

Article

Comparative Evaluation of Destructive (EEI-c) and Non-Destructive (BEARI) Macroalgal Indices for Ecological Status Assessment of Aegean Coastal Waters

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Abstract

This study assessed the ecological status of the Aegean Sea coasts of Türkiye using the destructive Ecological Evaluation Index continuous (EEI-c) and non-destructive Benthic Ecological Assessment Rapid Index (BEARI) macroalgal indices within the framework of coastal ecological monitoring. A total of 25 coastal stations were investigated and macroalgal taxa were classified into sensitive Ecological Status Group I (ESG I) and Benthic Ecological Group I (BEG I) and tolerant–opportunistic Ecological Status Group II (ESG II) and Benthic Ecological Group II (BEG II), according to their ecological characteristics. Ecological quality status (EQS) was evaluated using EEI-c and BEARI, while Bray–Curtis similarity analysis and Principal Component Analysis (PCA) were applied to examine spatial patterns and relationships with environmental variables. The EEI-c assessment classified 19 stations as “high” and five stations as “good”, whereas only İzmir-Bostanlı exhibited “bad” ecological status. According to BEARI, five stations were classified as “high”, 17 as “good”, and Çandarlı, Güllük, and İzmir-Bostanlı as “moderate”, “poor”, and “bad”, respectively. A significant relationship was detected between EEI-c and BEARI values ($R^2 = 0.71$). In addition, Macroalgae-Land Use Simplified Index (MA-LUSI) values were negatively correlated with both EEI-c and BEARI, indicating the sensitivity of macroalgal indices to anthropogenic pressures. Overall, the results demonstrate that macroalgae-based indices provide reliable tools for ecological assessment and support multi-metric approaches in coastal monitoring programs. This study provides one of the first comparative evaluations of destructive (EEI-c) and non-destructive (BEARI) macroalgal indices in relation to MA-LUSI pressure assessment along the Turkish Aegean coasts.

Keywords: macroalgae; ecological quality status; EEI-c; BEARI; coastal monitoring; anthropogenic pressures; water framework directive; Aegean Sea

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1. Introduction

Coastal ecosystems are among the most productive yet highly vulnerable environments, being particularly sensitive to anthropogenic pressures such as eutrophication, urbanization, industrial discharges, tourism activities, and coastal land-use changes [1–5]. These pressures may exceed ecological thresholds and trigger abrupt ecosystem shifts, leading to the replacement of structurally complex, late-successional communities by simplified assemblages dominated by opportunistic taxa [6–8]. Eutrophication is a complex ecological process associated not only with increases in algal biomass, but also with substantial alterations in biodiversity structure and community composition [9]. Because eutrophication affects multiple components of aquatic ecosystems simultaneously, integrated evaluation of pelagic and benthic primary producers has become increasingly important for understanding ecosystem functioning and ecological quality in marine environments [10]. Such ecological shifts reflect fundamental changes in ecosystem functioning and ecological quality, emphasizing the importance of reliable monitoring tools for sustainable coastal management [8].

Macroalgae constitute one of the most important benthic primary producer groups in coastal ecosystems, functioning by supporting primary productivity, increasing habitat complexity, stabilizing sediments, and providing shelter and nursery grounds for numerous marine organisms [11–13]. Due to their sensitivity to environmental gradients and anthropogenic disturbances, macrophytic communities are widely recognized as effective biological indicators for ecological monitoring and ecological quality assessment in coastal ecosystems [14–19]. Consequently, a wide range of methodological approaches, including mapping techniques, floristic analyses, functional group classifications, and ecological indices, have been developed for macroalgae-based monitoring programs [13,20]. Within the framework of the European Water Framework Directive (WFD; 2000/60/EC) and the Marine Strategy Framework Directive (MSFD; 2008/56/EC), marine macrophytes are recognized as one of the principal biological quality elements for evaluating ecological quality in coastal and transitional waters [5,21,22].

Among the available macroalgal assessment tools, the Ecological Evaluation Index continuous formula (EEI-c) has become one of the most widely applied approaches for ecological quality assessment in Mediterranean coastal waters [22]. The index is based on the relative dominance of sensitive late-successional taxa (ESG I) and opportunistic taxa (ESG II), allowing ecological quality to be quantified through ecological quality ratios (EQRs). Variations in the abundance and composition of these ecological status groups provide valuable information on environmental quality and anthropogenic disturbance in coastal ecosystems [6,23,24].

In Türkiye, macroalgae-based ecological assessment studies have expanded considerably in recent years, and EEI-c has been successfully applied for evaluating ecological quality gradients along Turkish coastal waters [24,25]. In parallel, non-destructive approaches based on photographic sampling and benthic ecological group classification have also been developed as rapid and practical alternatives for coastal ecological monitoring [26]. EEI-c and BEARI are complementary macroalgal ecological indices that assess the ecological status based on the composition of macroalgal ecological groups using destructive and non-destructive approaches, respectively [22,26]. Recent studies have placed increasing emphasis on the importance of rapid, cost-effective, and minimally invasive monitoring methodologies for ecologically sensitive Mediterranean coastal ecosystems [5,27,28].

Despite the increasing availability of macroalgal ecological indices, their comparative application within the same environmental framework remains limited. Existing approaches often differ in terms of sampling strategy, spatial scale, taxonomic resolution, ecological grouping systems, and methodological complexity, potentially leading to in-

consistencies in ecological status classification [22,28–30]. While destructive methods provide detailed floristic and taxonomic information, non-destructive approaches offer rapid, cost-effective, and minimally invasive alternatives suitable for large-scale and long-term coastal monitoring programs. Therefore, evaluating the consistency and applicability of these complementary methodologies is essential for developing reliable ecological monitoring frameworks for Mediterranean coastal ecosystems. Furthermore, ecological status cannot be fully interpreted without considering anthropogenic pressure. Pressure-based indices such as the Land Uses Simplified Index (LUSI) and its macroalgae-adapted form (MA-LUSI) provide a quantitative framework for linking land-based human activities to biological responses in coastal ecosystems [24,31,32]. Previous studies demonstrated significant negative relationships between MA-LUSI values and macrophytic ecological indices, confirming the sensitivity of benthic macrophyte assemblages to anthropogenic disturbances and eutrophication gradients [5,24,26,30].

This study aims to assess the ecological status of the Aegean Sea coastal waters of Türkiye by comparing the destructive EEI-c index with the non-destructive BEARI across 25 coastal stations. In addition, relationships between ecological quality assessments, anthropogenic pressure data (MA-LUSI), and environmental variables were examined using multivariate analyses. The study evaluates the consistency and applicability of these approaches and identifies spatial variations in ecological quality along the Turkish Aegean coast.

