significant fluctuations in salinity [20]. Since the first Spanish reports by Álvarez-Cobelas [21], new species of the genus have been added to the Spanish algal flora from both the Atlantic [22,23] and Mediterranean [24–29] regions.

In this study, the presence of *Vaucheria litorea* C. Agardh is reported for the first time in the hypersaline coastal lagoon of Mar Menor. In addition to creating a new floristic record, this finding is analyzed in relation to the system's environmental conditions, evaluating its possible ecological preferences and addressing the hypothesis that it represents a previously undetected species or a recent colonizer with invasive potential favored by environmental changes in the lagoon.

2. Materials and Methods

2.1. Sampling

Samples were collected during spring-summer 2018. The sampling design and method have been described in detail elsewhere [16,30] and are summarized here for context. A total of 22 stations (Figure 2.1) distributed across the lagoon were selected to represent a range of depths (<2 m, 2–4 m and >4 m), sediment types (sandy and muddy) and vegetation cover (bare, *Caulerpa*, *Cymodocea* or both). At each station, a 25 m linear transect was established, along which three surface sediment samples (upper 4.5 cm) were collected using cylindrical corers (7 cm diameter) at the beginning, middle, and end of the transect.

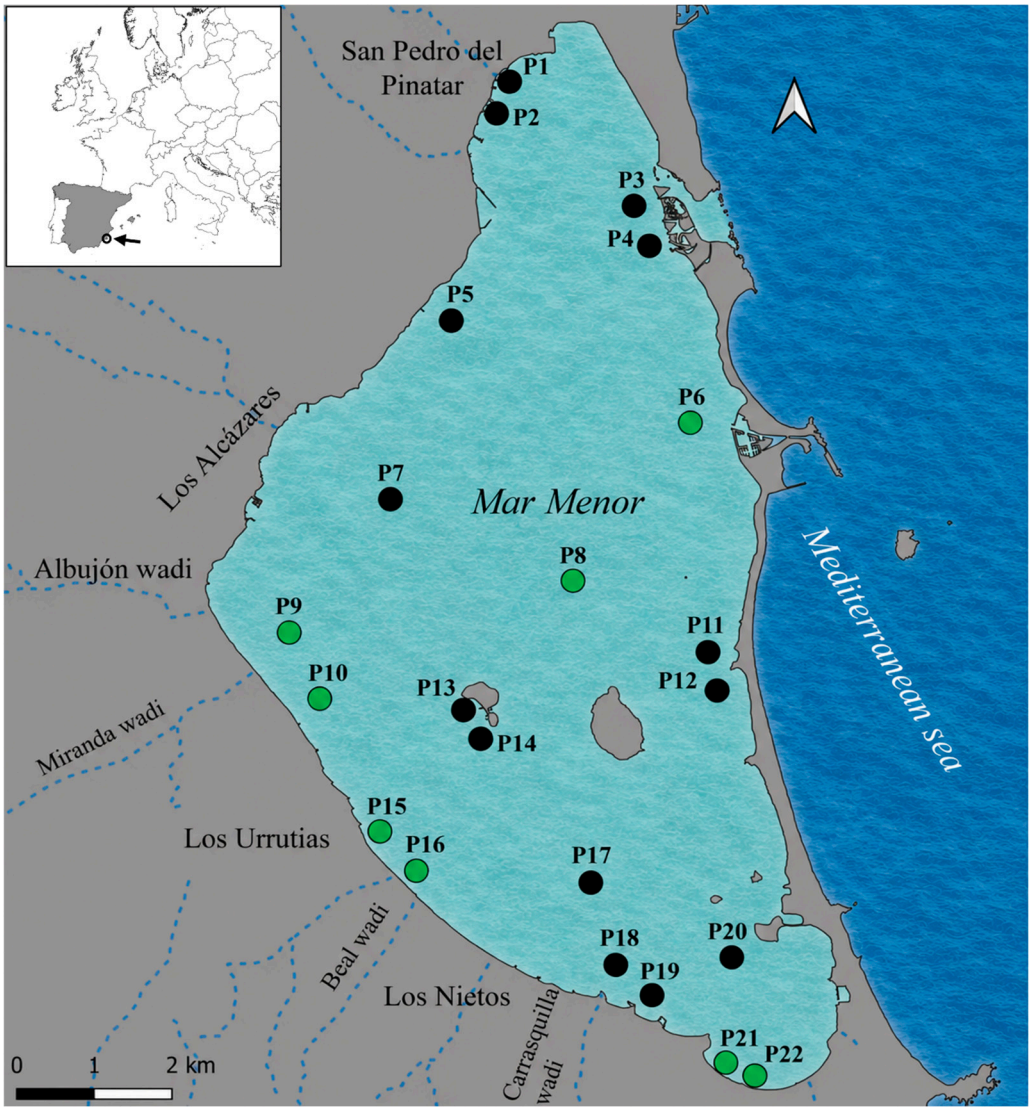


Figure 1. Distribution of *Vaucheria litorea* in the Mar Menor lagoon. Green circles indicate recorded presence; black circles indicate absence. The inset map shows the geographical location of the study area.

