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Assessment of Aquatic Ecosystems from Coastal Lakes (Agigea, Tuzla, and Costinești)

Ana Bianca Pavel* *, Catalina Gavrila, Irina Catianis, Gabriel Iordache, Catalin Gheablau, Florina Radulescu, Albert Scrieciu

National Institute for Research and Development on Marine Geology and Geoecology – GeoEcoMar, 024053 Bucharest, Romania

ABSTRACT

This study presents an integrated assessment of sedimentological, granulometric, physico-chemical, and biological characteristics in three Romanian coastal lakes, based on 2022 field surveys. A total of 59 sediment samples were analyzed lithologically and granulometrically, and 12 were examined for macrozoobenthic community composition. Water samples were assessed for nutrient and pigment concentrations to evaluate trophic status and ecological condition. Sediments were predominantly silty–clayey, indicating low-energy depositional environments. Organic matter content was highest in Lakes Agigea and Tuzla, suggesting enhanced primary productivity and organic detritus accumulation, while Lake Costinești showed higher biogenic carbonate content from mollusc shells. Macrozoobenthic assemblages were dominated by taxa tolerant to organic enrichment and hypoxia, including Chironomidae larvae, Oligochaeta, and Cyprideis torosa. Water quality analysis indicated good ecological status in Agigea Lake, whereas Tuzla Lake was severely eutrophic, with phosphate and nitrite in Class IV and chlorophyll-a exceeding Class V thresholds (>250 μg/L), consistent with cyanobacterial blooms. Elevated sulfate (Class III) and suspended solids further impaired Tuzla's transparency. In Costinești, marine taxa presence and variable salinity reflected periodic seawater exchange. Anthropogenic influences were evident—nutrient enrichment from fisheries in Tuzla and marine species introduction

*CORRESPONDING AUTHOR:
Ana Bianca Pavel, National Institute for Research and Development on Marine Geology and Geoecology – GeoEcoMar, 024053 Bucharest, Romania; Email: biancapavel@geoecomar.ro

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in Costinești—highlighting system vulnerability to human pressure. The integration of sediment, water quality, and biological indicators emphasizes the need for continuous, interdisciplinary monitoring to track ecological shifts, support adaptive management, and conserve biodiversity and ecosystem integrity in Romanian coastal lakes.

Keywords: Coastal Lakes; Sedimentology; Granulometry; Macrozoobenthos; Organic Matter; Anthropogenic Impact; Ecological Assessment; Romanian Black Sea Coast

1. Introduction

The lakes on the Romanian Black Sea coast have always been a subject of interest from both a scientific and practical points of view, preoccupying researchers from multiple fields. In this paper, our attention is focused on three coastal lakes, namely: Agigea Lake, Tuzla Lake, and Costinești Lake. From a limnological point of view, coastal lakes were classified according to the definition of Gâștescu [1], which integrates several essential criteria: the nature of the water balance (surplus, deficit, or constant), the hydrochemical particularities (degree of mineralization and hydrochemical type), the phase of evolution of the lake (sediment thickness, shore configuration and degree of vegetation coverage) and the biological criterion (capacity and degree of organization of living matter). Thus, these lakes fall into the Ponto-Danubian province, the subprovince of steppe lakes, delimited on the basis of the elementary water balance, and are grouped into four limnological regions, depending on the genesis of the lake basins [2].

A distinct type of lakes included in this classification is those fed predominantly by precipitation. Due to the low precipitation in the region, the water intake, including any secondary sources, does not compensate for the intense evaporation, determining a negative water balance in the long term. This phenomenon gradually leads to an increase in the concentration of salts in the water. The permanent decrease in the water level, caused by the negative water balance, favors the penetration of saline waters from neighboring basins (the sea or adjacent lakes). Thus, favorable conditions are formed for the development of a few species of lower organisms, which multiply intensively due to the lack of interspecific competition [2,3]. These organisms, together with mineral particles originating from the erosion of the slopes, contribute to the formation of sapropelic mud. Due to the curative properties of the mud and water, these lakes have an important balneo-therapeutic role. Lakes Agigea and Tuzla fall into this category, although Lake Agigea has recently evolved into a freshwater lake. The lakes analyzed in this study reflect different dynamics and evolutions of natural processes:

- Lakes characterized by an increased freshwater input, which results in a continuous rise in the level and the reduction of the salt concentration. This evolution favors abrasion processes and the development of macrophyte vegetation in the future (for example, Lakes Agigea and Techirghiol–Tuzla).
- Lakes with a relatively constant salt concentration, where the activity of littoral processes is minimal due to the stability of the water level or its reduced variations. In such cases, the degree of clogging is directly proportional to the surface area of the watershed compared to that of the lake, exemplified by Costinești Lake [2].

This study aims to comprehensively evaluate the lithological, granulometric and biological characteristics of sediment samples collected from the coastal lakes of Agigea, Tuzla and Costinești. By analyzing sediment composition, texture and benthic macroinvertebrate communities, the research aims to determine the ecological status, assess habitat quality and identify potential anthropogenic impacts influencing these coastal aquatic ecosystems.

Relevance and Impact of the Study

The relevance of this study lies in its contribution to the understanding of the ecological dynamics and environmental conditions of Romanian coastal lakes, which are crucial habitats for diverse biological communities. The data obtained provide insights into sedimentological processes and benthic community structures, essential for effective environmental management, conservation planning, and sustainable use of coastal resources. The impact of the research extends to informing policy decisions, guiding restoration initiatives, and increasing the ecological resilience of coastal wetland ecosystems in response to environmental and anthropogenic pressures.

2. Materials and Methods

2.1. Study Area

2.1.1. Agigea Lake

Lake Agigea is located south of the municipality of Constanța, in a wide valley open to the sea, resembling an amphitheater delimited by two limestone promontories. It has a rectangular shape, elongated towards the tail, and is oriented perpendicular to the Black Sea shore. The shores of the lake vary in height from the water level between 0 and 4 meters, presenting notable differences between the flanks: the northern one, made up of loess, and the southern one, made up of very friable oolitic limestones, subject to pronounced processes of erosion and collapses. On the side facing the perisip, the low and partially vegetated shore was consolidated by the construction of a road, but it is periodically affected by floods. The lake's hydrographic basin has an area of approximately 40 km² and is drained by three main valleys with temporary drainage. Agigea Lake, with an area of 35 ha, is a fluvial-maritime estuary classified as a natural protected area of zoological type (Category IV, IUCN). The lake has an average depth of 0.45 m, a maximum depth of 0.7 m, and a total volume of approximately 0.3 million m³. Its particularity lies in the fact that the lake bottom is 0.2 m above sea level, being unique on the Romanian coast from this point of view [2].

Historically, Agigea Lake was salty, similar to Techirghiol Lake, but anthropogenic activities, including its transformation into a fish farm in 1985 and the construction of the Danube-Black Sea Canal, led to its desalination and reduction in surface area. The specific reed vegetation, initially extending on the northern shore and towards the tail, was drastically reduced, affecting biodiversity, especially bird populations. If in 1967 there were between 5,000 and 10,000 birds of valuable species, today their number and diversity have decreased significantly, with migratory species prevailing. The lake is also known for its sapropelic mud, which was the basis for the establishment of the Agigea balneoclimatic resort. Currently, however, due to anthropogenic changes, the lake contains fresh water. Access to the lake is easy via the national road DN39, Constanța — Vama Veche [2].

2.1.2. Tuzla Lake

Balta Tuzla is an artificial lake, originally formed to protect Lake Techirghiol from excessive freshwater inflow. Located only 150 m from the Black Sea shore and in the immediate vicinity of Lake Techirghiol, the lake covers an area of 50.4 ha and has a watershed of 5.4 km². Its separation from Lake Techirghiol was achieved by a dam built in the 1980s, with a dual role: providing access to the local television tower and stopping freshwater leaks that affected the salinity of Lake Techirghiol. Before the 1970s, the area was predominantly arid, but anthropogenic changes and the increased freshwater input transformed it into a marshy area, later evolving into an independent permanent lake, starting in the 2000s. Today, Lake Tuzla is bordered by numerous dense reed formations, and its greening process is supported by the closure of the Eforie landfill and the stopping of discharges from the local treatment plant. Easy access to the lake is possible directly from the Constanța-Mangalia Road [2].

2.1.3. Costinești Lake

Costinești Lake, located between the towns of Schitu and Costinești, is the smallest of the lakes south of Cape Midia. It has an oval-elongated shape and is delimited in the southern part by a steep slope, and in the northern part by gentle slopes, which coincide with the opening of two small valleys where the Costinești locality is located. The bottom of the lake is largely made up of shelly sand arranged in dunes, partially fixed with grassy vegetation, and its hydrographic basin has an area of 21.25 km², being drained by several streams with temporary outflow. Currently, the lake and its surroundings are landscaped, facilitating access for tourists and locals [2].

2.2. Physico-chemical Parameters of Water

The characterization of surface water quality was carried out through in situ measurements of physicochemical parameters, using an EXO2 multiparameter probe (YSI, USA). The equipment is equipped with advanced sensors that apply physical, optical, and electrochemical detection methods, allowing the determination of a wide range of water quality indicators [4]. The monitored parameters included: temperature (°C), pH (pH units), turbidity (FNU), total dissolved solids (TDS, mg/L), conductivity (µS/cm), dissolved oxygen (ODO, mg/L), oxygen saturation (ODO, %), oxidation-reduction potential (ORP, mV), salinity (PSU), nitrate concentration (NitraLED, mg/L), chlorophyll a (RFU), and total algae content (TAL-PC, RFU).

The classification of water quality was carried out according to the criteria provided in Order no. 161/2006 [5], which establishes five quality classes: Class I (very good), Class II (good), Class III (moderate), Class IV (poor), and Class V (bad). The assessment integrated both national standards (Order no. 161/2006 on reference objectives for the classification of surface water quality) and international standards, in particular the European Water Framework Directive (WFD 2000/60/EC) [6], which provides a unified framework for the qualitative and quantitative management of water resources and for the preservation of the health of aquatic ecosystems in the Member States of the European Union. Physico-chemical analyses were performed according to internationally standardized methodologies, including: SR EN ISO 5667-1:2023 [7] for water sampling, SR EN ISO 10523:2012 [8] for pH determination, and SR EN ISO 5814:2013 [9] for dissolved oxygen measurement.

Nutrient determinations were performed for water samples collected from Lake Tuzla. The samples were preserved by freezing (-20°C) and subsequently analyzed in the INCD GeoEcoMar Constanta laboratory, according to standard procedures described by Grasshoff et al. [10]. The determined parameters included phosphates, silicates, nitrites, nitrates, and ammonium, used for the assessment of trophic status. The measurements were performed with a Perkin Elmer Lambda 35 spectrophotometer, applying colorimetric methods specific to each compound, with wavelengths adapted to the detected concentrations. The chlorophyll a content was determined by filtering the samples through nitrocellulose membranes (0.8 µm), extraction with 90% acetone, and spectrophotometric measurement using the Jeffrey–Humphrey trichromatic method [11].

2.3. Sediment Sample Collection and Analysis

Sediment sample collection required for sedimentological, geochemical, and biological analyses (macrozoobenthos) was performed using a Van Veen bodengraifer (SR EN ISO 10870:2012 [12]), the multiplication factor for reporting ecological indices per unit area being 25.2 (**Figure 1**).

In 2022, a total of 59 sediment samples were collected for detailed lithological and granulometric analyses aimed at characterizing sediment composition and texture. Additionally, 12 sediment samples were obtained specifically for the assessment and analysis of macrozoobenthic communities, to evaluate the ecological status and biodiversity within the studied aquatic systems (**Figure 2**).

Figure 1. Van Veen Bodengreifer.

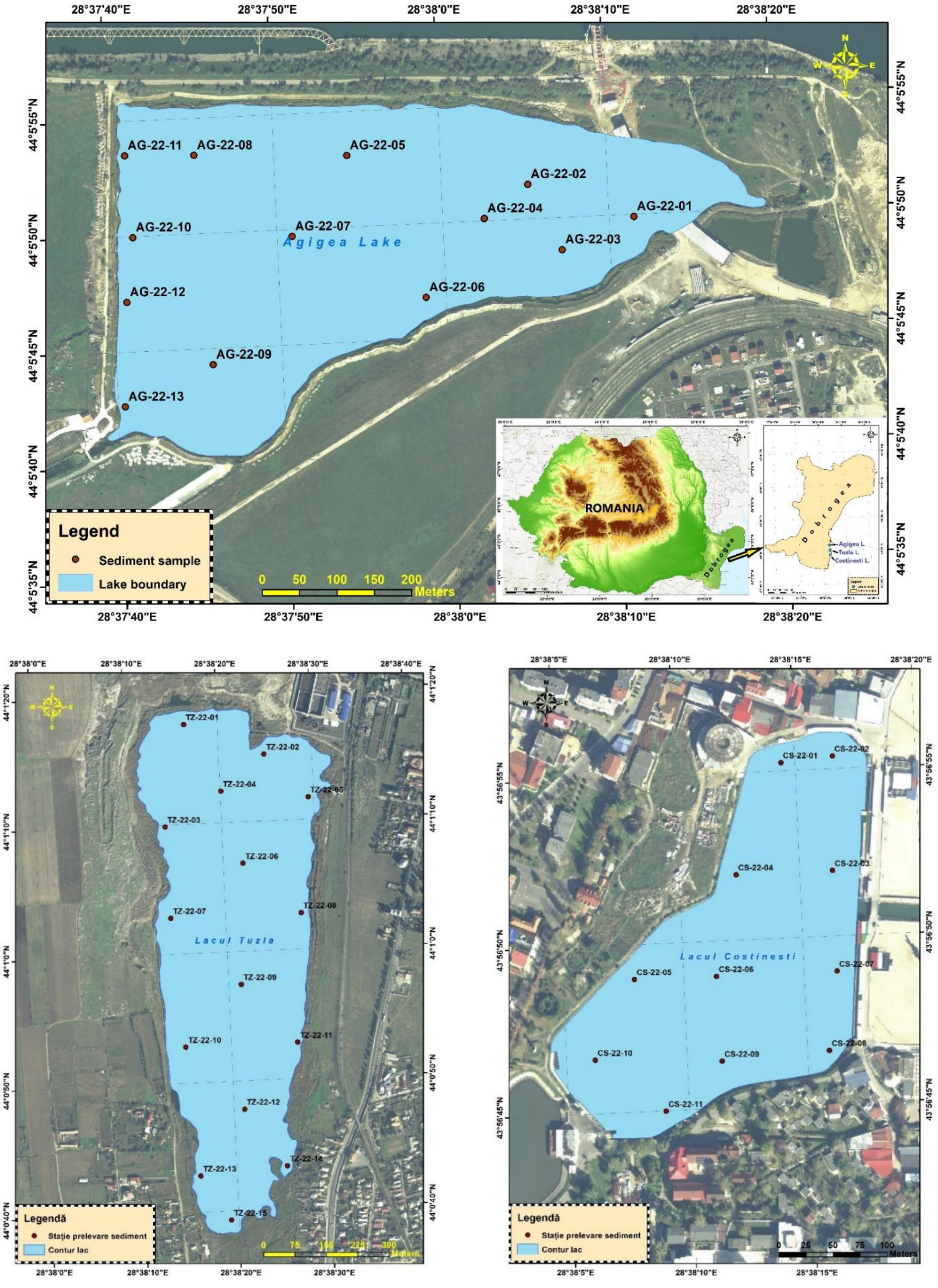


Figure 2. The three lakes (Agigea, Tuzla, and Costinești) in the study area, with sampling stations.