2. Materials and Methods

2.1. Study Area

The study was conducted along the Aegean Sea coasts of Türkiye, a region characterized by diverse coastal geomorphology, hydrodynamic conditions, and a gradient of anthropogenic pressure. A total of 25 coastal stations were selected, including Enez, Saros Bay, Gökçeada, Yeniköy, Bozcaada, Küçükkuyu, Altınoluk, Ayvalık, Dikili, Çandarlı, Foça, İzmir (Bostanlı), Urla, Ildır, Çeşme, Seferihisar, Kuşadası, Didim, Güllük, Bodrum, Akyaka, Gökova Bay, Datça, Bozburun-1, and Bozburun-2 (Figure 1). The selected stations represent different coastal environments along the Turkish Aegean coastline, including relatively impacted areas as well as locations exposed to urbanization, coastal development, and eutrophication-related pressures. Sufficient numbers of wastewater treatment plants (WWTPs) have been constructed along the Aegean Sea coastal areas and basins. However, pollution levels may increase due to operational problems and population changes associated with tourism activities. Several industrial sites are located around İzmir and Çandarlı Bay, particularly in Aliğa Bay, which hosts large-scale industrial facilities. Due to dense population, agriculture, and industrial activities, rivers pose a risk of pollution along their banks. The most significant rivers in terms of size and pollution load are the Küçük Menderes, Büyük Menderes, Gediz, Bakırçay, and Meriç Rivers. In addition, fish farms located within bays such as Ildır and Güllük are among the significant activities affecting coastal environments. The area under the highest pressure is the Inner Gulf of İzmir, while water quality at the mouths of the Meriç, Bakırçay, and Gediz rivers is relatively poor. This spatial gradient allowed ecological quality to be assessed under different environmental and anthropogenic conditions.

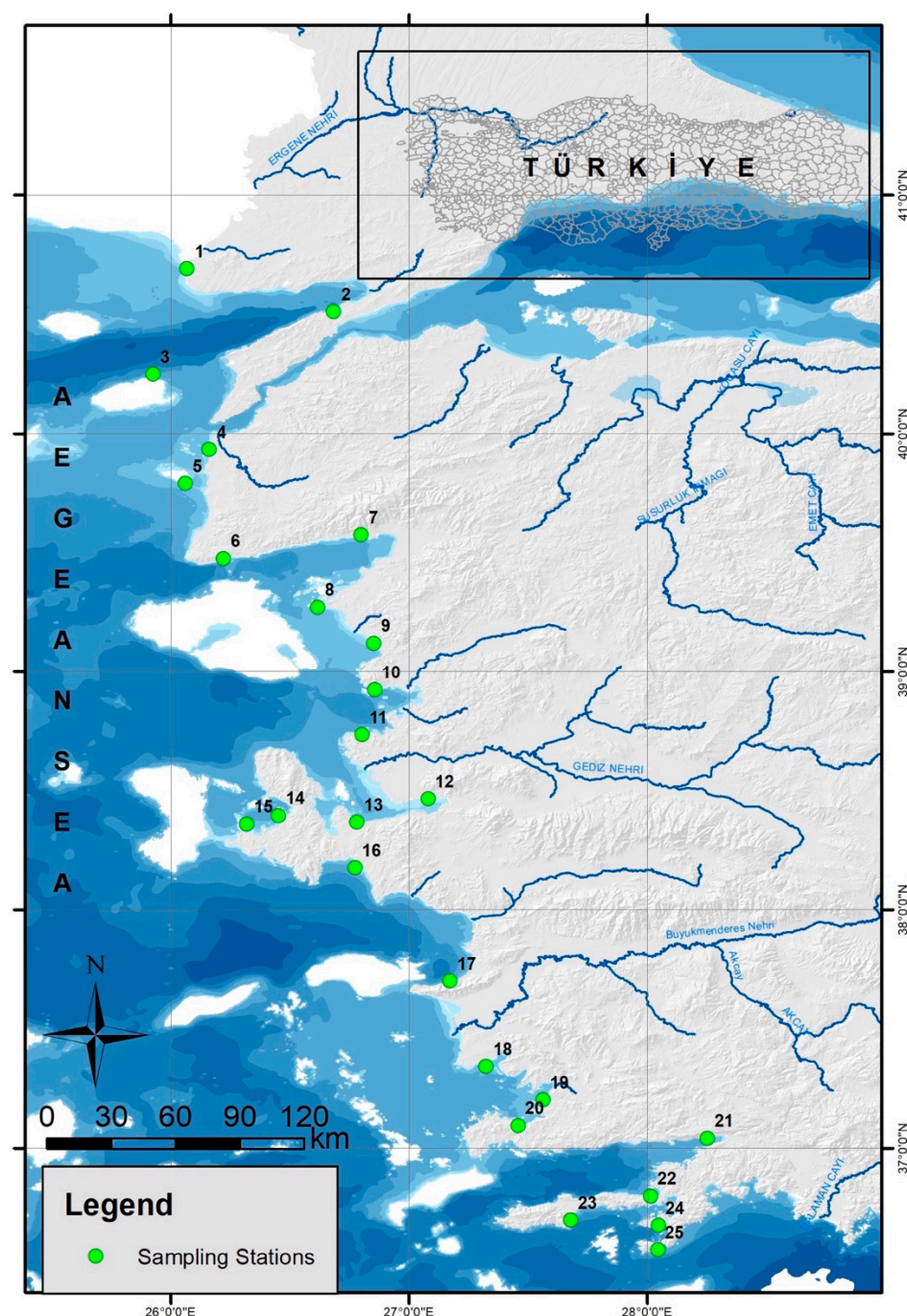


Figure 1. Sampling area on the coasts of Türkiye [1—Enez; 2—Saros Bay; 3—Gökçeada; 4—Yeniköy; 5—Bozcaada; 6—Küçükkuyu; 7—Altınoluk; 8—Ayvalık; 9—Dikili; 10—Çandarlı; 11—Foça; 12—İzmir; 13—Urla; 14—İldır; 15—Çeşme; 16—Seferihisar; 17—Kuşadası; 18—Didim; 19—Güllük; 20—Bodrum; 21—Akyaka; 22—Gökova Bay; 23—Datça; 24—Bozburun-1; 25—Bozburun-2].

2.2. Sampling

Macroalgal sampling was conducted between April and May 2022 using both destructive and non-destructive approaches. For EEI-c assessment, macroalgal samples were collected using 20 × 20 cm quadrats with three replicates per station at a depth of 0.5–1 m. Collected specimens were preserved in 2–5% formaldehyde in seawater for laboratory identification. For BEARI assessment, non-destructive photographic sampling was performed using 20 × 20 cm quadrats with ten replicates per station. Macroalgal specimens were examined under a light microscope (Nikon SE, Tokyo, Japan) and deposited in the

herbarium of Ergün Taşkın (ET) at Manisa Celal Bayar University. Taxonomic nomenclature was verified according to Guiry and Guiry [33].