For physicochemical characterization, five additional subsamples were collected along each transect at 5 m intervals and subsequently homogenized prior to analysis. All samples were transported to the laboratory under dark, refrigerated conditions (4 °C).

Upon arrival at the laboratory, the sediments intended for physicochemical analysis were processed immediately. Interstitial water was extracted by centrifugation (8000 rpm) under refrigerated conditions (4 °C) and a nitrogen atmosphere and subsequently filtered through 0.45 µm pore-size filters. The resulting samples were stored at 4 °C and analyzed

within one week to determine their electrical conductivity (EC) and nutrient concentrations (nitrate, ammonium, and orthophosphate). Nitrate and ammonium concentrations were determined spectrophotometrically following standard methods [31,32], while orthophosphate was measured spectrophotometrically at 825 nm according to [33].

Sediment samples were first observed fresh to detect and isolate live macro- and microepipelic organisms and were then stored frozen (−20 °C). A total of 66 sediment samples (three per station) were examined. Additionally, the sediments were sieved through a 250 µm nylon mesh.

2.2. Long-Term Water Temperature

Water temperature data from the lagoon were obtained from publicly available monitoring datasets for 2017–2026 [34,35]. For each year, the mean monthly temperatures for May–August (the period when the species grows) were calculated from individual measurements ($n = 171$). The trend in mean water temperature during the species' growth period was tested using linear regression of annual mean temperature against the year in R [36].

2.3. Microscopic Observations and Taxonomic Identification

Observations were performed using a Nikon SMZ800N stereomicroscope equipped with a U3CMOS digital camera and an Olympus X50 microscope with a ColorView I digital camera. At least 20 specimens were measured for morphometric characterization, and glycerin-gel slides were deposited in the MUB-ALGAS herbarium.

Taxonomic identification was based on the monographs [19,20,37,38], with nomenclature updated according to AlgaeBase [39].

2.4. Data Analysis

An unconstrained principal component analysis (PCA) was performed using CANOCO 5.1 [40] to explore the environmental gradients among the sites. Prior to analysis, nutrient concentrations in both interstitial and water column samples were log-transformed to reduce the influence of extreme values. The sediment type was coded as a binary variable (0 = sandy, 1 = muddy) based on granulometric classification from [16]. Sampling sites where *V. litorea* was recorded were subsequently coded for visual interpretation of the biplot. To assess the relationship between environmental variation and the occurrence of *V. litorea*, ordination scores were exported and evaluated using the "envfit" function with 9999 permutations. A permutational multivariate analysis of variance (PERMANOVA [41] was subsequently carried out using Euclidean distances with 9999 permutations to test differences in the environmental matrix between sites with and without *V. litorea*, using the "adonis2" function. The homogeneity of multivariate dispersion between groups was assessed using the "betadisper" function (vegan package) [42] in R 4.2.2 [36].

3. Results

3.1. Morphological Study and Distribution

Vaucheria was detected in a total of eight of the 22 sampling sites (Figure 2.1), covering a wide depth range, including shallow areas (<2 m), intermediate depths (2–4 m) and deeper zones (>4 m) (Table 1). Occurrences were mainly concentrated in the western sector of the lagoon and in areas close to stream discharges (P9, P10 and P16; Table 1).

Table 1. Depth of the selected sampling points.

Sampling Points	Depth (m)	Sampling Points	Depth (m)
P1	<2	P12	<2
P2	<2	P13	<2
P3	<2	P14	<2
P4	<2	P15	<2
P5	2–4	P16	<2
P6	>4	P17	>4
P7	>4	P18	2–4
P8	>4	P19	2–4
P9	2–4	P20	>4
P10	2–4	P21	<2
P11	<2	P22	<2

The *Vaucheria* filaments were 30–60 µm in diameter and contained multiple chloroplasts with pyrenoids, and male and female filaments were slightly different in size (Table 2, Figure 2). Antheridia were apical on branches of variable length and were consistently separated from the vegetative filament by an empty basal cell of 32.2–43.6 × 28.3–48.3 µm. The antheridia themselves measured 52.3–55.7 × 190–200 µm and had a diameter similar to the vegetative filaments, which were only slightly swollen, with one apical opening and 1–3 lateral openings. The oogonia were obovoid, measuring 164–168 × 200–240 µm, and were located at the end of a reflexed branch, also separated from the vegetative filament by an empty basal cell 91–107 µm in length. Immature oospores occupied only the upper portion of the oogonia and measured 130–140 × 140–180 (Table 2). Fructification was observed in May–June, and both monoecious and dioecious specimens were recorded.