2.4. Granulometric Analysis

Sediment granulometric analysis was performed by laser diffractometry, using the granulometric analyzer “Mastersizer 2000E Ver. 5.20” (Malvern). For samples composed exclusively of gravel and sand, the sieving method was used, and for heterogeneous sediments (containing also fine particles of silt and clay), the combined diffractometry-sieving method was applied. The separation of the granulometric classes (gravel, sand, silt, and clay) and the fractions within each class was carried out according to the Udden-Wentworth logarithmic scale, completed with the detailing of the fractions in the clay domain [13,14]. The classification of the sediments was made using the Shepard diagram. The calculated granulometric parameters were the median (Md = Ø50), the graphical mean (Mz), the standard deviation (σ), the skewness coefficient (SkI), and the kurtosis (KG), according to the original Folk and Ward formulas [15]:

$$Mz=\frac{(\O16+\O50+\O84)}{3}$$

$$\sigma=\frac{(\O84-\O16)}{4}+\frac{(\O95-\O5)}{6.6}$$

$$SkI=\frac{\O16+\O84-2(\O50)}{2(\O84-\O16)}+\frac{\O5+\O95-2(\O50)}{2(\O95-\O5)}$$

$$K_G=\frac{\O95-\O5}{2.44(\O75-\O25)}$$

2.5. Lithological Analysis

The sediment samples were analyzed for the main lithological components:

Water Content (WC%) - Water Content; Dry Matter (DM%) - Dry Matter; Total Organic Matter (TOM%) - Total Carbonates (CAR%); Siliciclastic Fraction (SIL%).

The lithological analysis was performed based on standard techniques and procedures used in sedimentology.

Determination of Mass Loss on Drying (LOD Method)

The water content and dry matter were estimated gravimetrically by the Loss of Drying (LOD) method at a temperature of 105°C [16,17]. This method involves the successive weighing of the samples before and after drying. The result expressed as a percentage reflects the difference in weight between the wet and dry sediment. Water content is an important physical property of aquatic sediments, varying significantly (30-50% in mineral sediments and up to 95–99% in highly organic sediments). The dry residue represents the amount remaining after drying the sediment and indicates its compaction degree.

Determination of Mass Loss on Ignition (LOI Method)

The main lithological components of the sediments (total organic matter, carbonates, and siliciclastic fraction) were determined in percentage by the loss on ignition (LOI) method, using a SNOL 8.2/1100 calcination furnace [18,19]. The method consists of successively measuring the weight loss of the sediment at specific temperatures: at 550°C for the determination of organic matter and at 950–1000°C for the determination of carbonate content.

The organic matter in sediments, consisting of plant, animal, and microbial particles, is determined by mass loss at 550°C. Sediments are classified based on this content into mineral sediments (<15–30% organic matter) and organic sediments (>15–30% organic matter) [20]. The carbonate content is determined by mass loss at 950°C and empirically classified as follows [21,22]: non-carbonate sediments (≤10% $CaCO_3$), slightly carbonate sediments (10–30% $CaCO_3$), and carbonate sediments (>30% $CaCO_3$). The siliciclastic fraction is the residue remaining after the removal of organic matter and carbonates.

2.6. Analysis of Biological Samples

To establish the ecological status of benthic populations in lakes Agigea, Tuzla, and Costinesti, the multihabitat technique was used, a modified version of the AQEM method (European standard used for monitoring surface water bodies in Romania). During the field campaign, quantitative and qualitative zoobenthos samples were collected, using a Van Veen type bodengraifer and a limnological stocking, depending on the heterogeneity of the substrate [12]. All habitats with a coverage greater than 5% were identified and classified according to SR EN ISO 16150:2012 [23].

The collected sediments, together with the benthic organisms, were initially washed through the limnological stocking and stored in plastic jars. The fixation and preservation of the samples were achieved by adding a mixed solution of 4% buffered formaldehyde and Congo Red or Pink Bengal dye. Three replicates were collected for each microhabitat. In the laboratory, the samples were processed according to the European standard methodology [12]. The sediment material was sieved through granulometric sieves with mesh diameters of 1 mm, 0.5 mm, and 0.250 mm, to separate the macro-, meio- and microfauna. The sorting and identification of benthic organisms were performed under the Carl Zeiss SteREO Discovery V8 stereomicroscope and the Carl Zeiss Axio Star microscope. Taxonomic identification was performed to the lowest possible taxonomic level, using the specialized literature. The number of individuals in each sample was quantified, calculating the average of the three replicates. Subsequently, the number of individuals per unit area was estimated by applying the factor corresponding to the mouth area of the bodengreifer used.

2.7. Statistical Analyses

All statistical analyses were performed using PRIMER 7 with the PERMANOVA+ add-on software package [24], XlSTAT 7.5.2 software [25], and Past 4 software [26].

3. Results

3.1. Analysis of Physicochemical and Chemical Parameters in Water "In Situ" and in the Laboratory

The measurements were made with the EXO2 device, a horizontal transect, over an interval of approximately 3 hours.

Dissolved oxygen (DO) values were exceptionally high at the beginning of the transect (~17–18 mg/L; 180–224% saturation) and remained at high levels throughout, a phenomenon characteristic of diurnal supersaturation generated by intense photosynthesis in shallow, warmed waters. Nitrate (NO_3–N) concentrations showed a sharp decrease from ~10.2 mg/L to ~2 mg/L, suggesting biotic consumption (phytoplankton and periphyton) and/or local dilution in areas with reduced hydrological mixing. Chlorophyll (a) values ranged from ~5–12 RFU and were associated with increases in turbidity, indicating a contribution from algal and particulate suspensions. Conductivity and TDS showed slight increases (1660→1717 µS/cm), while salinity remained constant (~0.81 PSU), reflecting physical stability of the water mass and the predominance of diurnal biological processes in the variability of the parameters. Water temperature increased gradually (~26.9→28.3 °C), favoring the intensification of algal metabolism and the maintenance of oxygen supersaturation conditions throughout the day (**Table 1**).

The physicochemical and chemical parameters of Lake Agigea fall into Class II quality according to Order No. 161/2006 [5], corresponding to waters with good ecological status and mesotrophic character.

Table 1. A synopsis of the physico-chemical parameters of water surface samples from Agigea lake.

Parameter	Min.	Max.	Mean ± SD
Chlorophyll RFU	4.8	11.5	7.0 ±1.4
Conductivity (µS/cm)	1658.4	1732.0	1702.1 ±20.6
NO3 -N mV	107.0	147.0	142.9 ±5.8
NO3 -N mg/L	2.0	10.2	2.4 ±0.9
Oxygen Saturation (ODO % sat)	130.5	223.5	189.7 ±14.7
Dissolved Oxygen (ODO mg/L)	10.4	17.8	14.8 ±1.1
Salinity psu	0.8	0.8	0.8 ±0.0
Total Algal Content (TAL PC RFU)	4.5	8.8	6.0 ±1.0
Total Dissolved Solids (TDS mg/L)	1045.0	1053.0	1049.8 ±1.4
Turbidity NTU	8.1	70.6	17.2 ±13.4
pH	9.1	9.4	9.2 ±0.1
Temperature °C	26.6	28.7	27.8 ±0.6

The physicochemical and chemical parameters of Lake Tuzla indicate a degraded ecological state, typical of eutrophic waters (Class IV according to Order no. 161/2006 [5]), mainly determined by high concentrations of nitrites (0.208–0.219 mg/L) and phosphates (1.89–2.04 mg/L). Chlorophyll a values exceed more than four times the threshold for class V (952–1133 µg/L), confirming episodes of massive blooms of blue-green algae (Cyanophyceae) (**Figure 3**). These conditions are associated with anthropogenic nutritional inputs, especially from fishing activities and agricultural sources, and lead to major trophic imbalances, characterized by alternation between diurnal supersaturation and nocturnal hypoxia, with the potential for high fish mortality (**Table 2**).

Figure 3. Algal bloom with Cyanophyceae in Tuzla lake.

Table 2. Physico-chemical and chemical parameters measured in Lake Tuzla and their classification according to Order No. 161/2006 [5].

Parameter	Station 1	Station 2	Permissible Values (Order 161/2006)	Class I (Very Good)	Class II (Good)	Class III (Moderate)	Class IV (Poor)	Class V (Bad)	Quality Class*
TSS (mg/L)	322	344	–	–	–	–	–	–	–
NO_2 (mg/L)	0.219	0.208	0.01 – 0.3	≤0.01	≤0.03	≤0.06	≤0.3	>0.3	IV
NO_3 (mg/L)	0.40	0.38	1 – >11.2	≤1	≤3	≤5.6	≤11.2	>11.2	I
PO_4 (mg/L)	2.04	1.89	0.1 – >0.9	≤0.1	≤0.2	≤0.4	≤0.9	>0.9	IV
SO_4 (mg/L)	260	190	60 – >300	≤60	≤120	≤250	≤300	>300	III
SiO_2 (mg/L)	7.785	2.40	–	–	–	–	–	–	–
Chlorophyll a (µg/L)	1133.160	952.373	25 – >250	≤25	≤50	≤100	≤250	>250	V
Chlorophyll b (µg/L)	379.725	324.713	–	–	–	–	–	–	–
Chlorophyll c (µg/L)	134.229	113.392	–	–	–	–	–	–	–

*Classification according to the limits set out in Order No. 161/2006 [5]. Green = Class I–II (good/very good); Yellow = Class III (moderate); Red = Class IV–V (poor/bad).

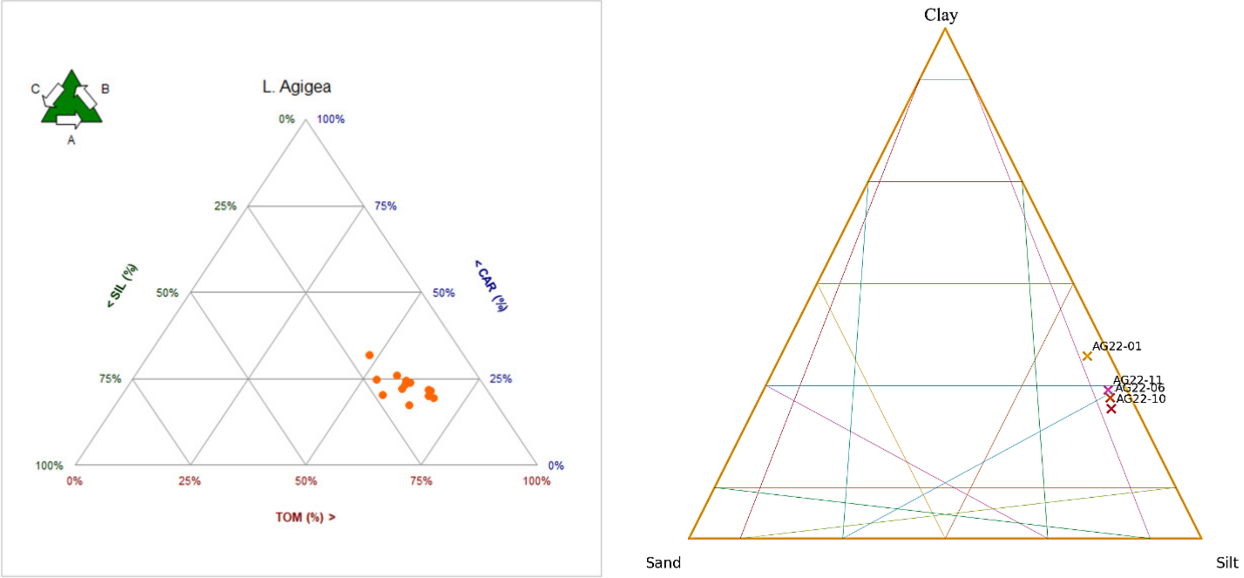
3.2. Lithological Analysis

3.2.1. Agigea Lake

Surface sediment samples from Agigea Lake are characterized by a high content of organic matter, exceeding 48% of the total weight of the dry sediment. The variation ranges of the main lithological parameters were as follows: total organic matter (TOM%) between 48.05–68.25, total carbonate content (CAR%) between 17.31–31.60, and siliciclastic fraction (SIL%) between 12.15–23.22 (**Table 3**). According to these values, the analyzed sediments fall into the category of mixed sediments with a predominance of organic and, subordinately, into the category of organo-mineral sediments, presenting a relatively pronounced carbonate influence, due to the high content of shelly detritus (**Figures 4** and **5**).

Table 3. Lithological analysis of sediment samples (bodengreifer samples) taken from Agigea Lake.