Physicochemical parameters, including pH, temperature, dissolved oxygen, turbidity, conductivity, and salinity, were measured in situ at each sampling station using a Water Quality Checker™ WQC-24 (DKK-TOA Corporation, Tokyo, Japan). Measurements were conducted simultaneously with macroalgal sampling between April and May 2022. Water samples were also collected and transported to the laboratory for nutrient analyses. Orthophosphate and ammonium nitrogen concentrations were determined according to Parsons et al. [34] and Strickland and Parsons [35], respectively. Water samples were stored at +4 °C until spectrophotometric analysis at Manisa Celal Bayar University (Türkiye). Nutrient variables, including orthophosphate and ammonium nitrogen, were included in the environmental dataset used for correlation and multivariate analyses. Anthropogenic pressure was assessed using the Macroalgae-Land Uses Simplified Index (MA-LUSI), which integrates direct and indirect land-based pressures affecting shallow-water macroalgal communities, including urbanization, industrial and agricultural inputs, sewage outfalls, harbors, mariculture, and irregular freshwater inputs [25,30–32].

2.3. Data Analysis

Marine macrophytes were assigned to ecological status groups (ESGs) according to Orfanidis et al. [22]. ESG I included sensitive and late-successional taxa, whereas ESG II comprised tolerant and opportunistic taxa. The Ecological Evaluation Index continuous formula (EEI-c) was calculated based on the relative percent cover of ESG I and ESG II groups following Orfanidis et al. [22]. The weighted contribution of each ecological group was integrated into an ecological quality ratio (EQR), allowing stations to be classified into five ecological quality classes: high, good, moderate, poor, and bad. The Benthic Ecological Assessment Rapid Index (BEARI) was calculated according to Taşkın [26] using the relative percent cover of benthic ecological groups (BEG I and BEG II) derived from non-destructive photographic sampling. BEG I represented sensitive and late-successional taxa, whereas BEG II included tolerant and opportunistic taxa. All recorded macrofloral taxa are classified into ESG I, ESG II, BEG I, and BEG II categories in Tables S1 and S2. The combined application of EEI-c and BEARI enabled the comparison of destructive and non-destructive macroalgal assessment approaches. The Macroalgae-Land Uses Simplified Index (MA-LUSI) was used to evaluate anthropogenic pressures affecting shallow-water macroalgal communities. Unlike EEI-c and BEARI, MA-LUSI does not incorporate macroalgal community composition and was used as an independent pressure indicator. The Macroalgae-Land Use Simplified Index (MA-LUSI) is a modified version of the land-use index interpreted with a different macroalgae indicator. This index assesses water bodies or stations by categorizing pressures such as marine aquaculture, nutrient release from sediments, sewage discharge, irregular freshwater inflows, ports (direct pressures), urbanization, commerce and industry, and agriculture (indirect pressures). Taşkın et al. [25] provide a detailed analysis on the MA-LUSI index and its application. MA-LUSI is based on coastal land-use characteristics, including urban, industrial, agricultural, and riverine pressures, together with coastline morphology [31,32]. The index values were derived from the Coordination of Information on the Environment (CORINE) Land Cover map within a 1.5 km buffer zone surrounding each sampling station, as described by Taşkın et al. [25]. MA-LUSI values were used to examine relationships between anthropogenic pressures and ecological quality assessments derived from EEI-c and BEARI.

Bray–Curtis similarity analysis was used to examine similarities among stations based on macroalgal ecological group composition and percent cover data. Spearman rank-order correlation analysis was applied to evaluate relationships among ecological groups, index values, MA-LUSI scores, and environmental variables. Principal Compo-

nent Analysis (PCA) was performed to identify the main environmental and ecological gradients structuring the stations. All statistical analyses were conducted using PAST 4.13 software [36] and R 4.6.0 software [37].

3. Results

The ecological status of the sampling stations based on the BEARI showed a predominance of high- and good-quality conditions across the study area. Five stations were classified as high, seventeen as good, one as moderate, one as poor, and one as bad. The highest ecological quality ratio (EQR = 1.00) was recorded at Bozburun-2, whereas the lowest value was observed at İzmir-Bostanlı (EQR = 0.00) (Figure 2). The highest percent cover of sensitive taxa (BEG I) was recorded at Didim (78.15%), Bozburun-2 (64.60%), and Kuşadası (62.12%). In contrast, opportunistic taxa (BEG II) reached maximum values at İzmir-Bostanlı (100%) and Enez (57%) (Table 1).

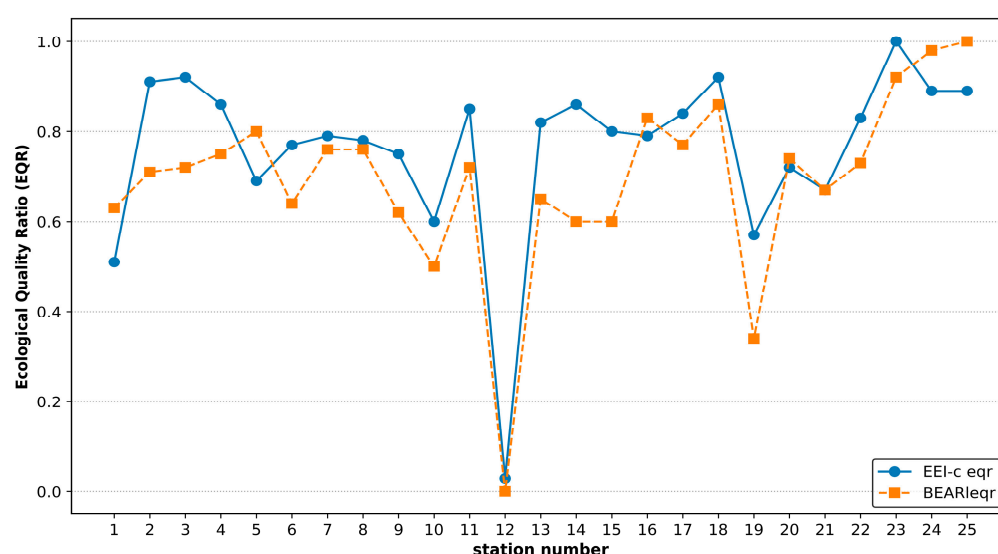


Figure 2. Ecological quality ratio (EQR) values derived from EEI-c and BEARI across the sampling stations [1—Enez; 2—Saros Bay; 3—Gökçeada; 4—Yeniköy; 5—Bozcaada; 6—Küçükkuyu; 7—Altınoluk; 8—Ayvalık; 9—Dikili; 10—Çandarlı; 11—Foça; 12—İzmir; 13—Urla; 14—İldır; 15—Çeşme; 16—Seferihisar; 17—Kuşadası; 18—Didim; 19—Güllük; 20—Bodrum; 21—Akyaka; 22—Gökova Bay; 23—Datça; 24—Bozburun-1; 25—Bozburun-2].