Table 2. Morphological and reproductive comparison of *Vaucheria litorea* specimens from Mar Menor and other geographical regions (reproductive characters reported by Entwisle [43] and Muralidhar et al. [44] were obtained from cultured material).

	Christensen (1986) Type [45]	Rieth (1980) [37]	Entwisle (1988) [43]	Muralidhar et al. (2014) [44]	Vishnyakov and Moseev (2022) [46]	Vishnyakov (2025) [47]	This Study
Filaments (µm)	62–67 ♂ 67–73 ♀	30–62 ♂ 55–70 ♀	62–103	90–150	65–95	60.5–133	30–60 ♂ 50–60 ♀
Antheridial pores	-	1 terminal 1–6 lateral	1 terminal, 4 lateral	1 terminal, 1–2 lateral	1 terminal, 1–3 lateral	1 terminal, 1–2 lateral	1 terminal, 1–3 lateral
Antheridium length(µm)	-	420–584	576–1008	400–650	405–960	300–800	190–200
Wall-bound cavity length (µm)	-	10–50	67–96	-	-	-	40–60
Oogonium (µm)	-	126–220 × 196–450	211–268 × 248–464	Not observed	310–390 × 195–235	304–402 × 166.5–240	164–200 × 168–240
Oogonia shape	-	Pyriform	Claviform	-	Claviform	Claviform	Pyriform
Oogonia reflection	Yes	Yes	None/little	-	Yes	Yes	Yes
Wall-bound cavity length (µm)	-	90–135	29–84	-	-	-	91–107
Oospores (µm)	203–217 × 197–209	120–175 × 150–210	172–250 (Diameter)	-	185–225 × 185–230	196–274.5 × 166.5–220.5	130–140 × 140–180
Sexuality	Dioecious	Dioecious	Dioecious	Dioecious	Dioecious	Dioecious	Monoecious–Dioecious
Location	Svinø, South Zealand	Hiddensee, Germany	Australia	Canterbury, New Zealand	White Sea, Russia	Black Sea, Georgia	Mar Menor, Spain