Nr. Crt.	Location	Indicative Sample	Water Content (WC %)	Residue Sec (DM %)	Organic Matter (TOM %)	Total Carbonates (CAR %)	Min. fr. (SIL%)
1	**Agigea Lake**	**AG22-01**	16.66	83.34	60.89	23.84	15.27
2	**Agigea Lake**	**AG22-02**	9.69	90.31	48.05	31.60	20.35
3	**Agigea Lake**	**AG22-03**	17.46	82.54	53.18	24.64	22.18
4	**Agigea Lake**	**AG22-04**	12.96	87.04	66.60	21.25	12.15
5	**Agigea Lake**	**AG22-05**	13.13	86.87	65.88	21.62	12.49
6	**Agigea Lake**	**AG22-06**	9.38	90.62	68.25	19.21	12.53
7	**Agigea Lake**	**AG22-07**	10.19	89.81	56.94	25.67	17.39
8	**Agigea Lake**	**AG22-08**	15.81	84.19	59.77	24.35	15.88
9	**Agigea Lake**	**AG22-09**	19.20	80.80	60.22	23.05	16.73
10	**Agigea Lake**	**AG22-10**	10.94	89.06	60.12	21.84	18.04
11	**Agigea Lake**	**AG22-11**	12.50	87.50	66.72	19.85	13.43
12	**Agigea Lake**	**AG22-12**	10.22	89.78	56.59	20.20	23.22
13	**Agigea Lake**	**AG22-13**	9.35	90.65	63.83	17.31	18.86
Minimum values			**9.35**	**80.80**	**48.05**	**17.31**	**12.15**
Maximum values			**19.20**	**90.65**	**68.25**	**31.60**	**23.22**
Average values (n = 13)			**12.88**	**87.12**	**60.54**	**22.65**	**16.81**



(**a**) (**b**)

Figure 4. (**a**) Ternary diagram representing the distribution of total organic matter (TOM%), carbonates (CAR%) and siliciclastic fraction (SIL%); (**b**) Ternary diagram representing the distribution of granulometry — Agigea Lake.

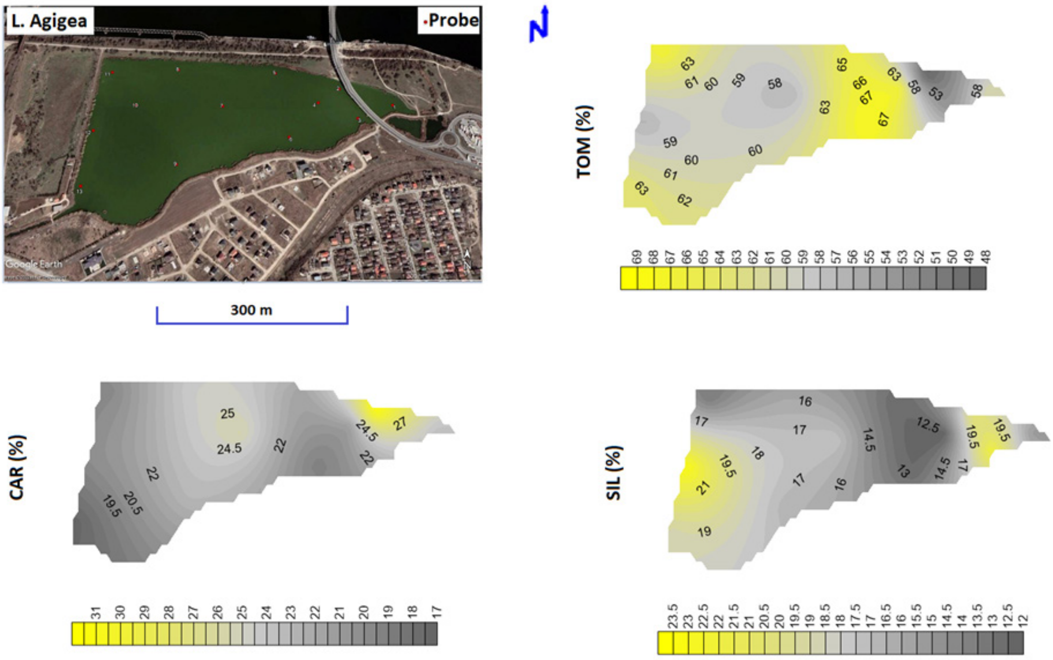


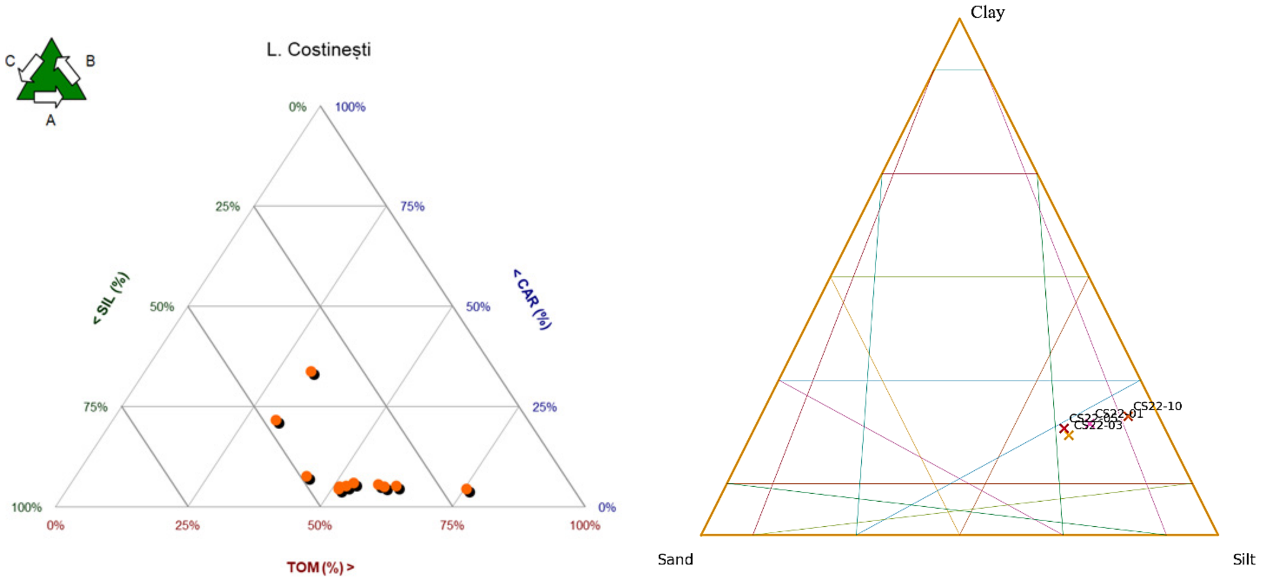
Figure 5. Spatial distribution of TOM%, CAR%, SIL% indicators in surface sediments — Agigea Lake.

3.2.2. Costinești Lake

The lithological parameters determined for the surface sediments from Costinești Lake (**Table 4**) indicate that organic matter represents the main component, with an average weight of 51.59% and varying in the range of 30.60–75.27% (TOM). The carbonate content is variable, with values ranging between 4.52–33.90% (CAR%) and an average of 9.52%. The siliciclastic fraction represents the rest of the analyzed sediment, varying between 20.21–48.77% (SIL%), with an average of 38.89%. Based on the results obtained (**Figure 6**), the surface sediments from Lake Costinești are predominantly classified in the category of organic sediments (TOM≥15-30%), subordinately organo-mineral (SIL≤15–30%), presenting a slight carbonate influence (10%<$CaCO_3$≤30%) in samples CS-22-08 and CS-22-09. The results were also represented in the form of thematic maps (**Figure 7**), made by geostatistical interpolation (kriging method) using the Surfer software [27].

Table 4. Variation of the main lithological parameters analyzed in sediment samples taken from Costinești Lake.

Nr. Crt.	Location	Indicative Sample	Water Content (WC %)	Residue Sec (DM %)	Organic Matter (TOM %)	Total Carbonates (CAR %)	Min. fr. (SIL%)
1	**Costinești Lake**	**CS-22-01**	11.91	88.09	58.02	5.63	36.35
2	**Costinești Lake**	**CS-22-02**	13.62	86.38	59.50	5.01	35.49
3	**Costinești Lake**	**CS-22-03**	6.47	93.53	53.23	6.09	40.67
4	**Costinești Lake**	**CS-22-04**	11.17	88.83	75.27	4.52	20.21
5	**Costinești Lake**	**CS-22-05**	11.74	88.26	61.67	5.18	33.16
6	**Costinești Lake**	**CS-22-06**	13.07	86.93	51.16	4.58	44.25
7	**Costinești Lake**	**CS-22-07**	17.40	82.60	52.23	5.29	42.48
8	**Costinești Lake**	**CS-22-08**	6.31	93.69	31.22	33.90	34.88
9	**Costinești Lake**	**CS-22-09**	8.85	91.15	30.60	21.78	47.62
10	**Costinești Lake**	**CS-22-10**	25.27	74.73	43.56	7.66	48.77
11	**Costinești Lake**	**CS-22-11**	5.81	94.19	51.05	5.06	43.89
Costinești Lake (n = 11) Max. Average		**Min.**	**5.81**	**74.73**	**30.60**	**4.52**	**20.21**
		25.27	**94.19**	**75.27**	**33.90**	**48.77**	
		11.97	**88.03**	**51.59**	**9.52**	**38.89**	



(**a**) (**b**)

Figure 6. (**a**) Ternary diagram representing the distribution of total organic matter (TOM%), carbonates (CAR%) and siliciclastic fraction (SIL%); (**b**) Ternary diagram representing the distribution of granulometry— Costinești Lake.

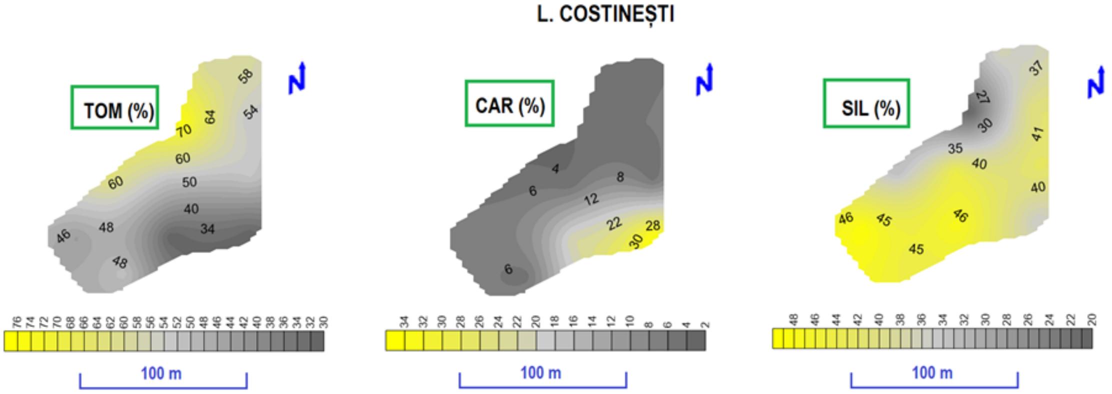


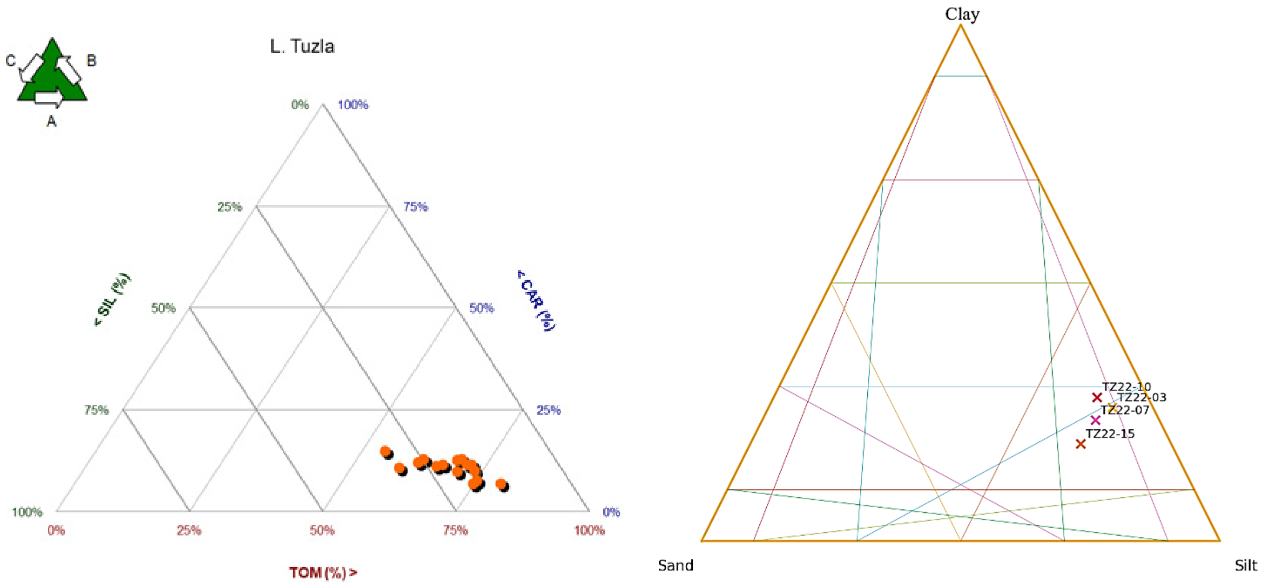
Figure 7. Areal distribution of specific indicators (TOM%, CAR%, SIL%) in Lake Costinești.

3.2.3. Tuzla Lake

The location of the surface sediment collection stations from Lake Tuzla is shown in **Figure 2**. The determined lithological parameters (**Tables 5** and **6**) indicate that organic matter represents the main component of the sediments, with average values of 68.31%, varying between 54.24–79.96% (TOM%). The total carbonate content shows relatively narrow variations, between 6.83–14.79% (CAR%), with an average value of 10.87%. The siliciclastic fraction has values between 13.21–30.97% (SIL%), with an average of 20.82%. The results of the analyses (**Figures 8** and **9**) indicate that the surface sediments of Tuzla Lake fall predominantly into the category of organic sediments (TOM≥15–30%), secondarily into the category of organo-mineral sediments (SIL≤15–30%), with a non-carbonate influence ($CaCO_3$≤10%). The results were represented in the form of thematic maps reflecting the spatial distribution of the main lithological components in the sediments of Tuzla lake.