Table 1. MA-LUSI values and relative cover (%) of ecological status groups (ESG I—II) and benthic ecological groups (BEG I—II), together with EEI-c eqr and BEARleqr values across the sampling stations.

Station Name	MA-LUSI	Taxa Number		EEI-c				BEARI			
				Coverage (%)		EEI-c eqr	Ecological Quality Status	Coverage (%)		BEARleqr	Ecological Quality Status
		ESG I	ESG II	ESG I	ESG II			BEG I	BEG II		
Enez	4	11	31	36.19	34.53	0.51	Good	3.88	57	0.63	Good
Saros B.	2.81	13	38	91.11	22.11	0.91	High	44.7	9.9	0.71	Good
Gökçeada	0.9375	15	37	99.02	23.68	0.92	High	34.05	12.1	0.72	Good
Yeniköy	1.125	15	48	85.37	21.87	0.86	High	45.5	7	0.75	Good
Bozcaada	1.875	13	41	57.35	21.45	0.69	Good	48.6	14	0.80	Good
Küçükkuyu	3	14	42	68.84	21.22	0.77	High	43.5	14.4	0.64	Good
Altınoluk	3	19	40	117.76	36.87	0.79	High	37.66	6.66	0.76	Good
Ayvalık	4.5	17	54	80.99	25.65	0.78	High	42.62	9.37	0.76	Good

Dikili	4.5	12	33	59.17	15.37	0.75	High	29.22	17.33	0.62	Good
Çandarlı	5.625	10	34	50.46	37.58	0.60	Good	36.5	23.6	0.50	Moderate
Foça	5	9	32	68.3	21.25	0.85	High	30.9	14.7	0.72	Good
İzmir-Bostanlı	11.25	0	28	0	65.65	0.03	Bad	0	100	0	Bad
Urla	6.25	19	50	130.34	60.81	0.82	High	51.7	16.8	0.65	Good
Ildır	4.68	14	37	67.72	22.2	0.86	High	38.37	23.13	0.60	Good
Çeşme	5	15	28	73.29	18.38	0.80	High	25.63	15.38	0.60	Good
Seferihisar	3.75	8	30	53.97	10.19	0.79	High	37.5	5.5	0.83	High
Kuşadası	1.875	15	28	95.46	16.36	0.84	High	62.12	16.12	0.77	Good
Didim	4.5	20	47	132.27	34.28	0.92	High	78.15	11.35	0.86	High
Güllük	5	19	44	102.18	78.53	0.57	Good	15.85	27.62	0.34	Poor
Bodrum	4.5	15	43	60.3	19.62	0.72	High	34.2	11.2	0.74	Good
Akyaka	4.7	10	26	32.8	14.18	0.67	Good	36	3.33	0.67	Good
Gökova B.	1.875	11	30	55.13	16.87	0.83	High	12.4	6.4	0.73	Good
Datça	3	20	39	112.23	9.3	1	Good	28.25	3	0.92	High
Bozburun-1	3.75	10	21	51.34	8.55	0.89	High	43.36	0.67	0.98	High
Bozburun-2	0.9375	11	21	76.57	5.1	0.89	High	64.6	0	1	High

Colors indicate ecological quality classes: blue = High, green = Good, yellow = Moderate, orange = Poor and red = Bad.

According to the EEI-c index, nineteen stations were classified as high, five as good, and one as bad. The highest ecological quality (EQR = 1.00) was observed at Datça, while the lowest value was recorded at İzmir-Bostanlı (EQR = 0.03). The highest number of sensitive taxa (ESG I) was recorded at Didim and Datça (20 taxa), whereas no ESG I taxa were detected at İzmir-Bostanlı. The highest richness of opportunistic taxa (ESG II) was observed at Ayvalık (54 taxa) and Urla (50 taxa). In terms of percent cover, ESG I values were highest at Didim (132.27%) and Urla (130.34%), whereas ESG II values peaked at Güllük (78.53%), İzmir-Bostanlı (65.65%), and Urla (60.81%) (Table 1).

The distribution of ecological status groups showed a clear dominance of ESG I through most sampling stations. Higher ESG I contributions were generally associated with elevated EEI-c and BEARI_{eqr} values, whereas increased ESG II proportions were observed at more impacted sites. İzmir-Bostanlı exhibited the clearest dominance of opportunistic taxa, while relatively high ESG II values were also recorded at Güllük and Urla. In contrast, Didim, Datça, and Bozburun-2 were characterized by high ESG I dominance. Overall, the spatial pattern of functional groups reflected a gradient from opportunistic-dominated assemblages at disturbed sites to sensitive taxa-dominated communities at less impacted locations (Figure 3).

Linear regression analyses revealed significant negative relationships between the MA-LUSI pressure index and both macroalgal ecological quality indices (Figure 4). EEI-c EQR values decreased with increasing MA-LUSI scores ($R^2 = 0.54$), while BEARI EQR values showed a similar negative trend ($R^2 = 0.57$). These findings indicate that increasing anthropogenic pressure levels are associated with reduced ecological quality in coastal ecosystems. The comparable response patterns of EEI-c and BEARI further demonstrate the sensitivity and consistency of both indices in detecting environmental degradation and pressure gradients along the Aegean Sea coast.