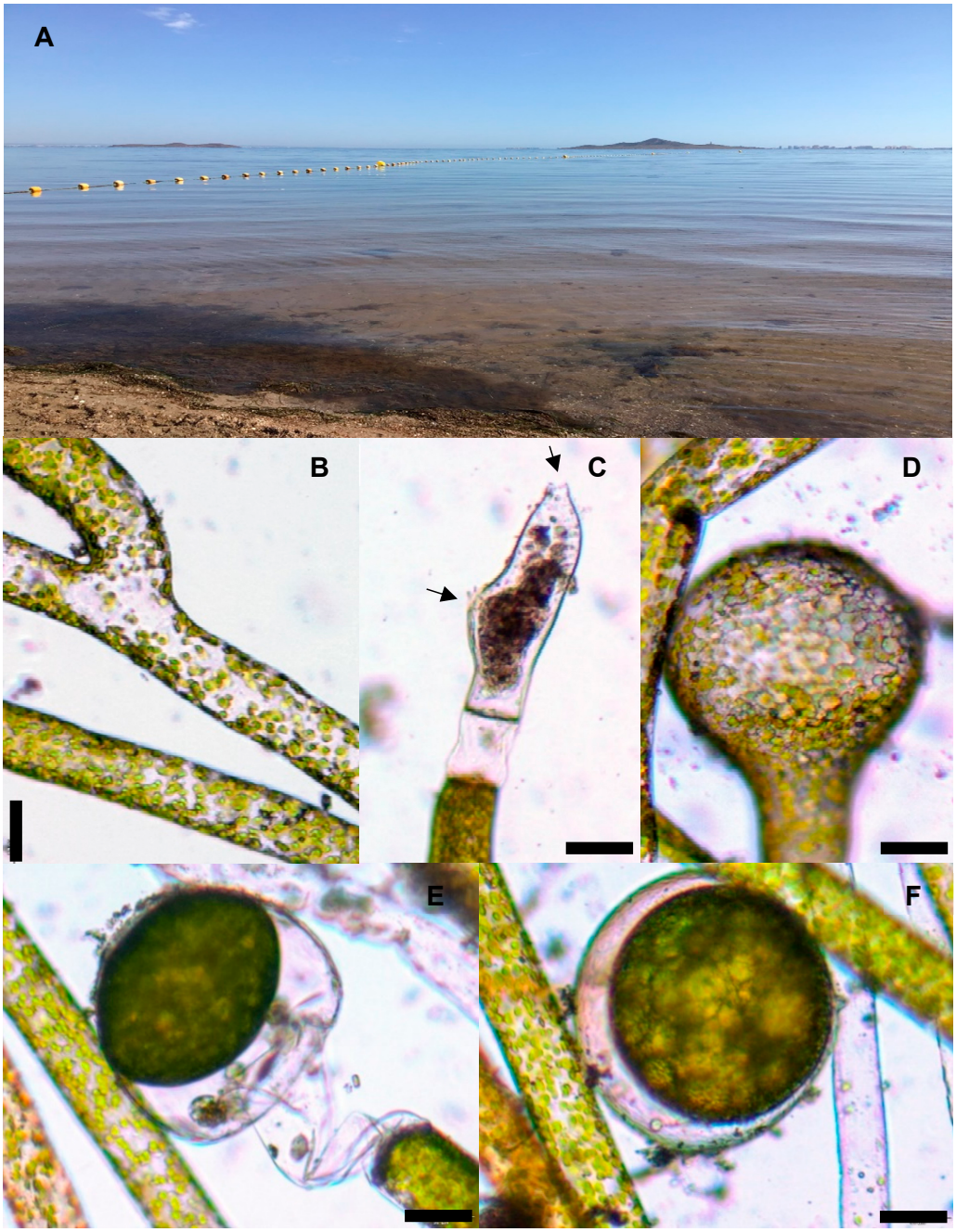


Figure 2. (**A**) View of *Vaucheria litorea* mats in shallow areas of the lagoon. (**B**) Vegetative filaments. (**C**) Antheridium with two openings (arrows) and an empty separation cell. (**D**) Young oogonium. (**E**,**F**) Mature oogonia with oospores inside. Scale bar represents 50 µm.

3.2. Environmental Parameters

At sites where *Vaucheria* was present, nitrate, ammonium and orthophosphate concentrations in interstitial water ranged between 24.4 and 86.29 µM, 10.77–987.4 µM and 1.01–12.85 µM respectively, while in the water column, those values ranged between <0.01–650.51 µM, <0.01–9.11 µM and 0.74–2.05 µM respectively (Table 3). Electrical conductivity ranged from 32.4 to 47.3 dS/m in interstitial water and from 43.1 to 47.0 dS/m in the water column.

Table 3. Environmental parameters of all the sampling sites. Stations where *Vaucheria* was present highlighted in green.

	Interstitial Water				Water Column			
Sampling Points	**Conductivity dS/m**	**Nitrate µM**	**Ammonium µM**	**Orthophosphate µM**	**Conductivity dS/m**	**Nitrate µM**	**Ammonium µM**	**Orthophosphate µM**
P1	24.8	538.02	11.8	1.62	50.3	58.28	0.82	1.07
P2	34.6	109.85	30.1	1.94	49	70.28	0.98	0.77
P3	36.1	106.67	54.3	4.71	43.5	49.71	0.7	1.1
P4	36	74.97	68.9	3.02	44.7	58.28	0.82	0.95
P5	32.56	78.84	32.26	1.66	48.5	601.65	8.42	2.08
P6	47.3	76.52	27.6	1.92	45.7	351.39	4.92	0.74
P7	26.5	58.44	45.85	1.8	46.2	432.81	6.06	0.98
P8	33.3	61.24	48.79	2.22	44.5	650.51	9.11	0.83
P9	37.4	73.67	22.34	3.36	46	<0.01	<0.01	1.48
P10	46.2	66.76	10.77	2.2	46.1	<0.01	<0.01	2.05
P11	34.9	77.69	37.95	2.11	47.3	180.84	2.53	1.01
P12	33.9	82.77	37.93	3.26	47.1	181.7	2.54	0.86
P13	41.3	58.96	10.94	1.17	43.2	227.12	3.18	1.25
P14	39	63.83	17.68	1.33	52.2	197.12	2.76	0.98
P15	43.4	86.29	987.4	1.01	44.8	42.85	0.6	0.83
P16	35.7	71.28	61.76	1.12	43.1	<0.01	<0.01	0.98
P17	37.9	68.25	53.09	1.70	50.2	152.56	2.14	1.51
P18	36.8	62.19	33.99	1.82	43.5	60.85	0.85	0.83
P19	36.4	35.43	40.63	1.64	45.7	53.99	0.76	0.65
P20	36.7	41.4	49.02	2.69	44.8	356.54	4.99	0.92
P21	32.4	24.4	47.56	3.02	47	156.84	2.2	0.8
P22	35.3	73.34	618.58	12.85	43.7	169.7	2.38	1.54

The mean water temperature during the 2018 sampling period was 26.2 °C (annual mean: 20.37 °C), with the lowest in May (21.66 °C) and the highest in August (29.70 °C).