Table 5. Variation of the main lithological parameters analyzed in sediment samples taken from Tuzla Lake.

Nr. Crt.	Location	Indicative Sample	Water Content (WC%)	Residue Sec (DM%)	Organic Matter (TOM%)	Total Carbonates (CAR%)	Min. fr. (SIL%)
1	**Tuzla Lake**	**TZ-22 -01**	6.27	93.73	71.27	11.54	17.19
2	**Tuzla Lake**	**TZ-22 -02**	10.55	89.45	73.32	10.12	16.56
3	**Tuzla Lake**	**TZ-22 -03**	11.95	88.05	70.23	9.83	19.94
4	**Tuzla Lake**	**TZ-22 -04**	14.31	85.69	69.56	12.89	17.56
5	**Tuzla Lake**	**TZ-22 -05**	5.49	94.51	65.58	11.20	23.22
6	**Tuzla Lake**	**TZ-22 -06**	6.68	93.32	68.85	12.60	18.55
7	**Tuzla Lake**	**TZ-22 -07**	10.90	89.10	72.09	11.50	16.41
8	**Tuzla Lake**	**TZ-22 -08**	13.94	86.06	62.38	12.86	24.76
9	**Tuzla Lake**	**TZ-22 -09**	6.67	93.33	54.24	14.79	30.97
10	**Tuzla Lake**	**TZ-22 -10**	14.43	85.57	66.79	11.47	21.75
11	**Tuzla Lake**	**TZ-22 -11**	14.70	85.30	61.78	12.13	26.09
12	**Tuzla Lake**	**TZ-22 -12**	15.02	84.98	74.65	6.92	18.42
13	**Tuzla Lake**	**TZ-22 -13**	10.57	89.43	58.98	10.74	30.28
14	**Tuzla Lake**	**TZ-22 -14**	10.51	89.49	79.96	6.83	13.21
15	**Tuzla Lake**	**TZ-22 -15**	10.35	89.65	74.94	7.68	17.38
Tuzla Lake (n = 15) Max. Average		**Min.**	**5.49**	**84.98**	**54.24**	**6.83**	**13.21**
		15.02	**94.51**	**79.96**	**14.79**	**30.97**	
		10.82	**89.18**	**68.31**	**10.87**	**20.82**	



(a) (b)

Figure 8. (**a**) Ternary diagram representing the distribution of total organic matter (TOM %), carbonates (CAR %) and siliciclastic fraction (SIL %); (**b**) Ternary diagram representing the distribution of granulometry — Tuzla Lake.

Table 6. Granulometric composition and textural parameters of sediments.

Grain Size Composition and Textural Parameters of Sediments										
Sample No.	**Granulometric Composition**				**Shepard Classification**	**Median Φ**	**Mz Φ**	**Standard Deviation**	**Asymmetry**	**Kurtosis**
	Gravel %	**Sand %**	**Silt %**	**Clay %**						
AG-22-01	0.00	4.81	65.17	39.02	clayey silt	7.10	7.14	1.97	0.09	1.24
AG-22-02	0.00	3.23	48.08	48.70	silty clay	7.91	7.87	2.08	0.02	1.25
AG-22-03	0.00	3.67	63.62	32.71	clayey silt	7.21	7.22	2.02	0.08	1.16
AG-22-04	0.00	3.49	68.27	28.25	clayey silt	7.03	7.12	1.89	0.14	1.24

Table 6. Cont.

Grain Size Composition and Textural Parameters of Sediments										
Sample No.	**Granulometric Composition**				**Shepard Classification**	**Median Φ**	**Mz Φ**	**Standard Deviation**	**Asymmetry**	**Kurtosis**
	Gravel %	**Sand %**	**Silt %**	**Clay %**						
AG-22-05	0.00	3.48	67.80	28.72	clayey silt	7.02	7.14	1.96	0.16	1.25
AG-22-06	0.00	4.04	68.32	27.65	clayey silt	6.98	7.05	1.94	0.13	1.22
AG-22-07	0.00	2.36	62.60	35.04	clayey silt	7.35	7.40	1.93	0.12	1.18
AG-22-08	0.00	3.86	67.87	28.27	clayey silt	6.95	7.07	1.99	0.16	1.20
AG-22-09	0.00	3.16	66.38	30.45	clayey silt	7.09	7.18	1.97	0.14	1.19
AG-22-10	0.00	4.90	69.61	25.49	clayey silt	6.78	6.91	1.98	0.16	1.22
AG-22-11	0.00	3.64	67.22	29.14	clayey silt	7.04	7.10	1.93	0.11	1.18
AG-22-12	0.00	4.57	63.55	31.88	clayey silt	7.14	7.15	2.05	0.08	1.14
AG-22-13	0.00	3.46	68.49	28.06	clayey silt	7.00	7.03	1.91	0.10	1.15

🟥 — minimum value 🟩 — maximum value of sand, silt and clay in samples.

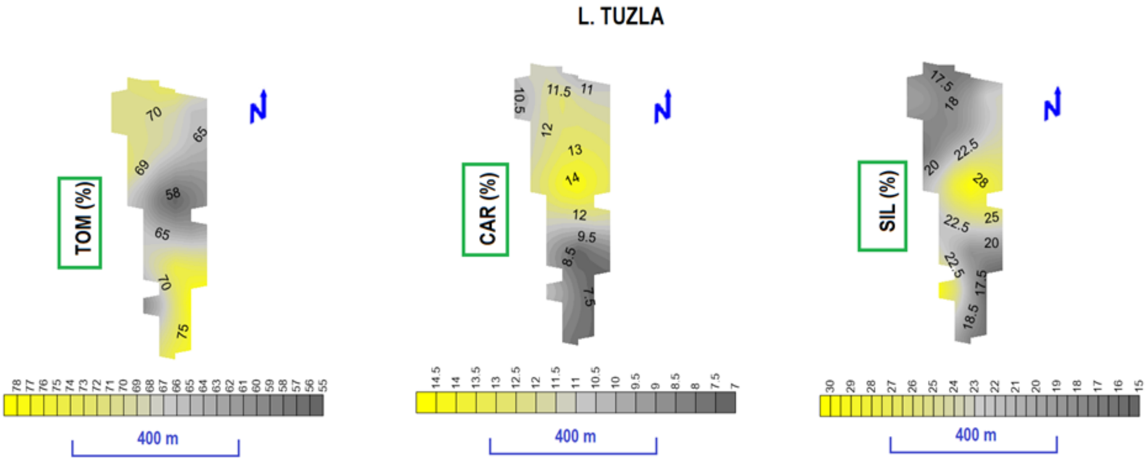


Figure 9. Areal distribution of specific indicators (TOM%, CAR%, SIL%) in Tuzla Lake.

3.3. Granulometric Analysis of Sediments

Granulometric analyses performed on sediment samples taken from Lake Agigea identified clayey-silty sediments (muds), consisting predominantly of silt and clay (**Figure 10**). In most samples, the clayey fraction predominates over the silty one, except for sample AG-22-02, which has an inverse composition (**Table 7**, **Figure 11**). Interpretation of granulometric results (percentages of sand, silt, clay, and associated textural parameters) provides relevant information about the dynamic conditions in which the sediments were formed.

The samples analyzed from Agigea lake indicate sediments texturally classified in the "clayey silt" category, except for sample AG-22-02, classified as "silty clay". Within the granulometric fractions, very fine, fine, and medium silt predominate. The mean and median values are positive. The standard deviation, with values between 1.89 and 2.08, indicates a weak to very weak sorting of the sediments. The asymmetry coefficient varies between +0.02 and +0.16, generally revealing a positive asymmetry (**Table 8**).

Granulometric analyses carried out on the sediments from Lakes Tuzla and Costinești also revealed clay-silty sediments (muds), mainly dominated by silty and clay fractions. In these lakes, the clay fraction is subordinate to the sandy one only in sample CS-22-04 (**Figures 12** and **13**).

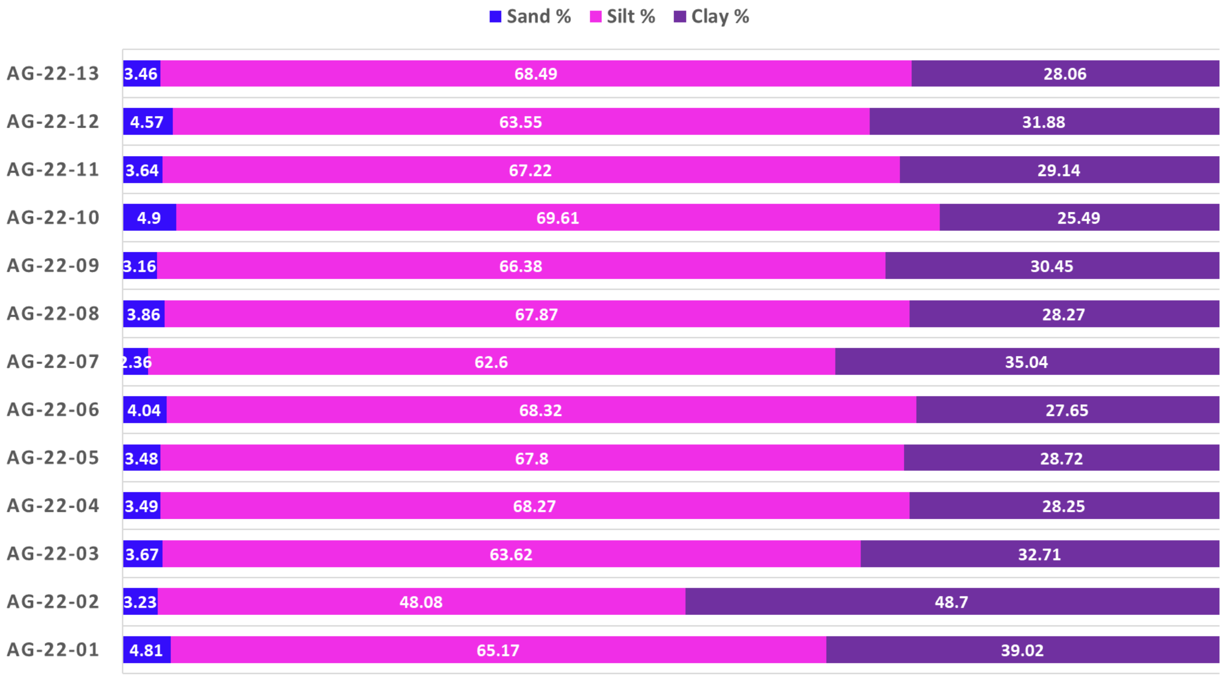


Figure 10. Granulometric weights in samples from Lake Agigea.

Table 7. Detailed grain size composition — Percentages by fractions according to Udden-Wentworth scale.

Sample No.	Gra-vel%	Sand%					Silt%				Clay%		
		Very Coarse	**Coarse**	**Medium**	**Fine**	**Very Fine**	**Coarse**	**Medium**	**Fine**	**Very Fine**	**Coarse**	**Medium**	**Fine**
	>200mm	**1.00–2.00 mm**	**0.500–1.00 mm**	**0.250–0.500 mm**	**0.125–0.250 mm**	**0.063–0.125 mm**	**0.031–0.063 mm**	**0.016–0.031 mm**	**0.008–0.016 mm**	**0.004–0.008 mm**	**0.002–0.004 mm**	**0.001–0.002 mm**	**<0.001 mm**
AG-22-01	0.00	0.00	0.00	0.00	1.47	3.34	5.34	15.01	21.76	23.06	14.29	7.91	7.82
AG-22-02	0.00	0.00	0.00	0.00	0.91	2.32	3.88	8.83	13.39	21.98	21.70	14.51	12.49
AG-22-03	0.00	0.00	0.00	0.00	0.47	3.20	7.36	14.20	19.21	22.85	15.58	8.81	8.32
AG-22-04	0.00	0.00	0.00	0.00	0.79	2.70	4.94	16.49	23.54	23.30	13.39	7.30	7.56
AG-22-05	0.00	0.00	0.00	0.00	0.73	2.75	5.27	16.59	23.43	22.51	12.69	7.41	8.63
AG-22-06	0.00	0.00	0.00	0.00	0.83	3.21	6.51	16.65	22.58	22.58	12.95	7.12	7.58
AG-22-07	0.00	0.00	0.00	0.00	0.64	1.72	4.53	13.63	20.33	24.11	16.67	9.41	8.97
AG-22-08	0.00	0.00	0.00	0.00	0.88	2.97	6.50	17.78	22.32	21.27	12.55	7.35	8.38
AG-22-09	0.00	0.00	0.00	0.00	0.46	2.70	6.17	16.09	21.72	22.40	13.91	8.03	8.51
AG-22-10	0.00	0.00	0.00	0.00	0.68	4.22	8.17	18.67	22.44	20.33	11.38	6.56	7.55
AG-22-11	0.00	0.00	0.00	0.00	0.79	2.85	6.46	16.47	21.78	22.51	13.91	7.67	7.57
AG-22-12	0.00	0.00	0.00	0.00	0.86	3.71	7.90	14.87	18.93	21.86	15.04	8.55	8.29
AG-22-13	0.00	0.00	0.00	0.00	0.04	3.42	7.82	16.99	21.06	22.61	13.98	7.08	7.00

--- — the maximum value of sand. silt or clay in the samples.

