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Spatiotemporal variation in marine litter distribution along the Bulgarian Black Sea sandy beaches: amount, composition, plastic pollution, and cleanliness evaluation

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The threat of anthropogenic marine litter, particularly plastic pollution, to marine ecosystems and human health, has spurred mitigation initiatives and global scientific research. Following the Marine Strategy Framework Directive guidelines, this study evaluated marine litter distribution, cleanliness, and plastic pollution indices along Bulgarian Black Sea beaches in 2023. The survey integrates visual assessment, manual sampling, and drone mapping, distributing the beaches along the coastline to encompass a broader range, totaling 45, including 28 remote/natural, 10 semi-urban, and 7 urban beaches. Results indicate a 48% decrease in marine litter distribution on beaches from 1462 ± 147 items/100 m in 2021 to 753 ± 97 items/100 m in 2023, with Artificial polymer materials/plastic materials constituting 88.62% of the total litter amount. A comprehensive plastic macro litter pollution assessment was carried out along Bulgarian beaches using PAI for the first time. In 2023, the average cleanliness status of Bulgarian beaches was classified as "*moderate*" (CCI: 7.61 ± 1.00), with clean northern and central beaches contrasting with dirty southern beaches. Urbanized beaches were assessed with the highest level of pollution ($PAI_{AV,23}$: 5.51; $CCI_{AV,23}$: 18.16). In the long term, cleanliness and plastic pollution maintain "*moderate*" values with $CCI_{AV,18-23}$: 8.81 ± 0.89, and $PAI_{AV,18-23}$: 2.35 ± 0.32, persisting throughout the period, necessitating ongoing monitoring and intervention strategies. Despite identifying a significant number of clean beaches, none meet the EU threshold value of 20 litter items/100 m. This study highlights the urgent need for effective interventions to combat litter accumulation and plastic pollution, particularly in urban or semi-urban beaches, emphasizing multi-stakeholder collaboration for sustainable solutions and coastal ecosystem preservation.

KEYWORDS

marine litter, beach litter, macro litter, monitoring, Clean Coast Index (CCI), Plastic Abundance Index (PAI), Marine Strategy Framework Directive (MSFD), Bulgarian Black Sea coast

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1 Introduction

Marine litter (ML) poses a significant threat to marine wildlife, as recognized by the European Marine Strategy Framework Directive (MSFD) (Directive 2008/56/EC, 2008) and the United Nations Sustainable Development Goal 14 (UN RES/70/1, 2015). The United Nations has initiated efforts to combat plastic pollution by signing a global resolution, aiming for a legally binding treaty by 2024 (UNEP, 2022).

In recent years, there has been a marked increase in ML, mainly plastic debris, in various environments worldwide (Galgani et al., 2013a, 2013b, 2015; Galgani, 2015; Monteiro et al., 2018). Plastic accounts for the majority of ML, constituting 60–80% of the total (Barboza et al., 2019). Despite their convenience, plastics pose an enduring environmental threat due to their resistance to degradation, with an estimated 8.3 billion metric tons produced since the 1950s, of which around 60% have been discarded into landfills or natural environments (UNEP, 2021). The breakdown of plastics into microplastics and nanoplastics further exacerbates this crisis, infiltrating various habitats and disrupting ecosystems, as outlined by Williams and Rangel-Buitrago (2019, 2022). This anthropogenic debris poses significant risks to marine, coastal, and terrestrial ecosystems, endangering species and human health (Wright et al., 2013; Filho et al., 2019; Panti et al., 2019).

However, it is important to note that most of the proposed strategies for collecting stranded ML litter in coastal areas are primarily applicable to the subaerial beach (e.g., Wenneker et al., 2010; Galgani et al., 2013a; GESAMP, 2019). Marine Beach Litter represents a global strategy that provides real-time information about the ML issue, particularly plastic pollution, in the world's oceans and coastal regions (Rangel-Buitrago et al., 2018; Bhuyan et al., 2021; Cesarano et al., 2023; Diem et al., 2023; Mugilarasan et al., 2023, 2021; Zielinski et al., 2022).