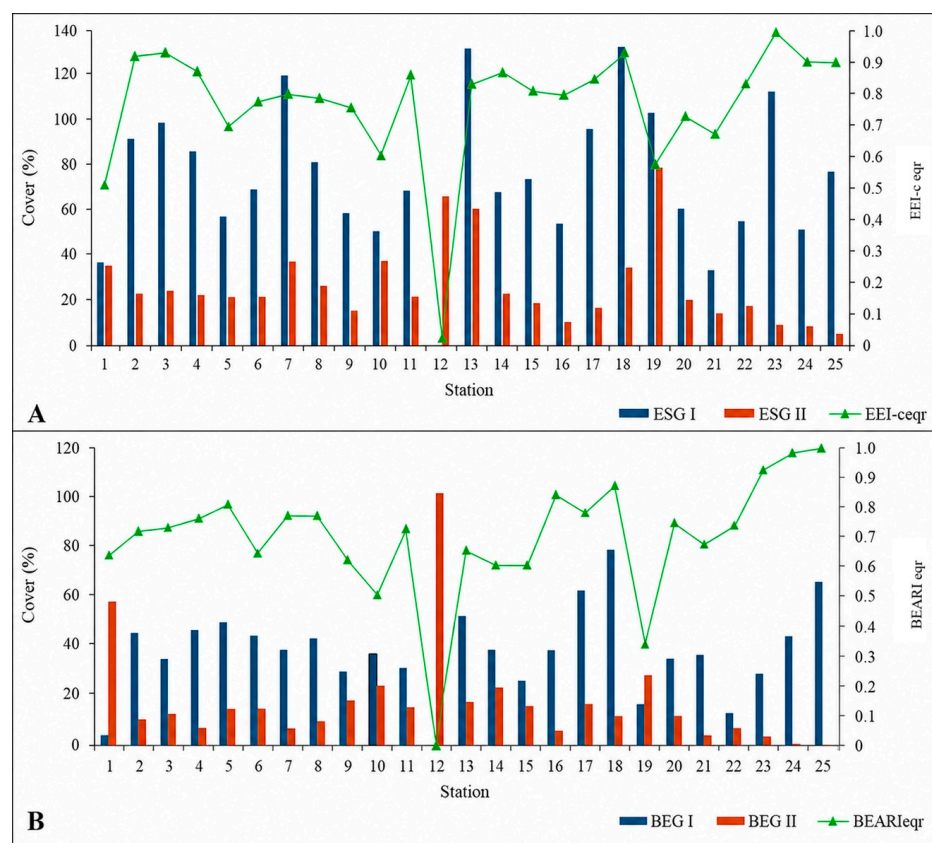


Figure 3. Distribution of ecological functional groups and corresponding ecological quality ratios across sampling stations. (A) Percent cover (%) of ESG I and ESG II groups together with corresponding EEI-c EQR values. (B) Percent cover (%) of BEG I and BEG II groups together with corresponding BEARI EQR values. [1—Enez; 2—Saros Bay; 3—Gökçeada; 4—Yeniköy; 5—Bozcaada; 6—Küçükkuyu; 7—Altınoluk; 8—Ayvalık; 9—Dikili; 10—Çandarlı; 11—Foça; 12—İzmir; 13—Urla; 14—İldır; 15—Çeşme; 16—Seferihisar; 17—Kuşadası; 18—Didim; 19—Güllük; 20—Bodrum; 21—Akyaka; 22—Gökova Bay; 23—Datça; 24—Bozburun-1; and 25—Bozburun-2].

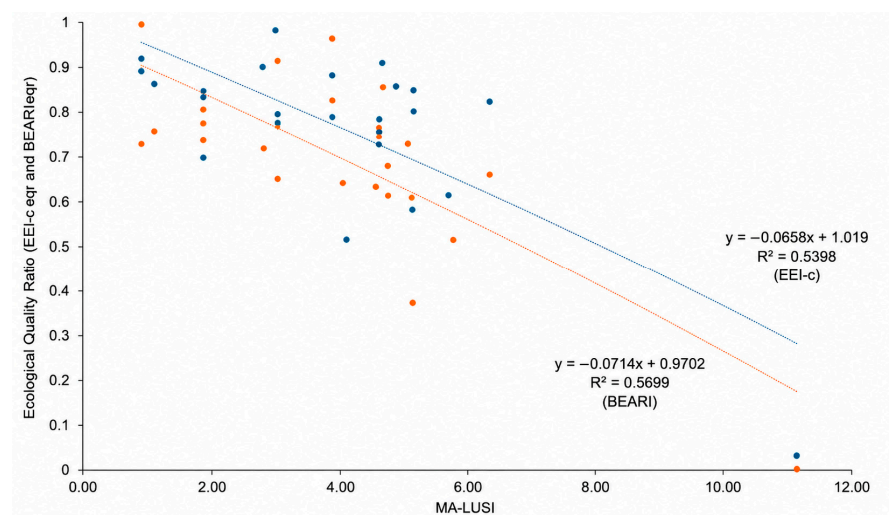


Figure 4. Relationships between the MA-LUSI pressure index and the ecological quality ratios (EQRs) derived from EEI-c and BEARIs across the investigated sampling stations along the Aegean coast ($p < 0.001$). Blue dots indicate EEI-c EQR values, and orange dots indicate BEARI EQR values.

Bray–Curtis similarity dendrogram analysis revealed distinct spatial groupings among the investigated stations based on their macroalgal community structure and en-

vironmental characteristics (Figure 5). Most stations clustered together at relatively high similarity levels, indicating that ecological conditions along the Aegean coast are generally comparable and supporting the predominance of high- and good-ecological-quality classes obtained from the EEI-c and BEARI assessments. In contrast, stations exposed to higher anthropogenic pressures, particularly İzmir-Bostanlı, formed separate or weakly connected clusters, reflecting the influence of eutrophication, coastal urbanization, and local pollution sources on macroalgal assemblages. Intermediate clustering patterns observed for stations such as Çandarlı and Güllük further suggest transitional ecological conditions associated with localized environmental stress. Overall, the dendrogram analysis demonstrated that Bray–Curtis similarity revealed differences among stations based on macroalgal community composition. Although the clustering results were generally consistent with the ecological quality assessments, some stations with different ecological classifications, such as İzmir-Bostanlı and Enez, were grouped together, indicating that community similarity does not always correspond directly to ecological quality classes derived from EEI-c and BEARI.

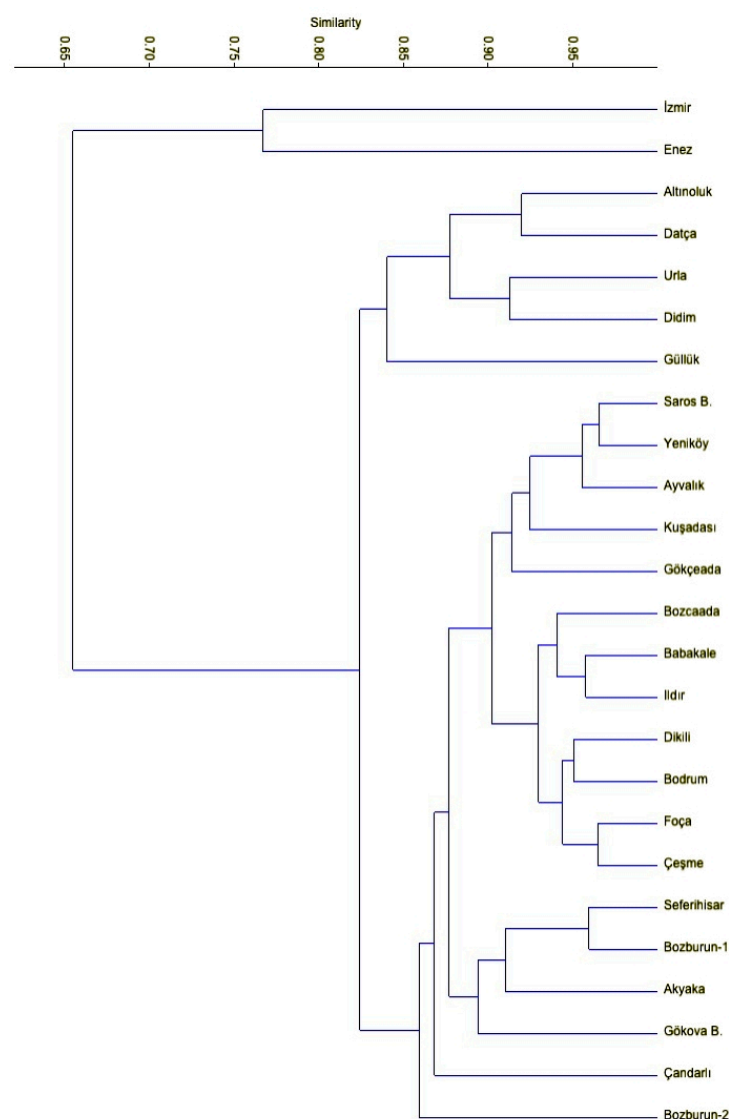


Figure 5. Bray–Curtis similarity dendrogram of sampling stations based on abiotic and biotic variables.