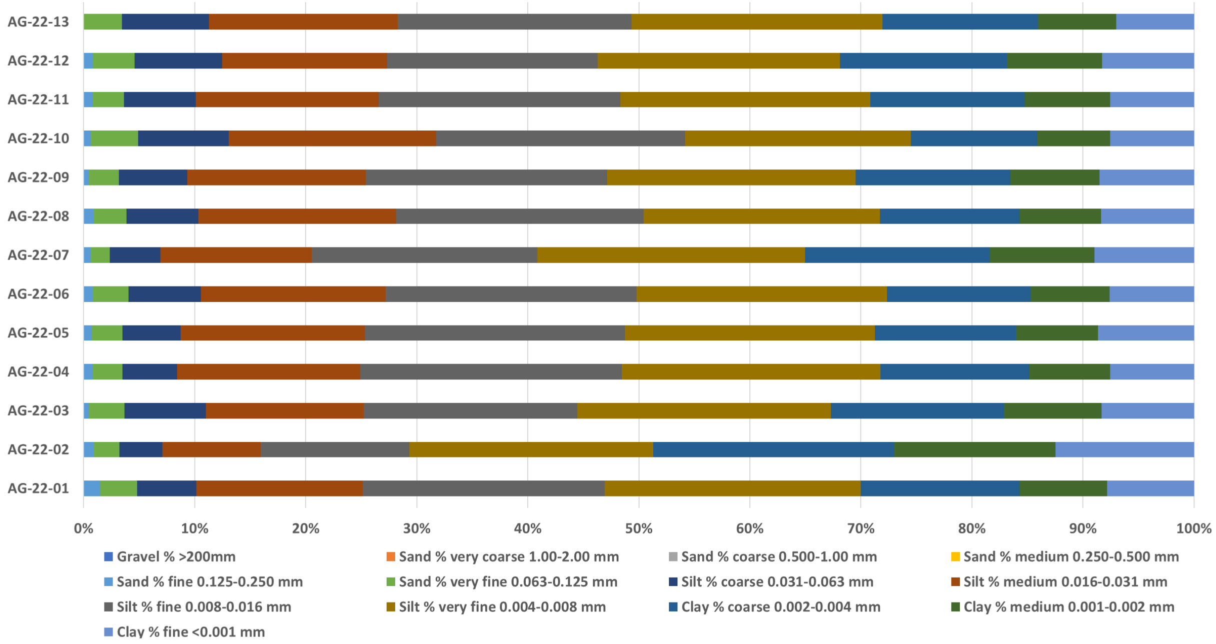


Figure 11. Granulometric weights in samples from Lake Agigea, divided into subclasses.

Table 8. Granulometric composition and textural parameters of sediments from Costinesti and Tuzla lakes.

Sample No.	Granulometric Composition			Shepard Classification	Median Φ	Mz Φ	Standard Deviation	Asymmetry	Kurtosis
	Sand %	Silt %	Clay %						
TZ-22-01	🟥 5.40	67.45	27.15	clayey silt	6.78	6.85	1.99	0.10	1.04
TZ-22-02	7.71	66.45	25.84	clayey silt	6.67	6.71	2.03	0.07	1.04
TZ-22-03	7.86	66.26	25.88	clayey silt	6.56	6.64	2.11	0.11	1.02
TZ-22-04	12.51	🟥 60.05	27.43	clayey silt	6.68	6.59	2.24	0.02	0.96
TZ-22-05	8.14	🟩 68.32	23.55	clayey silt	6.42	6.53	2.03	0.12	1.00
TZ-22-06	10.50	65.90	23.61	clayey silt	6.44	6.49	2.12	0.09	1.01
TZ-22-07	12.32	64.24	23.45	clayey silt	6.36	6.41	2.14	0.08	0.95
TZ-22-08	🟩 14.72	66.19	19.09	clayey silt	5.80	6.05	2.08	0.19	0.93
TZ-22-09	7.60	67.63	24.77	clayey silt	6.35	6.51	2.10	0.16	0.97
TZ-22-10	9.78	62.34	27.88	clayey silt	6.76	6.74	2.18	0.04	1.05
TZ-22-11	8.21	61.68	30.12	clayey silt	6.93	6.89	2.16	0.04	1.06
TZ-22-12	6.61	62.18	🟩 31.21	clayey silt	7.08	7.05	2.03	0.01	1.10
TZ-22-13	9.02	62.96	28.02	clayey silt	6.85	6.78	2.08	-0.01	1.02
TZ-22-14	9.53	63.67	26.80	clayey silt	6.64	6.67	2.19	0.08	1.05
TZ-22-15	17.50	63.71	🟥 18.80	clayey silt	5.80	5.99	2.11	0.17	0.90
CS-22-01	14.04	64.34	21.62	clayey silt	6.33	6.31	2.08	0.02	0.92
CS-22-02	9.50	64.58	🟩 25.93	clayey silt	6.62	6.62	2.09	0.04	1.00
CS-22-03	19.27	61.38	🟥 19.36	clayey silt	5.95	5.98	2.46	-0.07	1.10
CS-22-04	🟩 27.08	🟥 57.66	15.25	clayey silt	5.70	5.65	2.40	-0.07	0.99
CS-22-05	19.48	59.88	20.64	clayey silt	6.24	6.09	2.47	-0.14	1.10
CS-22-06	11.99	63.50	24.51	clayey silt	6.51	6.48	2.09	0.01	0.95
CS-22-07	11.88	63.59	24.52	clayey silt	6.55	6.52	2.10	-0.01	1.00
CS-22-08	5.82	68.82	25.36	clayey silt	6.56	6.62	1.95	0.09	0.91
CS-22-09	12.77	64.28	22.95	clayey silt	5.92	6.23	2.23	0.21	0.95
CS-22-10	🟥 5.95	🟩 71.05	23.00	clayey silt	6.11	6.42	2.02	0.27	0.95
CS-22-11	7.90	69.07	23.02	clayey silt	6.33	6.45	1.98	0.11	0.90

🟥 minimum value; 🟩 maximum value of sand, silt and clay.

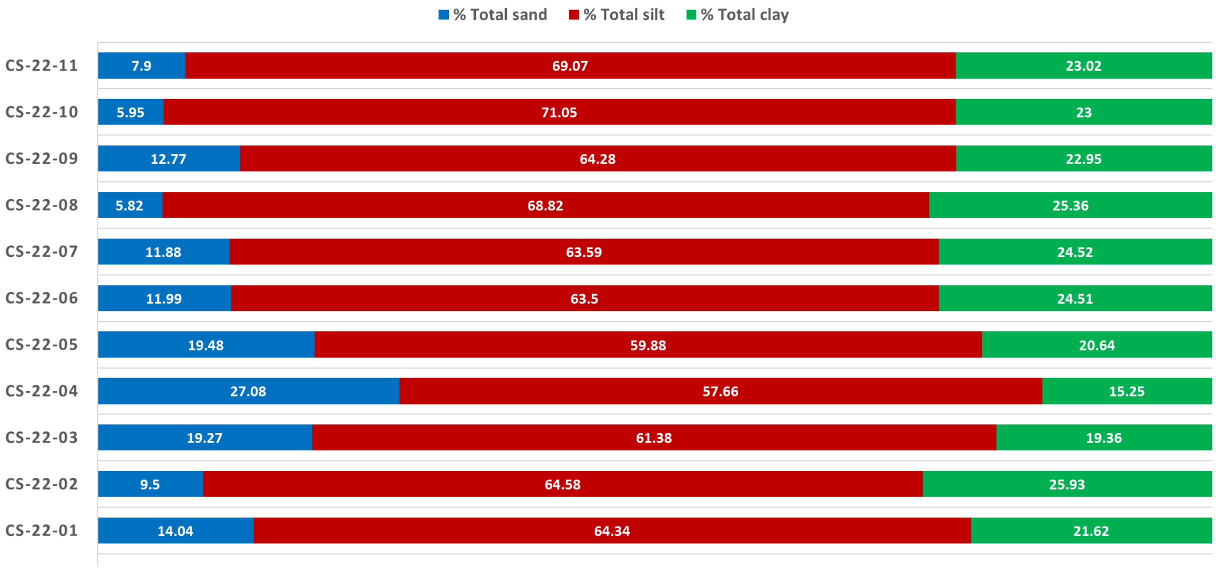


Figure 12. Granulometric weights in samples from Costinești Lake.

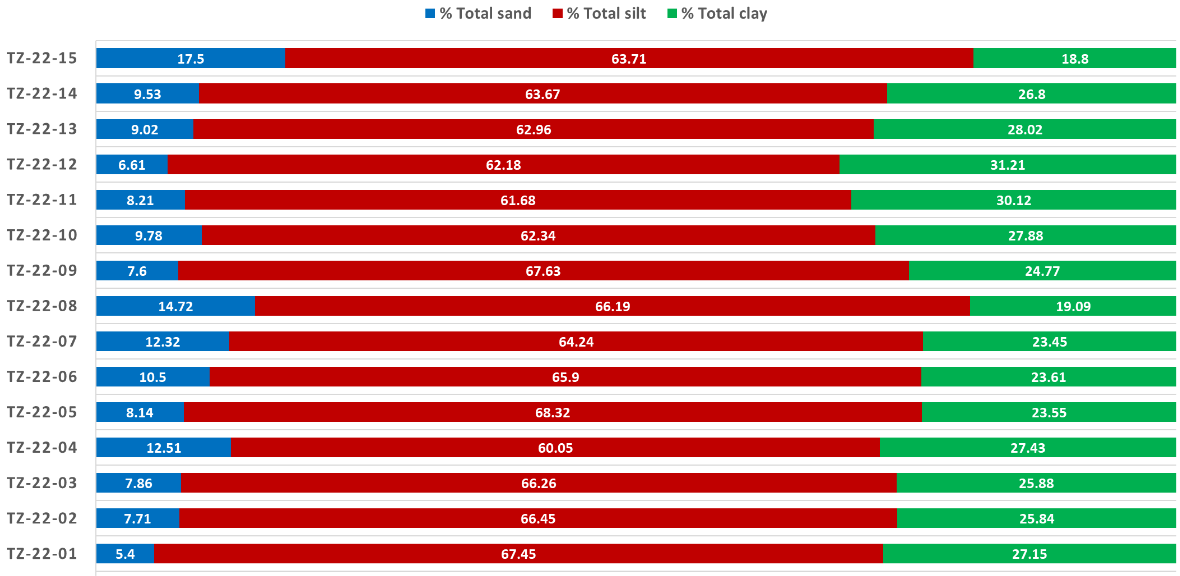


Figure 13. Granulometric weights in samples from Tuzla Lake.

In Costinești lake, alongside the inorganic material, a biogenic component represented by shells, shell fragments, and plant remains was also identified. Some sediments present a muddy, blackish, and unctuous appearance, associated with a pronounced decomposition of organic matter, accompanied by a specific odor. Also, in samples TZ-22-08 and TZ-22-09 from Tuzla lake, angular lithic gravel elements of millimeter size were identified, indicating a potentially significant anthropogenic impact (**Table 8** and **9**; **Figures 14** and **15**).

Table 9. Detailed granulometric composition - Percentages by fractions according to the Udden-Wentworth scale.

Sample No.	Sand %					Silt %				Clay %			% Total sand	% Total silt	% Total clay	TOTAL
	Very Coarse	Coarse	Medium	Fine	Very Fine	Coarse	Medium	Fine	Very Fine	Coarse	Medium	Fine				
	1.00–2.00mm	0.500–1.00mm	0.250–0.500mm	0.125–0.250mm	0.063–0.125mm	0.031–0.063mm	0.016–0.031mm	0.008–0.016mm	0.004–0.008mm	0.002–0.004mm	0.001–0.002mm	<0.001mm				
TZ-22-01	0.00	0.00	0.00	0.13	5.28	11.00	18.15	18.92	19.39	13.33	7.41	6.42	5.40	67.45	27.15	100.0
TZ-22-02	0.00	0.00	0.00	0.35	7.37	11.23	18.05	18.38	18.80	12.95	6.99	5.90	7.71	66.45	25.84	100.0
TZ-22-03	0.00	0.00	0.00	0.41	7.46	13.66	18.36	16.94	17.29	12.37	7.15	6.36	7.86	66.26	25.88	100.0
TZ-22-04	0.00	0.00	0.00	0.50	12.01	12.21	13.94	15.78	18.13	13.46	7.56	6.41	12.51	60.05	27.43	100.0
TZ-22-05	0.00	0.00	0.00	0.30	7.84	14.20	19.80	17.24	17.08	11.67	6.30	5.58	8.14	68.32	23.55	100.0
TZ-22-06	0.00	0.00	0.00	0.54	9.96	13.83	17.36	17.36	17.34	11.53	6.24	5.83	10.50	65.90	23.61	100.0
TZ-22-07	0.00	0.00	0.00	0.54	11.78	14.71	16.50	16.33	16.70	11.58	6.31	5.56	12.32	64.24	23.45	100.0
TZ-22-08	0.00	0.21	2.40	0.94	11.17	18.95	19.69	14.64	12.91	9.44	5.35	4.30	14.72	66.19	19.09	100.0
TZ-22-09	0.00	0.00	0.00	0.75	6.85	17.08	19.55	15.01	16.00	12.00	6.69	6.07	7.60	67.63	24.77	100.0
TZ-22-10	0.00	0.00	0.00	1.03	8.76	10.47	15.88	17.53	18.46	13.36	7.82	6.70	9.78	62.34	27.88	100.0
TZ-22-11	0.00	0.00	0.00	0.73	7.48	9.76	15.29	17.43	19.20	14.39	8.47	7.25	8.21	61.68	30.12	100.0
TZ-22-12	0.00	0.00	0.00	0.86	5.75	7.66	14.71	18.52	21.28	15.79	8.68	6.74	6.61	62.18	31.21	100.0
TZ-22-13	0.00	0.00	0.00	1.04	7.98	10.15	15.08	17.74	20.00	14.39	7.72	5.90	9.02	62.96	28.02	100.0
TZ-22-14	0.00	0.00	0.00	1.09	8.44	11.80	17.00	17.22	17.66	12.52	7.38	6.90	9.53	63.67	26.80	100.0
TZ-22-15	0.00	0.00	0.00	2.98	14.52	16.85	18.86	14.83	13.17	9.17	5.19	4.44	17.50	63.71	18.80	100.0
CS-22-01	0.00	0.00	0.00	1.91	12.13	13.16	16.50	17.13	17.55	11.60	5.68	4.34	14.04	64.34	21.62	100.0
CS-22-02	0.00	0.00	0.00	1.78	7.72	12.17	17.30	16.87	18.24	13.28	7.06	5.60	9.50	64.58	25.93	100.0
CS-22-03	0.73	4.59	0.42	1.46	12.06	15.36	15.61	14.38	16.03	10.98	4.88	3.50	19.27	61.38	19.36	100.0
CS-22-04	0.58	4.34	0.63	4.74	16.79	12.34	14.57	15.81	14.95	8.54	3.71	3.01	27.08	57.66	15.25	100.0
CS-22-05	0.60	4.32	0.47	3.17	10.92	10.43	15.51	16.45	17.49	11.59	5.24	3.81	19.48	59.88	20.64	100.0
CS-22-06	0.00	0.00	0.00	2.45	9.54	12.33	16.76	16.48	17.94	12.98	6.61	4.93	11.99	63.50	24.51	100.0
CS-22-07	0.00	0.18	0.56	2.73	8.42	11.08	17.02	17.11	18.38	12.90	6.55	5.08	11.88	63.59	24.52	100.0
CS-22-08	0.00	0.00	0.00	0.07	5.75	15.83	18.89	15.92	18.17	13.49	6.69	5.18	5.82	68.82	25.36	100.0
CS-22-09	0.54	3.39	0.23	0.66	7.96	19.37	18.74	12.51	13.66	10.74	6.44	5.77	12.77	64.28	22.95	100.0
CS-22-10	0.00	0.00	0.00	0.04	5.91	19.41	22.52	15.00	14.13	10.66	6.61	5.73	5.95	71.05	23.00	100.0
CS-22-11	0.00	0.00	0.00	0.35	7.56	17.49	18.88	15.65	17.06	12.13	6.15	4.75	7.90	69.07	23.02	100.0

🟩 maximum value of sand, silt or clay.