The principal component analysis (PCA) (Figure 3) showed great environmental heterogeneity among the sampling sites, with the first two axes accounting for 47.3% of the cumulative total variation (Axis 1: 24.0%; Axis 2: 23.3%). Sites where *Vaucheria litorea* was present were distributed in the negative region of Axis 1, associated with muddy sediments and elevated interstitial electrical conductivity (ECi), ammonium and orthophosphate concentrations. In contrast, absence sampling sites were distributed across both axes, with stations on sandy substrate (P1, P2, P11, P12, P13, and P14) clustering in the positive region of Axis 1, associated with water-column electrical conductivity (ECc) and interstitial nitrate. Consistent with this pattern, the environmental descriptors differed significantly between sites where *V. litorea* was present and absent ($R^2 = 0.098$, $F_{1.20} = 2.18$, $p = 0.035$), with no significant difference in multivariate dispersion between groups ($F_{1.20} = 2.02$, $p = 0.171$). Fitting *V. litorea* occurrence onto the ordination axes corroborated this habitat association, with significant correlations with PC1 and PC2 ($r^2 = 0.176$, $p = 0.014$). *Vaucheria* stations formed three distinct groups based on visual clustering of the physicochemical variables: sites P9, P10 and P16 characterized by muddy substrata, higher interstitial electrical conductivity and moderate interstitial phosphate concentrations; sites P15, P21 and P22 also characterized by muddy sediments but higher interstitial ammonium and phosphate concentrations; and sites P6 and P8 located at greater depth with moderate interstitial ammonium and phosphate concentrations (Figure 3). *V. litorea* was absent from all six sandy sampling sites regardless of depth, vegetation cover, or water column chemistry.

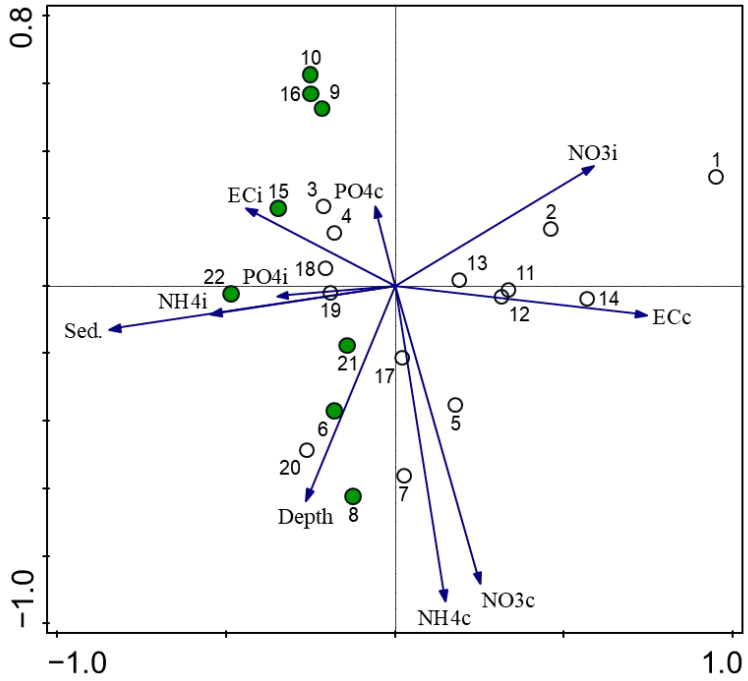


Figure 3. Principal component analysis (PCA) biplot of the ten environmental variables at the 22 sampling sites in the Mar Menor coastal lagoon (Axis 1: 24.0%; Axis 2: 23.3%); cumulative: 47.3%. The arrows represent the environmental variables, where ECc and ECi are the water column and interstitial electrical conductivity; NH4c and NH4i are the water column and interstitial ammonium, respectively; NO3c and NO3i are the water column and interstitial nitrate; PO4c and PO4i are the water column and interstitial orthophosphate; and Depth is the water depth. The colored circles represent sampling sites where *Vaucheria litorea* was recorded; clear circles denote sampling sites where *V. litorea* was absent.

3.3. Trend in Temperature Evolution

Mean water temperature over the entire May–August period ranged from 25.98 °C in 2017 to 27.45 °C in 2026 (Figures 4 and 5), showing a significant increase ($R^2 = 0.709$, $F_{1.8} = 19.49$, $p = 0.002$). The highest temperatures were generally recorded in July and August, reaching 31.22 °C in August 2026.