Spearman rank-order correlations were used to examine the relationships among the variables (Table 2), with statistical significance considered at $p < 0.05$. Principal Compo-

nent Analysis (PCA) was performed to evaluate relationships between abiotic and biotic variables. The first two axes explained 59.44% of the total variance (Figure 6). BEG I was positively correlated with BEARLeqr ($r = 0.54$), whereas BEG II was negatively correlated with BEARLeqr ($r = -0.79$), indicating contrasting responses of sensitive and opportunistic groups. EEI-c was positively associated with BEARLeqr ($r = 0.57$), while MA-LUSI showed a positive relationship with BEG II ($r = 0.56$). İzmir-Bostanlı and Enez were associated with ESG II, MA-LUSI, and nutrient variables, whereas several stations were associated with EEI-c, BEARLeqr, and ESG I, reflecting comparatively better ecological conditions. A strong positive relationship was observed between EEI-c eqr and BEARLeqr values across the sampling stations, with an R^2 value of 0.71, indicating substantial agreement between destructive and non-destructive assessment approaches (Figure 7).

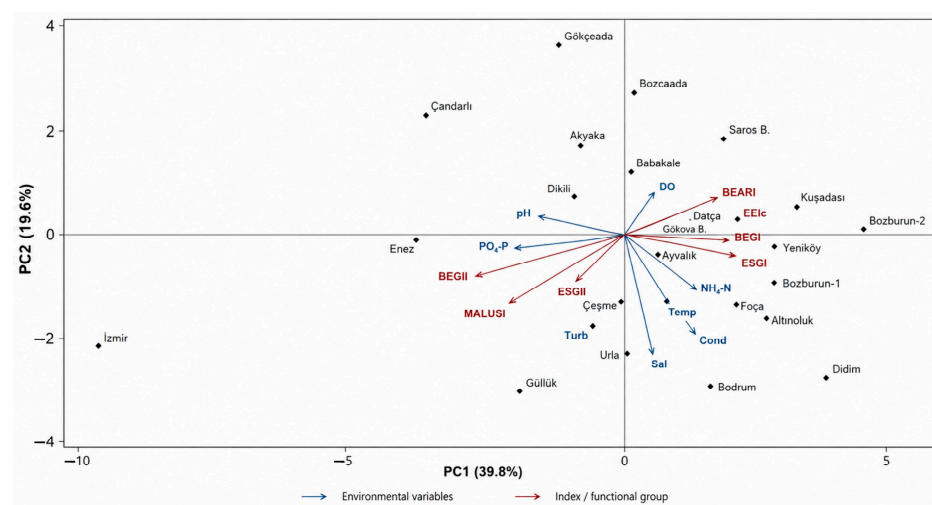


Figure 6. Principal Component Analysis (PCA) ordination of sampling stations based on biotic and abiotic variables: [1—Enez; 2—Saros Bay; 3—Gökçeada; 4—Yeniköy; 5—Bozcaada; 6—Küçükkuyu; 7—Altınoluk; 8—Ayvalık; 9—Dikili; 10—Çandarlı; 11—Foça; 12—İzmir; 13—Urla; 14—İldır; 15—Çeşme; 16—Seferihisar; 17—Kuşadası; 18—Didim; 19—Güllük; 20—Bodrum; 21—Akyaka; 22—Gökova Bay; 23—Datça; 24—Bozburun-1; 25—Bozburun-2].

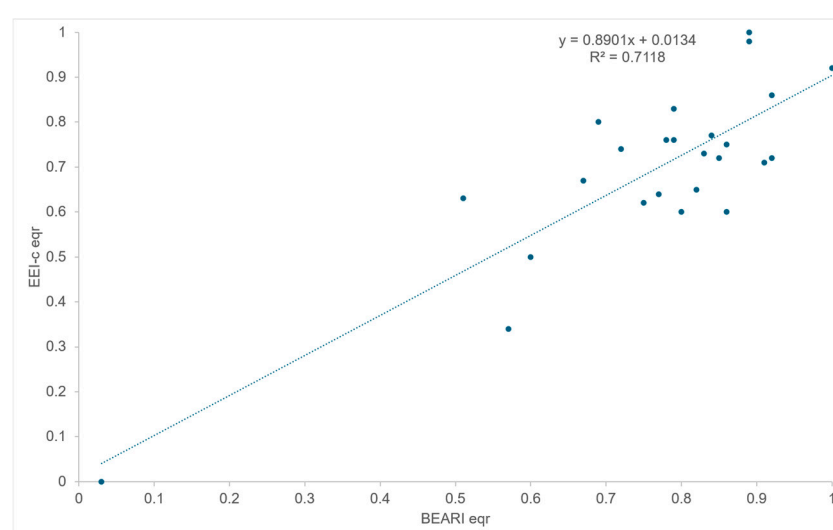


Figure 7. Relationship between EEI-c eqr and BEARLeqr values across the sampling stations. The dashed line represents the linear regression model ($R^2 = 0.71$).

Table 2. Spearman rank-order correlation coefficients among ecological groups, ecological quality indices (EEI-c and BEARleqr), physicochemical variables, nutrient parameters, and MA-LUSI across the sampling stations.