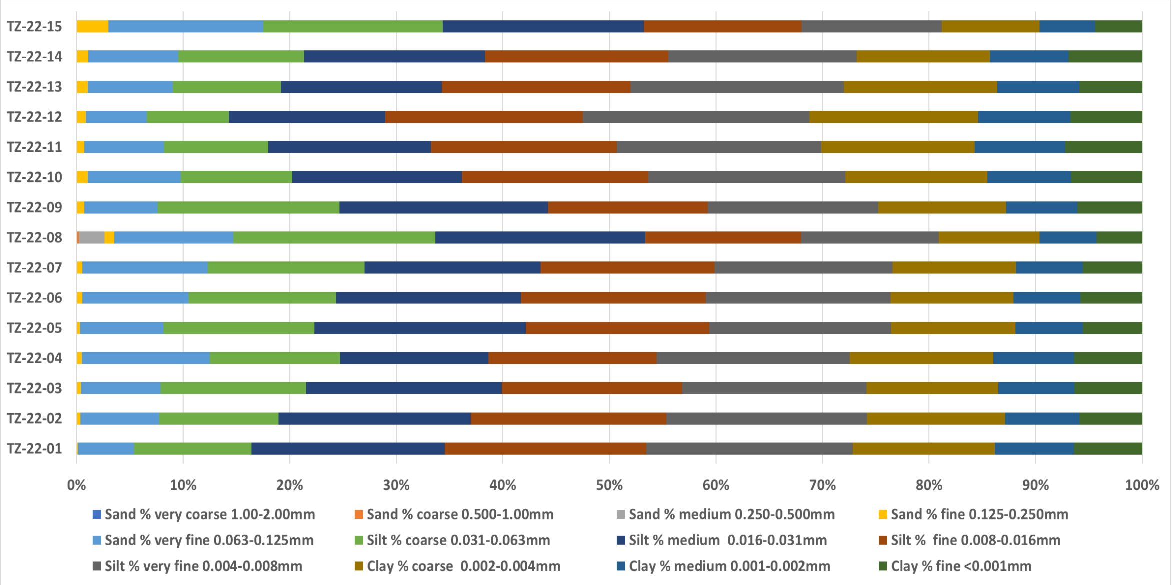


Figure 14. Granulometric weights in samples from Tuzla lake, divided into subclasses.

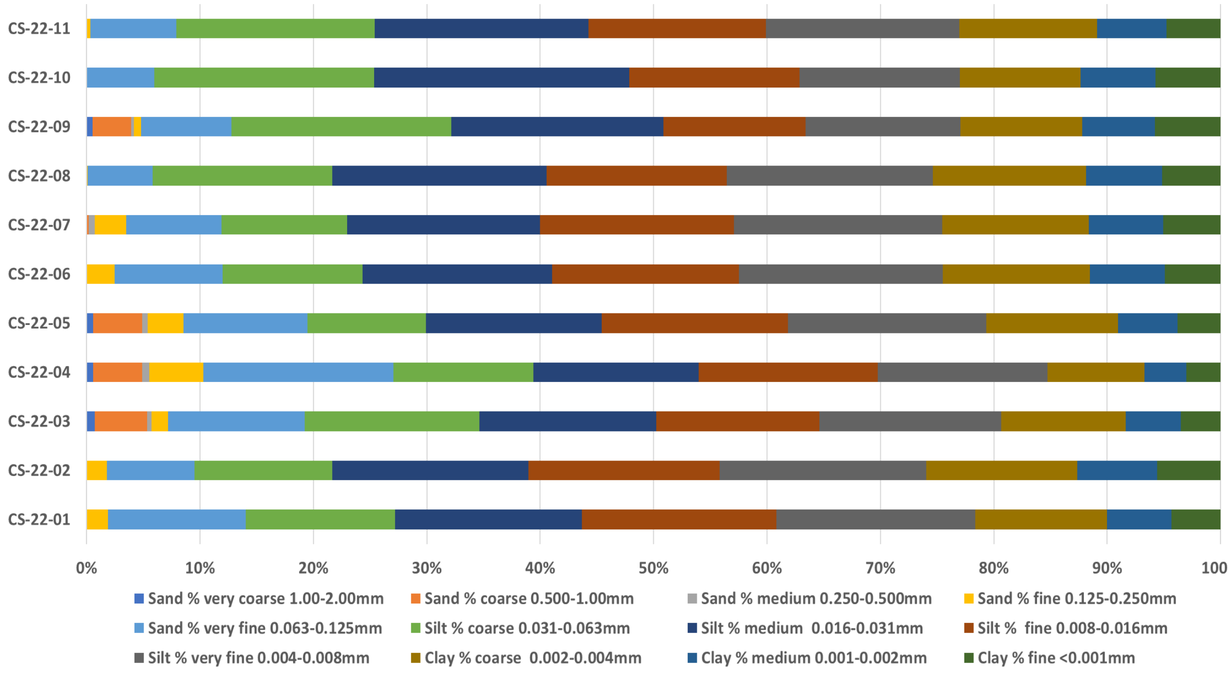


Figure 15. Granulometric weights in samples from Costinești lake, divided into subclasses.

3.4. Analysis of the Benthic Fauna

In order to understand and explain the biological processes in the studied area, it is essential to know the natural framework in which they unfold and evolve. The geological and geographical characteristics, the structure of the benthic facies, as well as the hydrological and hydrochemical conditions of the waters of the investigated lakes represent essential factors in explaining the dynamics of biotopes and biocenoses. Among the factors that determined the formation of benthic biocenoses in coastal lakes, an essential role belongs to the type of benthic facies, along with the speed of water currents and the depth of the basins.

Faunistic research carried out in the Agigea, Tuzla and Costinești lakes highlighted the presence of 12 taxa belonging to a number of 6 major taxonomic groups of invertebrates (Oligochaeta, Polychaeta, Ostracoda, Chironomidae, Decapoda, and other insect larvae), as well as a group of vertebrates (fish) (**Table 10**).

Table 10. General characterization of benthic populations from the three lakes studied.

Crt. No.	Species/Station	A	D %	Noc	F%	Davg	Deco	W
1.	Oligochaeta	3124.8	8.51	4	33.33	260.4	781.2	16.84
2.	*Polydora* sp. (Bosc, 1802)	11188.8	30.47	4	33.33	932.4	2797.2	31.87
3.	*Alitta succinea, (*Kinberg, 1865)	1234.8	3.36	4	33.33	102.9	308.7	10.59
4.	*Ficopomatus enigmaticus, (*Southern, 1921)	25.2	0.07	1	8.33	2.1	25.2	0.76
5.	*Heteromastus* sp.,(Eisig, 1887)	25.2	0.07	1	8.33	2.1	25.2	0.76
6.	*Cyprideis torosa, (*Jones, 1850)	17564.4	47.84	4	33.33	1463.7	4391.1	39.93
7.	Chironomidae larvae	2041.2	5.56	4	33.33	170.1	510.3	13.61
8.	*Chironomus plumosus, (*Linnaeus, 1758)	1234.8	3.36	4	33.33	102.9	308.7	10.59
9.	Chironomidae pupa	25.2	0.07	1	8.33	2.1	25.2	0.76
10.	Larvae varia	100.8	0.27	1	8.33	8.4	100.8	1.51
11.	*Gambusia holbrooki,* (Girard, 1859)	100.8	0.27	2	16.67	8.4	50.4	2.14
12.	*Rhithropanopeus harrisii*, (Gould, 1841)	50.4	0.14	1	8.33	4.2	50.4	1.07

*Total Abundance — A, Dominance — D%, Occurrence number — Noc, Frequency — F%, Average density — Davg ind.m-2, Ecological density — Deco ind.m-2, Ecological significance index — W.

The presence of a large number of individuals from the insect larval category is explained by the permanent nature of the lakes, which provide optimal conditions for the continuous reproduction of species with aquatic larval stages. This phenomenon is not found in temporary ponds, where the diversity and abundance of insect larvae are much reduced [28].

Chironomidae larvae are widely recognized as the main dominant group in the macrozoobenthic, both numerically and in terms of biomass [29–32]. This dominance can be explained by the great diversity of feeding strategies and the various types of food that these organisms can exploit [33– 36].

The increased abundance of Chironomidae larvae suggests the existence of a high organic load and an oxygen deficit in the lake substrate.

From a quantitative point of view, the general average density of benthic populations in the studied lakes was 3059.7 individuals per square meter, and the total abundance of organisms in the samples was 36716.4 individuals. The percentage composition was as follows: crustaceans 48%, worms 43% and insect larvae 9%.

The highest frequency of occurrence in the samples taken from the studied lakes was recorded by six taxa specific to wetlands with muddy sedimentary substrate, namely: Oligochaeta, *Polydora* sp., *Alitta succinea, Cyprideis torosa,* Chironomidae larvae, and *Chironomus plumosus*, each having a frequency of over 33% of the total samples analyzed (**Figure 16**).

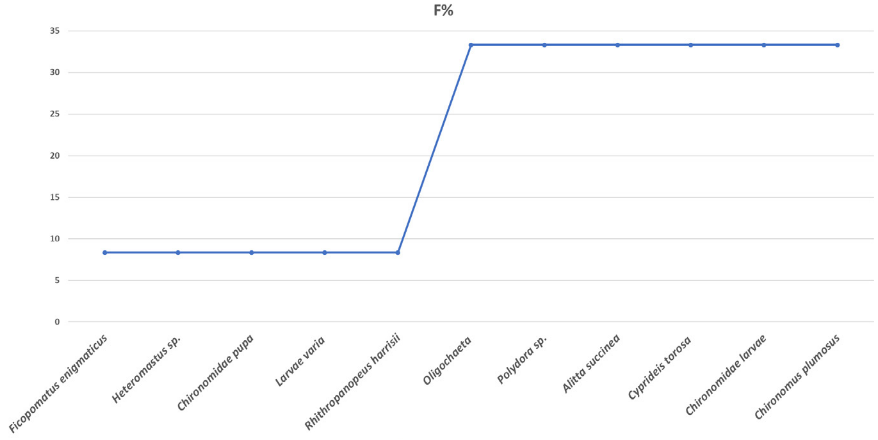


Figure 16. Frequency of benthic taxa in the studied lakes.

Of the 12 taxa identified, three species show an increased abundance, totaling over 80% of the overall average density: *Cyprideis torosa* with nodules, *Polydora* sp. and Oligochaeta (**Figure 17**).

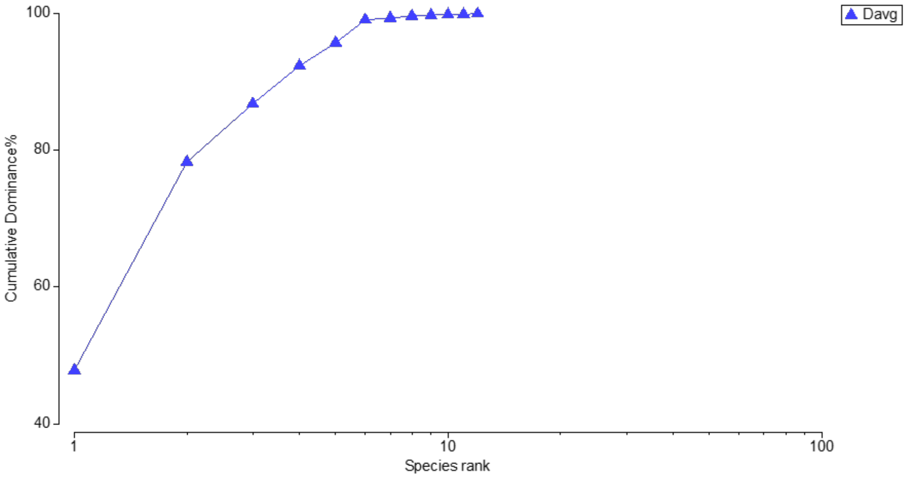


Figure 17. Cumulative curve of the average density of benthic populations in the studied lakes.

The analysis of the variation in the number of taxa revealed that most species were identified in stations CS22-03 and CS22-10 from Costinești Lake, and the highest densities of organisms were observed in stations CS22-03 (Costinești Lake) and TZ22-10 (Tuzla Lake) (**Figure 18**).