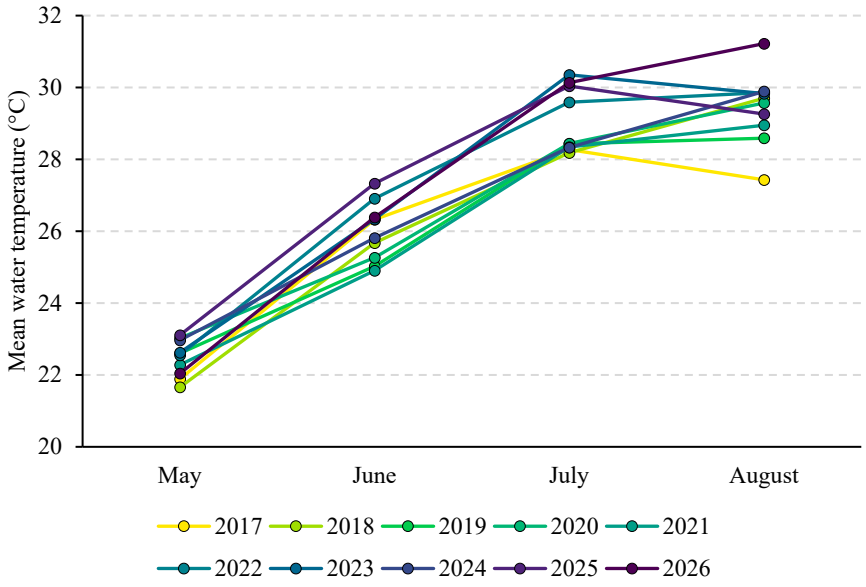


Figure 4. Mean monthly water temperature during the growth period of *Vaucheria litorea*, 2017–2026.

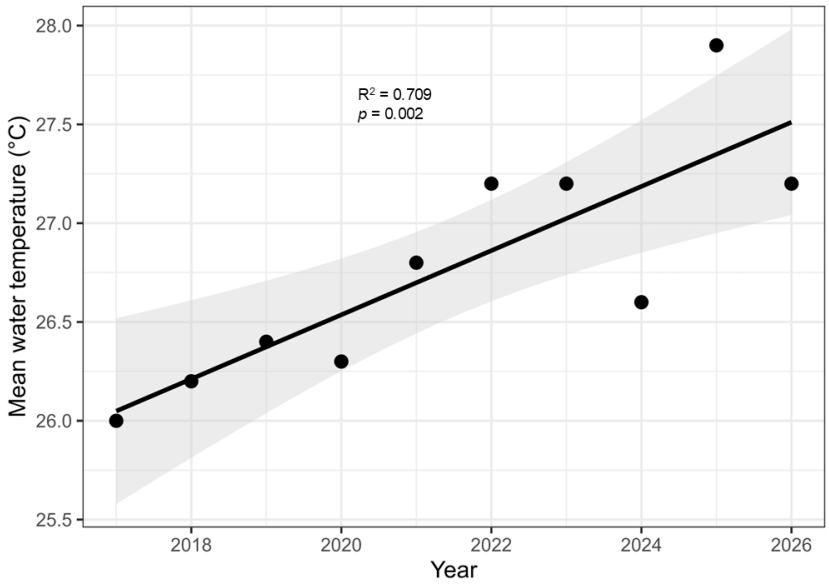


Figure 5. Trend in mean May–August water temperature in the Mar Menor lagoon from 2017 to 2026. Black points indicate annual mean temperature; the solid line shows the fitted linear regression; and the grey band indicates the 95% confidence interval for the fitted trend.

4. Discussion

4.1. Taxonomy and Distribution

The specimens from the Mar Menor lagoon display features consistent with the original description of *Vaucheria litorea* by Agardh [48], later typified by Christensen [45]. Agardh [48] indicated that the material had been collected by Hofman Bang at Hofmansgave, Odense Fjord, Denmark, and sent to him under the name *Vaucheria litorea*. Later, Nordstedt [49] examined historical material in Herbarium Agardhii, including a specimen labeled by Hofman Bang as *Vaucheria litorea* from Hofmansgave, and Christensen [45] typified the species after studying the preserved material and new collections from a saltmarsh close to the type locality. Subsequent reports of the species show a great variation in size (Table 3), suggesting the need for a detailed morphological and genomic study to elucidate whether we are dealing with a very highly plastic species or a species complex [20,37,38,43,45–47,49–51]. Christensen [45] noted wide variation in antheridium length. Moreover, it is not only the changes in size that are sometimes significant; Rieth [37] considered reflection of oogonia as a discriminant, whereas Entwisle [43] regarded this characteristic as of minor importance.

Rieth [37] and Christensen [45] remarked on the sexual dimorphism of the filaments, with the female being broader than the male, and in Entwisle's [43] data there are differences in diameter among cell-bound cavities from oogonia and antheridia-bearing filaments. Rieth [37] referred to the presence of pyrenoids inside chloroplasts.

One particularly noteworthy finding was the observation of both monoecious and dioecious specimens in the Mar Menor samples. Although both reproductive strategies are relatively common within the genus *Vaucheria*, this condition has not previously been reported for *V. litorea*. This finding may therefore reflect greater reproductive variability in the species than previously recognized, or it may be related to the taxonomic complexity of the genus.