Spearman Rank-Order Correlations															
	BEG I (%)	BEG II (%)	BEARleqr	ESG I (%)	ESG II (%)	EEI-c	MA-LUSI	pH	T	DO	Turb.	Cond.	Sal.	PO4-P	NH4-N
BEG I (%)		-3.15×10^{-1}	0.5407	0.41385	-1.18×10^{-1}	4.27×10^{-1}	−0.36361	−0.36035	0.050808	0.080092	0.063945	0.099635	9.17×10^{-2}	0.014615	0.004615
BEG II (%)	−0.31538		−0.797	-1.15×10^{-1}	6.59×10^{-1}	-5.22×10^{-1}	0.55681	0.056593	−0.36682	0.19792	−0.2057	−0.25466	-2.58×10^{-1}	0.41385	−0.09846
BEARleqr	0.5407	−0.797		0.274	−0.55301	0.5791	−0.63097	0.037173	0.26516	−0.11327	0.30931	0.37356	0.37514	−0.34404	0.11276
ESG I (%)	0.41385	−0.11462	0.274		0.21462	0.57819	−0.22566	−0.16362	0.010778	0.084713	0.28852	0.33122	0.34007	0.006923	0.075385
ESG II (%)	−0.11846	0.65923	−0.55301	0.21462		-3.57×10^{-1}	0.43393	0.050433	−0.3341	0.12168	−0.2057	−0.12387	-1.23×10^{-1}	0.41231	0.090769
EEI-c	0.42739	−0.52241	0.5791	0.57819	−0.35738		−0.48909	−0.27166	−0.00712	−0.16676	0.31612	0.2728	2.68×10^{-1}	0.008463	−0.16772
MA-LUSI	−0.36361	0.55681	−0.63097	−0.22566	0.43393	−0.48909		−0.02882	−0.11485	0.19923	0.1341	0.18744	0.18011	0.17234	−0.01314
pH	−0.36035	0.056593	0.037173	−0.16362	0.050433	−0.27166	−0.02882		−0.05683	0.13683	−0.25911	−0.32538	−0.31284	0.030414	0.19134
T	0.050808	−0.36682	0.26516	0.010778	−0.3341	−0.00712	−0.11485	−0.05683		0.16551	0.39071	0.3794	0.3729	−0.25712	0.4642
DO	0.080092	0.19792	−0.11327	0.084713	0.12168	−0.16676	0.19923	0.13683	0.16551		1.55×10^{-1}	9.94×10^{-2}	0.11567	0.17251	0.25992
Turb.	0.063945	−0.2057	0.30931	0.28852	−0.2057	0.31612	0.1341	−0.25911	0.39071	0.15465		8.67×10^{-1}	0.86519	−0.26579	−0.01618
Cond.	0.099635	−0.25466	0.37356	0.33122	−0.12387	0.2728	0.18744	−0.32538	0.3794	0.099365	0.86689		0.9973	−0.31429	0.16118
Sal.	0.091662	−0.25843	0.37514	0.34007	−0.12324	0.26772	0.18011	−0.31284	0.3729	0.11567	0.86519	0.9973		−0.3162	0.17562
PO4-P	0.014615	0.41385	−0.34404	0.006923	0.41231	0.008463	0.17234	0.030414	−0.25712	0.17251	−0.26579	−0.31429	−0.3162		−0.19615
NH4-N	0.004615	−0.09846	0.11276	0.075385	0.090769	−0.16772	−0.01314	0.19134	0.4642	0.25992	−0.01618	0.16118	0.17562	−0.19615	

Significant correlations ($p < 0.05$) are shown in bold.

Based on BEARI ecological quality ratios, most sampling stations were classified under sustainable management targets, reflecting generally good ecological conditions along the Turkish Aegean coast (Figure 8). In contrast, İzmir-Bostanlı and Güllük were identified as restoration-priority areas due to their low-ecological-quality ratios and the dominance of opportunistic taxa. Çandarlı was also associated with restoration-oriented management because of its moderate ecological condition. These conditions may be associated with anthropogenic pressures identified by MA-LUSI, including urbanization, coastal development, riverine inputs, and other land-based sources of disturbance affecting the investigated coastal sectors.

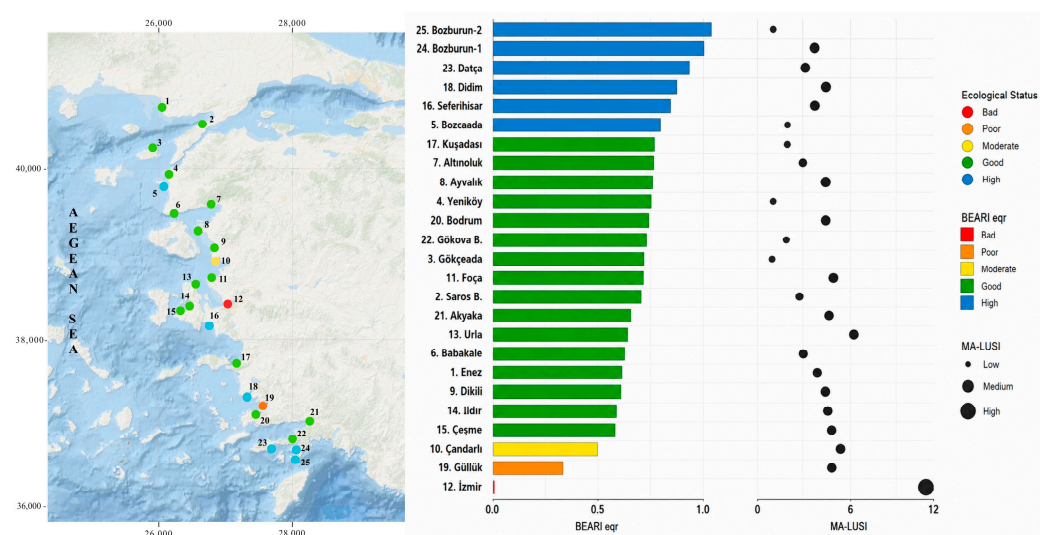


Figure 8. Spatial distribution of ecological quality classes together with BEARIEqr values and MA-LUSI-based anthropogenic pressure levels along the Turkish Aegean coast. Station numbers correspond to the following sampling locations: 1—Enez; 2—Saros Bay; 3—Gökçeada; 4—Yeniköy; 5—Bozcaada; 6—Küçükkeyu; 7—Altınoluk; 8—Ayvalık; 9—Dikili; 10—Çandarlı; 11—Foça; 12—İzmir; 13—Urla; 14—İldır; 15—Çeşme; 16—Seferihisar; 17—Kuşadası; 18—Didim; 19—Güllük; 20—Bodrum; 21—Akyaka; 22—Gökova Bay; 23—Datça; 24—Bozburun-1; and 25—Bozburun-2.

4. Discussion

The present study showed that most coastal stations along the Aegean Sea of Türkiye exhibited high-to-good ecological status according to both EEI-c and BEARI assessments. The consistency between these indices supports previous studies showing that macroalgal functional groups respond sensitively and predictably to environmental gradients and anthropogenic pressures, thereby serving as reliable indicators of coastal ecological quality [6,22,24,25]. The spatial distribution of ecological status revealed a clear difference between relatively less disturbed southern Aegean stations and locally impacted coastal areas. Stations such as Datça and Bozburun-2 were characterized by high ecological quality, reflecting the dominance of sensitive and late-successional taxa. In contrast, İzmir-Bostanlı exhibited markedly lower ecological quality, indicating strong local anthropogenic influence. Similar ecological patterns have previously been reported from Turkish coastal waters, where degraded sites were associated with elevated anthropogenic pressure levels and the dominance of opportunistic macroalgal taxa [6,22,24–26]. The degraded condition of İzmir-Bostanlı was mainly reflected by the dominance of ESG II and BEG II taxa. Opportunistic algae are widely known to increase under nutrient enrichment, eutrophication, and coastal disturbance, whereas sensitive late-successional macroalgae tend to decline under such pressures [6,38,39]. Therefore, the dominance of opportunistic taxa at İzmir-Bostanlı provides strong biological evidence of