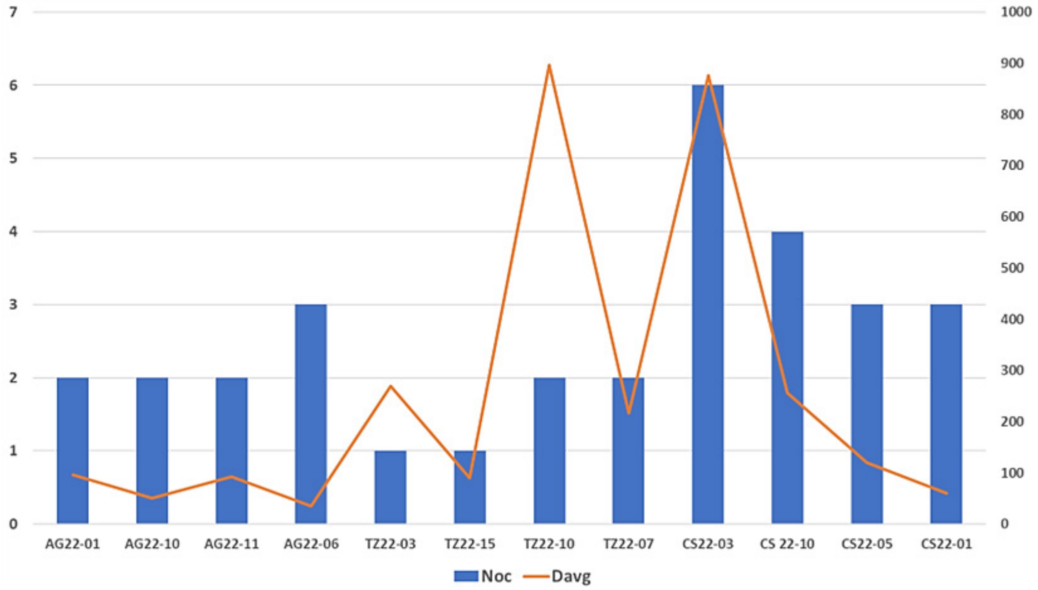


Figure 18. Distribution of the number of species and their average densities by stations in the lakes studied in 2022.

Ternary diagrams (**Figures 4b**, **6b**, and **8b**) indicate a predominance of fine sediments (silty clay, clayey silt) across all lakes. Slightly higher sand content occurred at Costinești (CS22-03, CS22-05), while Tuzla was dominated by the finest fractions. CLUSTER analysis (Bray–Curtis, √x, UPGMA) grouped stations strictly by lake (**Figure 19**), and PERMANOVA confirmed significant community differences (Pseudo-F = 31.03; *p* = 0.002). BIOENV identified CAR + SIL as the strongest predictor of biotic patterns (ρ = 0.756), suggesting a combined influence of bioclastic and fine mineral fractions. RDA (**Figure 20**) separated Costinești along the SIL vector, Agigea along CAR, and Tuzla along high TOM, the latter associated with a monodominant *Cyprideis torosa* assemblage.

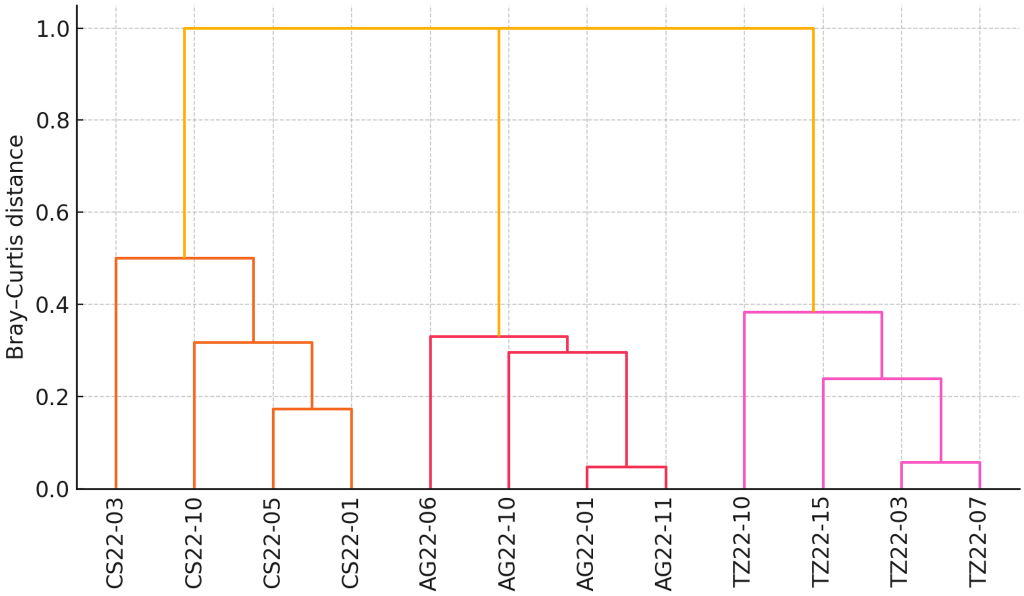


Figure 19. CLUSTER analysis (Bray–Curtis, square-root; UPGMA).

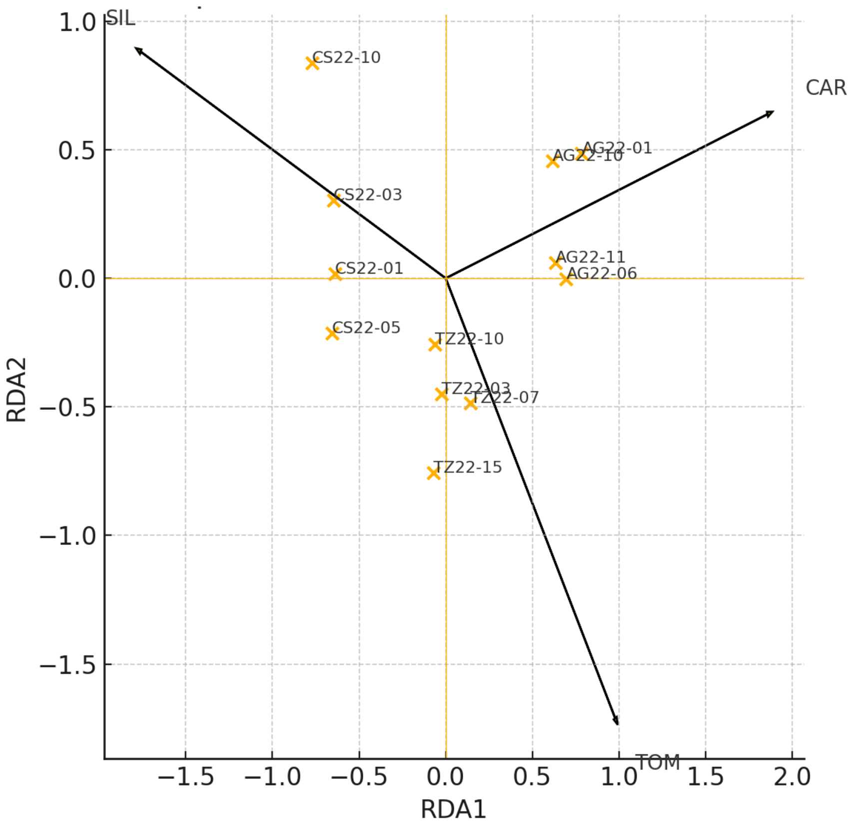


Figure 20. RDA biplot (sites and environmental vectors).

For Agigea Lake, the Shannon index (H′ ≈ 1.32) indicates moderate diversity, with a relatively balanced distribution among taxa, but dominated by a few key groups, especially the larvae of Chironomidae and Chironomus plumosus. The Pielou index (J′ ≈ 0.83) suggests a high uniformity of the abundance distribution, and the Simpson (1–D ≈ 0.66) confirms a moderate dominance without the monopoly of a single taxon. The community is characteristic of environments with moderate organic loading. The diversity is low (H′ ≈ 0.76), in Tuzla Lake, reflecting the marked dominance of the ostracod *Cyprideis torosa*. The evenness of the community is low (J′ ≈ 0.38), and the Simpson index (1–D ≈ 0.46) confirms the clear predominance of a single taxon. The simplified structure is typical of ecosystems under intense anthropogenic pressure (fishing, organic fertilization), *C. torosa being* tolerant to salinity variations and eutrophication. But in Costinești Lake, H′ ≈ 1.63 indicates the highest diversity among the three lakes, supported by a mixture of freshwater and marine species. Evenness is moderate (J′ ≈ 0.67), and Simpson (1–D ≈ 0.74) suggests a relatively balanced structure. The community is dominated by Polydora sp. and Oligochaeta, but also includes marine species such as *Alitta succinea* and *Rhithropanopeus harrisii*, reflecting the direct influence of the channel connecting with the Black Sea (**Table 11**).

The comparative analysis of the three lakes shows that biodiversity is highest in Costinești, driven by the coexistence of marine and freshwater species, followed by Agigea with moderate diversity, while Tuzla exhibits the lowest diversity and a clear monospecific dominance. In terms of community uniformity, Agigea displays the most balanced distribution of abundances, Costinești shows a moderate balance, and Tuzla presents the most uneven structure. Regarding anthropogenic influence, Tuzla is the most impacted, with a simplified community structure dominated by stress-tolerant species, Agigea experiences moderate human pressure, and in Costinești, the main ecological driver is the direct marine connectivity through its link to the Black Sea.

Table 11. Diversity indices for Agigea, Costinesti and Tuzla lakes.

	AG22-01	**AG22-10**	**AG22-11**	**AG22-06**	**TZ22-03**	**TZ22-15**	**TZ22-10**	**TZ22-07**	**CS22-03**	**CS 22-10**	**CS22-05**	**CS22-01**
Taxa_S	2	2	2	3	1	1	1	1	6	4	3	3
Individuals	1159	604	1108	427	3225	1083	10684	2570	10506	3072	1436	730
Dominance_D	0.64	0.72	0.57	0.56	1.00	1.00	1.00	1.00	0.54	0.56	0.67	0.57
Simpson_1-D	0.36	0.28	0.43	0.44	0.00	0.00	0.00	0.00	0.46	0.44	0.33	0.43
Shannon_H	0.55	0.45	0.63	0.76	0.00	0.00	0.00	0.00	0.82	0.85	0.62	0.75
Evenness_e^H/S	0.87	0.79	0.94	0.71	1.00	1.00	1.00	1.00	0.38	0.58	0.62	0.70
Brillouin	0.55	0.44	0.62	0.72	0.00	0.00	0.00	0.00	0.82	0.84	0.62	0.73
Menhinick	0.06	0.08	0.06	0.14	0.02	0.03	0.01	0.02	0.06	0.07	0.08	0.11
Margalef	0.14	0.16	0.14	0.33	0.00	0.00	0.00	0.00	0.54	0.37	0.28	0.30
Equitability_J	0.79	0.65	0.90	0.69	-	-	-	-	0.46	0.61	0.57	0.68
Fisher_alpha	0.24	0.26	0.24	0.44	0.10	0.11	0.09	0.10	0.62	0.45	0.36	0.40
Berger-Parker	0.76	0.83	0.68	0.70	1.00	1.00	1.00	1.00	0.69	0.73	0.81	0.72
Chao-1	2	2	2	3	1	1	1	1	6	4	3	3
iChao-1	2	2	2	3	1	1	1	1	6	4	3	3
ACE	2	2	2	3	1	1	1	1	6	4	3	3
Squares	2	2	2	3	1	1	1	1	6	4	3	3

Diversity indices were low to moderate in Agigea (H′ 0.45–0.75; median 0.59) and Costinești (H′ 0.62–0.85; median 0.78), and null in Tuzla (H′ = 0; monodominance). All lakes fell below the H′ < 2 threshold, indicating simplified communities, with Tuzla in a severely degraded state (**Table 11**).

The nMDS (Bray-Curtis dissimilarity) ordination revealed a clear separation of samples by lake, with Agigea and Tuzla forming distinct clusters, while the Costinești stations clustered more loosely, reflecting the composition of their mixed freshwater and marine community. The Tuzla stations clustered tightly, indicating a high degree of similarity, dominated by *Cyprideis torosa*, while the Agigea samples showed moderate dispersion determined by variation in Chironomidae abundances. The Costinești stations showed the greatest spread, consistent with a diverse assemblage that included both freshwater and marine taxa (**Figure 21**).

The abundance heatmap confirmed these patterns, with distinct blocks of high density corresponding to the dominant taxa in each lake (e.g., Chironomidae in Agigea, *C. torosa* in Tuzla, *Polydora* sp., and Oligochaeta in Costinești). These results highlight the strong structuring of benthic communities by both environmental conditions and anthropogenic pressures (**Figure 22**).

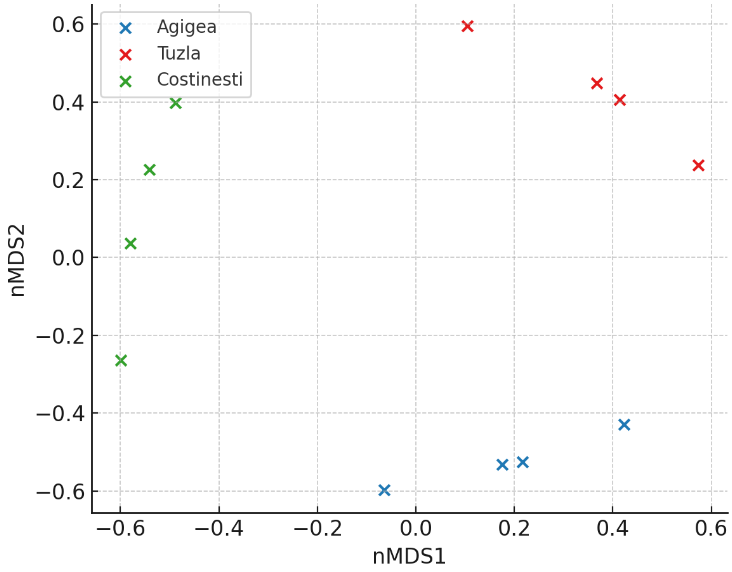


Figure 21. nMDS (Bray-Curtis) — Benthic communities.