The species has previously been recorded in various regions of northern and western Europe, including the Baltic Sea, Great Britain, France, Germany, Ireland, Norway, Scandinavia, and Russia, as well as in other geographical areas such as the United States, Iraq, Australia, and New Zealand (https://doi.org/10.15468/w48pii accessed via https://www.gbif.org/ on

15 September 2026). Rieth [37], however, stated that the species was distributed throughout Europe and North America. Records from coastal lagoon systems appear to be scarce, although it has been reported at Tyligul Liman, a Black Sea coastal lagoon in Ukraine, where it was listed among rare macrophyte algae [51]. More recently, it has also been reported along the coast of Georgia in the Black Sea region [47].

Molecular studies based on the chloroplast *rbc*L gene have shown that the main morpRhological sections of the genus are supported phylogenetically, confirming the usefulness of traditional reproductive characters at least for infrageneric classification [44,52,53], and have also demonstrated the existence of cryptic species, revealing genetically distinct lineages that may be difficult or impossible to distinguish using classical morphological criteria. This taxonomic complexity is particularly relevant to *V. litorea*, as strains assigned to this species do not always appear as closely related lineages in molecular analyses [52]. Moreover, the high genetic variability reported within *Vaucheria*, which in some cases exceeds the variability observed between species or even between genera of angiosperms, must also be interpreted in relation to the molecular markers and analytical approaches used across different studies [52,54]. A genomic study of *Vaucheria litorea* type material is necessary to elucidate the true distribution of the species (De Clerck et al. 2026) [55]. The current distribution found through GBIF or GenBank databases is very unlikely, but neither morphologic nor genomic studies alone are enough to elucidate a problem that is probably frequent [56].

4.2. Ecology and Importance of Interstitial Water Chemistry

V. litorea mats were found to be concentrated in the western sector of the Mar Menor lagoon, particularly in areas close to stream discharges. These zones are influenced by freshwater derived from both surface runoff and groundwater discharge, altering the physicochemical conditions. Conductivity values recorded in the interstitial water at stations where the species was present ranged between 32.4 and 47.3 dS/m, indicating considerable variability associated with the mixing of waters of different salinities. This variability contrasts with the more homogeneous values observed in the water column (43.1–47 dS/m), revealing salinity heterogeneity concentrated in the sediment rather than the overlying water. The high conductivity values recorded in the Mar Menor are consistent with the euryhaline character previously reported for *V. litorea*. The species has been recorded in the field in habitats of low salinity, between 1.0 and 2.6‰ [57], and laboratory cultures indicate growth up to approximately 50‰, with an optimum of around 15‰ [58], whereas [37,43,45] reported a range of 30–50 ‰. Rieth [37] indicated a high tolerance to variations in salt content, and that it can survive almost in freshwater. Salinity has traditionally been regarded as the primary factor governing the distribution of *Vaucheria* species, whereas the role of nutrients has received comparatively less attention [37,38].

Nutrient data from the Mar Menor underscore the importance of the sediment compartment. Ammonium concentration in interstitial water showed considerable variability, with values of up to 987.4 µM at P15 and 618.58 µM at P22. In contrast, nitrate concentrations in both interstitial and water columns showed lower variability and relatively homogeneous values across stations. Orthophosphate concentrations in interstitial water were generally moderate, with occasional peaks at specific stations (e.g., P22), while values in the water column remained low.

The multivariate analyses support the relevance of interstitial conditions in understanding the distribution of *V. litorea* in the Mar Menor. The presence of the species showed a significant association with environmental data, driven primarily by interstitial rather than water-column variables. This is consistent with the species' reported development on soft, muddy substrates, where the interstitial water may directly influence the chemical environment for the filaments. However, specific studies on the nutrient preferences of

V. litorea are scarce, and the role of interstitial water chemistry in mat development and growth has rarely been examined.

Current evidence suggests that the relationship between *Vaucheria* and nutrient availability is not uniform but varies with the species involved and the environmental context of each system. Studies from different habitats show contrasting patterns: in some systems, *Vaucheria*'s abundance has been associated with nutrient availability in the water column, whereas in others high nutrient concentrations within mats or sediments do not necessarily represent the main source supporting growth [59–61]. In addition, changes in nutrient loading and water transparency can alter benthic algal assemblages, as shown by the disappearance of *Vaucheria dichotoma* (Linnaeus) Martius from most sites following restoration of the eutrophicated lake Botshol [62].

4.3. Effect of Water Temperature Increase

Mean water temperature during the species' growth period showed a significant upward trend between 2017 and 2026. Recent work on a non-native *Vaucheria* sp. has shown that high temperature (up to 32 °C) and light availability can directly enhance primary production, suggesting that warming may act as a driver of performance and spread within the genus [63]. This warming trend is consistent with the hypothesis that increasing temperature could contribute to environmental conditions favoring *V. litorea* in this lagoon, although *V. litorea*'s thermal requirements remain unknown.