localized ecological degradation. These findings may be associated with differences in the dominant anthropogenic drivers affecting individual coastal sectors. The degraded ecological condition observed at İzmir-Bostanlı is consistent with the intense urbanization and population pressure characterizing the Inner Gulf of İzmir. In addition, riverine inputs associated with major river basins, including the Meriç, Bakırçay, Gediz, Küçük Menderes, and Büyük Menderes rivers, may contribute to nutrient enrichment and ecological disturbance in adjacent coastal areas. Local pressures related to mariculture activities, particularly fish farms located in Ildır and Güllük bays, may also influence macroalgal community structure. Furthermore, seasonal increases in population associated with tourism activities may contribute to localized environmental pressures in several coastal areas along the Aegean coast. The comparison between EEI-c and BEARI indicated substantial consistency despite methodological differences. EEI-c is based on destructive sampling and detailed taxonomic resolution, whereas BEARI offers a rapid, non-destructive alternative based on photographic percent-cover assessment and functional group classification. The positive relationship between EEI-c and BEARLeqr ($R^2 = 0.71$) supports the reliability of BEARI as a complementary tool for rapid ecological assessment, although some station-level discrepancies suggest that both approaches should be interpreted together when possible. In the present study, BEARI appeared to be more sensitive to localized anthropogenic impacts than EEI-c. While EEI-c classified most stations as having high or good ecological status, BEARI also identified moderate and poor ecological conditions at Çandarlı and Güllük, respectively. This suggests that the non-destructive BEARI approach may provide finer discrimination of local ecological disturbances, particularly in areas exposed to multiple anthropogenic pressures. Similar macroalgae-based ecological assessment approaches have been widely applied across Mediterranean coastal ecosystems, particularly in Greece, Italy, Algeria, and other regions subjected to increasing anthropogenic pressures [22,23,28,30]. Previous studies demonstrated that EEI-c effectively reflects eutrophication gradients and ecological degradation in Mediterranean coastal waters through shifts in macroalgal functional groups [22,24,30]. The present findings are consistent with these studies, confirming that sensitive late-successional taxa dominate in relatively undisturbed environments, whereas opportunistic taxa increase in areas exposed to nutrient enrichment and coastal disturbance. In recent years, increasing attention has also been given to rapid and non-destructive monitoring methodologies due to their operational advantages, lower ecological impact, and suitability for long-term monitoring programs in sensitive habitats [5,26,27]. In this context, the substantial agreement observed between EEI-c and BEARI supports the applicability of non-destructive approaches as complementary tools for ecological quality assessment. Such methodologies may be particularly valuable within the framework of the European Water Framework Directive (WFD) and Marine Strategy Framework Directive (MSFD), where cost-effective, repeatable, and ecologically sustainable monitoring strategies are becoming an increasingly important aspect of large-scale coastal assessment programs. The results also highlight the importance of combining biological indices with pressure-based and multivariate analyses. MA-LUSI was associated with opportunistic groups, particularly BEG II, while stations with higher EEI-c and BEARLeqr values were generally associated with sensitive taxa. Similar relationships between anthropogenic pressure indices and macrophyte-based ecological quality metrics have previously been reported from Turkish coastal waters [24,26]. The multivariate analyses further demonstrated that ecological status was influenced by the combined effects of functional group composition and environmental variables. Stations associated with nutrient-related variables and MA-LUSI reflected greater anthropogenic pressure, whereas stations associated with ESG I and higher index values represented less disturbed

ecological conditions. These findings support the use of macroalgal functional groups as sensitive indicators of coastal environmental gradients.

Overall, the present study demonstrates that the combined application of destructive and non-destructive macroalgal indices can provide a more reliable assessment of ecological status. EEI-c offers detailed taxonomic and functional information, whereas BEARI provides a rapid and practical tool for ecological monitoring, particularly where non-destructive approaches are preferred. The complementary use of these indices may therefore strengthen coastal monitoring and management strategies within the framework of the Water Framework Directive.

Despite the robustness of the applied indices, the present study represents a spatial assessment restricted to a single sampling period. Seasonal variability of macroalgal assemblages may influence ecological quality assessments; therefore, future studies should incorporate multi-seasonal monitoring approaches to improve temporal resolution and ecological interpretation.

5. Conclusions

The present study shows that the Aegean Sea coastal waters of Türkiye generally have high to good ecological status according to both destructive EEI-c and non-destructive BEARI macroalgal indices. Localized degradation occurred in İzmir-Bostanlı and Güllük, with opportunistic taxa dominating, and the lowest ecological quality ratios were reported. The important positive relationship between EEI-c and BEARIEqr supports the use of BEARI as a fast, cost-effective and non-invasive complementary tool for large-scale coastal monitoring, which can be easily incorporated into national marine monitoring strategies and the operational frameworks of the European Water Framework Directive (WFD). The inclusion of these biological indices in the MA-LUSI pressure index and multivariate analysis offers an integrated approach to detect pressure-related ecological gradients, implying that the most degraded areas should be classified as high-priority areas for ecological restoration. Although this spatial assessment provides a solid baseline along the Turkish Aegean coast, future research should include multi-seasonal and long-term monitoring designs to distinguish between permanent anthropogenic degradation and natural temporal variability of macroalgal assemblages.

These findings are consistent with previous studies conducted in Greece, Italy, and Algeria, supporting the broader applicability of macroalgal ecological indices for ecological status assessment across Mediterranean coastal ecosystems [22,23,28,30]. Accordingly, immediate and target-specific management interventions are required to mitigate environmental degradation in coastal sectors with high MA-LUSI scores and intense anthropogenic pressures. First, the efficiency and capacity of municipal and industrial wastewater treatment plants (WWTPs) should be upgraded to the advanced tertiary level in order to strictly control the nutrient enrichment and prevent localized eutrophication in vulnerable zones. There is a need for strict enforcement of sustainable agricultural practices and creation of riparian buffer zones to minimize diffuse nitrogen and phosphorus runoff in river and agricultural-dominated landscapes, such as river catchments. Moreover, local mariculture activities, especially fish farms in enclosed bays, should be tightly controlled with carrying capacity assessments and be moved to offshore or integrated multi-trophic aquaculture (IMTA) systems in order to reduce the organic load on benthic habitats. Finally, these technical interventions should be integrated in broader Integrated Coastal Zone Management (ICZM) plans that restrict destructive coastal development and support the conservation of native macroalgal communities, thus enhancing the overall ecological resilience of coastal ecosystems of the Aegean Sea.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/d18070404/s1>. Table S1. Classification of macrofloral taxa into ecological status groups (ESG I and ESG II) (Orfanidis et al., 2011). Table S2. Classification of macrofloral taxa into benthic ecological groups (BEG I and BEG II) (Taşkın, 2020).

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