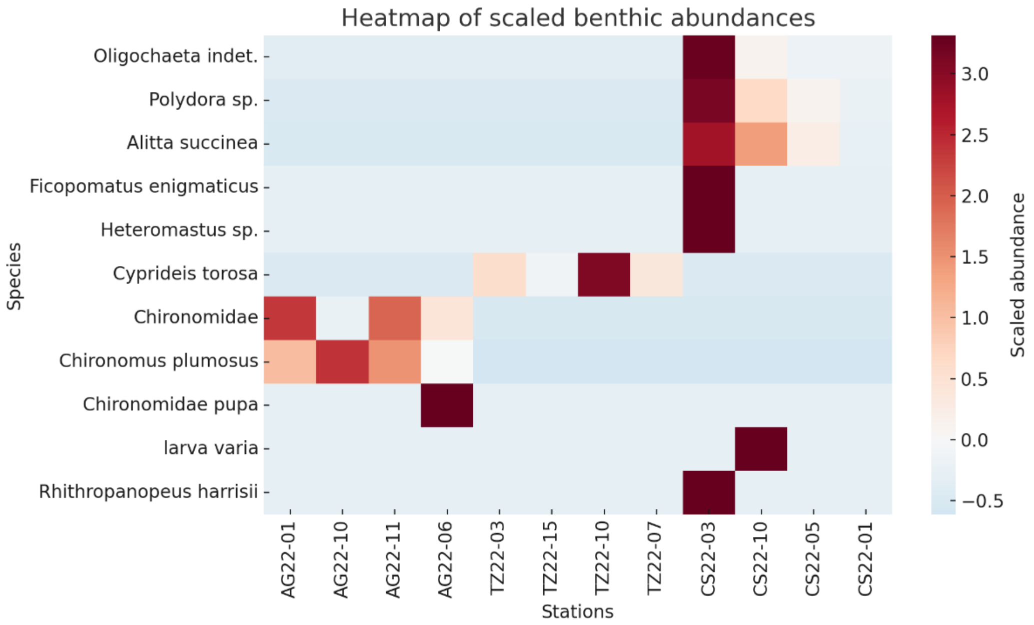


Figure 22. Heatmap of scaled benthic abundances.

4. Discussions

The findings of this study provide an integrated characterization of the sedimentological, granulometric, chemical, and biological properties of the coastal lakes Agigea, Tuzla, and Costinești, incorporating both sediment features and in situ water quality parameters, including nutrient and pigment concentrations.

The physicochemical parameters of Lake Agigea indicate waters with a good ecological status, corresponding to Class II and a mesotrophic status according to Order no. 161/2006 [5]. The recorded values reflect a relatively balanced system, with moderate nutrient concentrations and stable oxygen dynamics. Dissolved oxygen reached supersaturated levels during the day (~17–18 mg/L; saturation 180–224%), a typical pattern for warm and shallow waters, under intense photosynthetic activity [37].

The minimal influence of astronomical tides in the Black Sea (amplitudes of only a few centimeters) means that the water level dynamics in Agigea are mainly determined by wind and seiche, with local freshwater inputs influencing the transport of fine particles and turbidity [38,39]. Slight increases in chlorophyll a (~5–12 RFU) coincided with increased turbidity, suggesting suspended algal biomass, rather than sediment resuspension, as the primary cause.

Nitrate concentrations decreased from ~10.2 mg/L to ~2 mg/L along the transect, which is consistent with biotic uptake by phytoplankton and periphyton [40]. Variations in conductivity, TDS, and salinity were minor, suggesting that the observed changes in water quality were dominated by biological processes rather than significant changes in water mass.

In general, Lake Agigea exhibits environmental conditions characteristic of mesotrophic, wind-mixed coastal lakes, where photosynthetic activity strongly modulates oxygen and nutrient dynamics on a daily scale. The classification under Directive 2000/60/EC [6] supports its designation as a water body with good ecological status, but its proximity to anthropogenic activities means that continuous monitoring is necessary to prevent nutrient enrichment beyond mesotrophic thresholds (Order No. 161/2006 [5]).

Nutrient and pigment concentrations recorded in Lake Tuzla indicate severe ecological degradation, consistent with advanced eutrophication [5,16]. Nitrite (NO_2) and phosphate (PO_4) levels fell into Class IV according to Order No. 161/2006 [5], exceeding the thresholds for good ecological status and indicating substantial nutrient enrichment. These values, together with chlorophyll a concentrations well above Class V limits (>250 µg/L; measured up to ~1133 µg/L), reveal intense phytoplankton blooms dominated by cyanobacteria (Cyanophyceae), a common indicator of nutrient overload in shallow, low-flow coastal lakes [41,42].

Extremely high levels of chlorophyll a, b, and c, combined with high levels of total suspended solids (TSS > 300 mg/L), suggest a water column heavily loaded with algal biomass and suspended particles, which may reduce light penetration and promote hypoxic conditions during nocturnal respiration [37]. Although nitrate (NO_3) remained in Class I, high nitrite concentrations imply active microbial transformation processes and possibly oxygen stress in the bottom waters, consistent with the opportunistic benthic dominance observed in biological samples [40].

Sulfate concentrations placed the system in Class III, which — although less critical than nutrient and pigment indicators — still reflects deviations from baseline conditions [39]. Silica (SiO_2) levels were variable and not related to class, but may influence diatom productivity [43].

From a management perspective, these findings place Lake Tuzla well below the ecological thresholds reported for other European coastal lagoons affected by aquaculture and tourism (H′ ≈ 1–1.5 for transitional states; <1 for degraded systems) [44,45]. The combination of Class IV nutrient status and Class V pigment load indicates an advanced eutrophic state, in which functional diversity is severely reduced and resilience is low. Such conditions are likely related to intensive fisheries management practices (e.g., organic fertilization to increase productivity), as documented in similar systems [44,46].

Granulometric analyses indicate that sediments in Lakes Agigea, Tuzla, and Costinești are predominantly silty–clayey, reflecting low-energy depositional environments with limited hydrodynamic exchange. Poor particle sorting across all sites supports the interpretation of stable sedimentation under restricted circulation. The lithological composition reveals a high proportion of organic-rich sediments, particularly in Agigea and Tuzla, consistent with enhanced accumulation of organic detritus under mesotrophic to eutrophic conditions. In contrast, Costinești exhibited greater carbonate contributions, likely of biogenic origin from mollusk shells and other calcareous organisms, emphasizing the role of biological processes in sediment formation [47].

Water quality data provide critical ecological context: Agigea maintains a mesotrophic state with moderate nutrient and pigment levels (Class II, good ecological status). Tuzla, however, exhibits severe eutrophication, with nitrite and phosphate in Class IV and chlorophyll a in Class V (extremely high concentrations), alongside elevated TSS—signaling dense phytoplankton blooms and potential nocturnal hypoxia [40,48].

Macrozoobenthic communities were dominated by opportunistic, hypoxia-tolerant taxa such as Chironomidae larvae, Oligochaeta, and the ostracod *Cyprideis torosa*, bioindicators of organic enrichment and low-oxygen conditions [49,50]. The extreme case of Tuzla, where benthic diversity indices dropped to H′ = 0 due to *C. torosa* monodominance, reflects functional simplification and low ecological resilience. In Agigea and Costinești, diversity was somewhat higher but still below the H′ = 2 threshold considered typical for healthy coastal lagoons in Europe.

The prevalence of larval insect populations highlights the permanence of aquatic conditions in these lakes, supporting continuous life cycles in contrast to temporary wetlands, where biodiversity is limited by seasonal drying [51]. However, the detection of angular lithic clasts (“breccia”) in Tuzla sediments suggests direct mechanical disturbance, likely linked to fisheries activities and shoreline access. In Costinești, the occurrence of marine species at station CS-22-03 confirms a direct hydrological and ecological connection with the Black Sea via the channel, influencing species composition and potentially facilitating periodic salinity fluctuations.

These findings align with broader studies of European shallow coastal ecosystems, where cumulative anthropogenic pressures (e.g., fisheries, agriculture, tourism) drive eutrophication, sediment alteration, and benthic community simplification [44].

Additionally, the integration of sediment, water quality, and biological data reveals that these lakes are shaped by a combination of natural low-energy hydrodynamics and strong anthropogenic pressures. Tuzla represents the most degraded system, with severe eutrophication, organic enrichment, and reduced biodiversity, while Agigea retains better ecological status despite signs of moderate enrichment, and Costinești shows mixed marine–lagoonal characteristics influenced by its open connection to the sea.

The micro-tidal regime of the Black Sea, characterized by typical amplitudes in the order of centimeters and maximums around 18 cm, implies a low astronomical influence on coastal hydrodynamics [52]. At Constanța, measured values for peak astronomical tides are ~0.05–0.08 m, and recent syntheses show slightly higher amplitudes in the northwestern sector of the basin [53,54]. In this context, water level dynamics are dominated by wind and seiche action, while local freshwater inputs control turbidity and fine fraction transport in coastal lagoons and lakes. This hydrological setting favors fine fraction deposition and total organic matter (TOM) accumulation, especially in water bodies with low renewal, such as Lake Tuzla.

European studies on Mediterranean and Baltic lagoons have shown that Shannon-Wiener index (H′) values below 2 are associated with high organic loading, habitat simplification, and the dominance of opportunistic taxa such as ostracods and chironomids [55,56]. In many cases, thresholds of $H' \approx 1$–1.5 mark the transition to eutrophic or degraded states, driven by fish farming discharges and coastal tourism developments [45,57,58]. The values obtained in this study, in particular $H' = 0$ at Tuzla, are well below these thresholds, indicating severe functional simplification and low resilience of benthic communities.

The Shannon-Wiener index presented low–moderate values in Agigea (0.45–0.75; median 0.59) and Costinești (0.62–0.85; median 0.78), but was null in Tuzla ($H' = 0$), indicating the monodominance of the species *Cyprideis torosa*. All the lakes analyzed recorded values below the threshold $H' < 2$, which reflects simplified communities, and in the case of Tuzla, this status is corroborated with high levels of TOM and water parameters indicating severe eutrophication (NO_2 and PO_4 in class IV, chlorophyll "a" in class V, according to Ord. 161/2006 [5]).

In addition, the presence of angular lithic clasts ("breccia") in samples TZ-22-08 and TZ-22-09 suggests a localized anthropogenic mechanical input, probably associated with fishing activities and access. CLUSTER analysis (Bray–Curtis on $\sqrt{x}$ transformed abundances; UPGMA) clearly grouped the stations into lakes, highlighting compositional differences. PERMANOVA, with the factor "Lake", confirmed significant differences between communities (Pseudo-F = 31.03; $p = 0.002$; 999 permutations). BIOENV analysis indicated that the best combination of explanatory variables is CAR + SIL ($\rho = 0.756$; Spearman), suggesting a combined control exerted by bioclastic input and the fine mineral fraction on the structure of benthic communities. "In situ" and laboratory results confirm the correlation of this sedimentological context with water chemical parameters and with the dominance of hypoxia-tolerant species, such as *C. torosa* and chironomid larvae.

These results underscore the necessity for continuous ecological monitoring of coastal lake systems. Understanding sediment dynamics, organic matter distribution, nutrient and pigment levels, and benthic community responses to both natural and anthropogenic drivers is essential for developing effective conservation strategies and sustainable management practices that preserve ecological integrity and biodiversity in coastal aquatic environments.

This study is particularly important given the scarcity of integrated research that combines sedimentological, granulometric, chemical, and biological analyses in highly anthropized coastal lakes along the Romanian coast. In the context of increasing anthropogenic pressure on coastal ecosystems, the comprehensive assessment of sediment characteristics, water quality parameters (e.g., nutrient concentrations, chlorophyll pigments, and suspended solids), and benthic community structure becomes critical for understanding the impacts of human activities on biodiversity and ecosystem functioning. Through its interdisciplinary approach, this work provides an updated and relevant knowledge base to inform conservation strategies and guide sustainable management policies, supporting the efforts of authorities and decision-makers in safeguarding Romania's marine and coastal environment.

5. Conclusions

This study provides a comprehensive assessment of sedimentological, granulometric, chemical, and biological characteristics of the coastal lakes Agigea, Tuzla, and Costinești, offering valuable insights into their current ecological status and the factors shaping their condition.

Sediments in all three lakes were dominated by fine silty–clayey fractions and exhibited high organic matter content, indicative of low-energy depositional environments with limited hydrodynamic exchange. Agigea and Tuzla displayed particularly high levels of organic-rich sediments, while Costinești showed a greater carbonate contribution from biogenic sources. Poor sediment sorting across all sites reflected stable accumulation under restricted water dynamics.

Water quality data revealed distinct ecological contrasts between the lakes. Agigea fell within Class II (good ecological status, mesotrophic) under Order 161/2006 [5], while Tuzla exhibited severe degradation, with nitrite and phosphate concentrations in Class IV and chlorophyll a exceeding Class V thresholds (>250 µg/L, measured up to ~1133 µg/L), indicating advanced eutrophication and frequent cyanobacterial blooms. Elevated total suspended solids in Tuzla further supported the presence of dense phytoplankton and particulate matter, potentially driving light limitation and nocturnal hypoxia.

Macrozoobenthic communities were dominated by opportunistic and hypoxia-tolerant taxa such as *Cyprideis torosa*, Chironomidae larvae, and *Oligochaeta*, reflecting high organic loading and nutrient enrichment. In Tuzla, extreme monodominance and reduced diversity indices ($H' = 0$) confirmed a functionally simplified system with low resilience, in contrast to the more diverse, albeit still simplified, communities of Agigea and Costinești.

Signs of direct anthropogenic influence, including angular lithic clasts (“breccia”) in Tuzla sediments, suggest ongoing mechanical disturbance associated with fisheries exploitation. Combined with nutrient enrichment and poor water exchange, these pressures threaten ecosystem stability.

The integrated sediment–water–benthos analysis presented here highlights the interplay between physical, chemical, and biological processes in determining ecological condition. The findings underscore the urgent need for sustained, multidisciplinary monitoring programs to track changes, inform conservation measures, and guide sustainable management of Romania’s coastal lakes in the face of increasing anthropogenic pressures.

Author Contributions

All authors contributed equally to the conception, design, data collection, analysis, and writing of this study. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data will be made available on request.

Conflicts of Interest

All authors declare no conflict of interest.

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