Establishing the temperature and nutrient requirements of *V. litorea* would require controlled laboratory cultures in which its growth and reproductive response to different nutrient concentrations, salinity, temperature, and light conditions could be tested experimentally. Therefore, long-term monitoring of nutrients, paying particular attention to sediment interstitial water in areas where *V. litorea* occurs, should be complemented by laboratory culture studies.

4.4. Cryptic or Invasive Species

Since *V. litorea* had not previously been recorded in the lagoon, its presence can be interpreted in two non-mutually exclusive ways: as a previously undetected component or as a recent colonizing species whose establishment may have been facilitated by recent environmental changes. The hypothesis of a cryptic presence cannot be ruled out, as several species in the genus exhibit seasonal and ephemeral development in warm regions, making them difficult to detect and identify [27]. Furthermore, its growth on soft substrates may have further reduced its detectability, since soft-bottom communities in the Mar Menor have hardly been studied, apart from macrophyte meadows [6,7,64]. This limited attention to soft-bottom communities, together with the need for fertile material for accurate identification, may have contributed to the absence of prior records in the lagoon.

The hypothesis of recent colonization, or the recent expansion of a previously unnoticed population, is also plausible. The intense eutrophication of the lagoon, particularly since the 2016 crisis, and rising temperatures have profoundly altered its ecological functioning [14], increasing nutrient inputs, modifying hydrological dynamics and sediment biogeochemistry, and generating new ecological conditions that could favor the establishment of opportunistic or stress-tolerant species.

Another factor that could facilitate the establishment of Vaucheria is the lagoon's increasing shallowness. Although the bathymetry most commonly used for the Mar Menor is based on relatively old data [65], various studies have documented the accumulation of fine sediments and organic matter associated with both terrestrial runoff and episodes of extreme rainfall [66–68]. These processes are consistent with the natural tendency of Mediterranean coastal lagoons towards siltation [69] and with a progressive reduction

in depth in certain areas. The shallowness may favor *V. litorea*, which grows to 4 m in depth [37].

The presence of *V. litorea* in the lagoon under altered environmental conditions has parallels with other coastal systems where species of *Vaucheria* have exhibited expansive behavior. Evidence from the Wadden Sea and Arctic coastal environments indicates that dense *Vaucheria* mats can contribute to sediment stabilization, fine-particle accumulation, colonization of previously unoccupied substrates, and modification of benthic habitats [61,70,71]. Although these cases involve different species and environmental contexts, they suggest that the formation of dense *Vaucheria* mats may contribute to the physical modification of the habitat, particularly in shallow environments rich in fine sediments and subject to recent environmental changes. Furthermore, certain biological traits of the genus could favor the persistence of its populations once established. The life cycle of *Vaucheria* includes resistant structures such as oospores and aplanospores, which can remain in the sediments and act as propagule reservoirs. It has been demonstrated that these propagules can survive adverse conditions, including prolonged periods of desiccation and repeated cycles of freezing and thawing, whilst maintaining their viability and regenerative capacity [72,73]. This could enable populations to recover following disturbance events and favor their persistence in environmentally variable systems [74]. There is scarce information on the persistence of vegetative algal cells in sediments, but live diatoms were recently recovered from sediments dating back to 1954 [75].

4.5. Potential Economic Effects

The potential ecological significance also has a socio-economic aspect in lagoon systems where fishing occurs. In the Venice Lagoon, *Vaucheria submarina* (Lyngb.) Berk. has been linked to direct impacts on fishing due to its accumulation in nets [76]. Although it cannot be assumed that *V. litorea* will have equivalent impacts in the Mar Menor, the existence of a traditional fishing sector in the lagoon makes it important to consider the potential implications of the species' increase in biomass.

Our results do not allow us to determine whether *V. litorea* is a recent introduction or a previously undetected component of the lagoon's biota. However, its presence under the current environmental conditions of the Mar Menor, together with the ecological characteristics of the genus and the documented expansion of related species in other coastal systems, suggests that it should be considered a species of interest within the context of invasion biology. From a precautionary perspective, its detection can be interpreted as a warning sign warranting more detailed monitoring.

Future work should focus on analyzing its spatial distribution, seasonal dynamics, reproductive strategies, genomics, optimal growth, and interactions with sedimentary processes and benthic communities to assess its potential for expansion and possible role in ecosystem transformation.

5. Conclusions

- *Vaucheria litorea* C. Agardh has been reported for the first time in the hypersaline coastal lagoon of Mar Menor (Murcia, southeastern Spain).
- In this lagoon, the species prefers areas influenced by freshwater inputs from streams and groundwater discharge, characterized by marked variability in salinity and high nutrient concentrations, especially ammonium in interstitial water.
- The increase in temperature observed in recent years may favor the spread of the species in the lagoon.
- A review of the ecological requirements, taxonomy, and genomics of the *Vaucheria* species should be carried out.

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