1.1 Beach litter along the Black Sea coast

Six nations surround the Black Sea, which is more vulnerable because of the large river discharge into this semi-enclosed basin. ML poses a significant and intricate environmental challenge within the Black Sea basin, with its origins predominantly traced back to terrestrial sources, notably through river inflows (BSC, 2007). The inflow of litter via the Danube alone is estimated at 4.2 tons per day (Lechner et al., 2014). Particularly in the Turkish Black Sea region, municipal, industrial, and hazardous waste disposal, often mingled with medical waste, occurs primarily in nearby lowlands, river valleys, or directly into the sea (Berkun et al., 2005). First aerial observations indicate a notable increase in marine litter influx into the Russian Black Sea during late spring and early summer, marked by snowmelt and heavy rainfall, facilitating litter transport to the sea due to elevated river discharge (BSC, 2007; UNEP, 2009). Vessel-based studies have reported varying densities of floating plastic marine litter across different regions, ranging from 6.6 to 135.9 items per square kilometer, with particularly high concentrations observed in the northwestern part of the Black Sea (Suaria et al., 2015).

Plastic emerges as the predominant type of marine litter across various environmental compartments in the Black Sea, including beaches, sea surface, and seafloor (Topçu and Öztürk, 2010; Suaria et al., 2015; Moncheva et al., 2016; Öztekin and Bat, 2017; Simeonova et al., 2017; Muresan et al., 2018; Simeonova and Chuturkova, 2019; Terzi and Seyhan, 2020; Bekova and Prodanov, 2023; Pogojeva et al., 2023). Over the past ten years, nations bordering the Black Sea have undertaken numerous investigations (since 2013) to better understand the issue's extent and devise strategies for mitigating the flow of ML into the basin. These research endeavors have encompassed a considerable number of research locations along the coasts of Romania (Paui et al., 2017; Muresan et al., 2018), Bulgaria (Brouwer et al., 2017; Simeonova et al., 2017, 2020; Bobchev, 2018; Simeonova and Chuturkova, 2019; Toneva et al., 2019, 2020; Panayotova et al., 2020; Chuturkova and Simeonova, 2021; Bekova, 2023; Bekova and Prodanov, 2023; Prodanov and Bekova, 2023), Georgia (Machitadze et al., 2020), and Turkey (Topçu et al., 2013; Erüz and Özşeker, 2017; Terzi and Seyhan, 2017; Şahin et al., 2018; Öztekin et al., 2020; Atabay et al., 2020; Aytan et al., 2020, 2024; Gülenç et al., 2020; Terzi et al., 2020; Bat et al., 2022; Erüz et al., 2023; Ismail et al., 2023). Different surveys of beaches, dunes, and streamside litter sampling indicated that plastic constitutes the majority (>75%) of the collected items, highlighting its pervasive presence in the area (Topçu et al., 2013; Paiu et al., 2017; Simeonova et al., 2017; Terzi and Seyhan, 2017; Mureşan et al., 2018; Öztekin et al., 2020; Atabay et al., 2020; Aytan et al., 2020; Panayotova et al., 2020; Stoica et al., 2020; Terzi et al., 2020, 2021; Machitadze et al., 2020; Bat et al., 2022; Bekova, 2023; Bekova and Prodanov, 2023; Erüz et al., 2023; Prodanov and Bekova, 2023).

1.2 Aim of study

The article aims to provide a comprehensive analysis of the distribution and dynamics of beach macro litter, aligning with the latest "Guidance on the Monitoring of Marine Litter in European Seas" (Galgani et al., 2023) while assessing plastic pollution indices alongside beach cleanliness. The study encompasses data from four seasonal measurements of beaches in 2023, conducted at 45 sites along the Bulgarian coastline. In addition to an assessment of ML abundance (items/100 m), the research sheds light on other important aspects, such as ML categories (Fleet et al., 2021) and sources (Veiga et al., 2016). Data analysis using statistical tools, the Clean Coast Index (Alkalay et al., 2007) and Plastic Abundance Index (Rangel-Buitrago et al., 2021), contributes to visualizing and categorizing the level of pollution, identifying problematic areas concerning plastic pollution. By comparing newly acquired data with archives from the past five years, the study seeks to identify long-term trends that explain the dynamics of ML along the Bulgarian coast. The study's purpose was to compare the current state and the long-term variations in the distribution of ML along the Bulgarian coast. The research locates litter hotspots to facilitate local analysis of the ML sources and formulates effective strategies for mitigating beach litter at the municipal level. In addition, the research aims to raise awareness among local authorities, policymakers, and stakeholders of the extent and sources of beach litter, focusing attention on this pressing environmental issue.

2 Data and methods

2.1 Monitoring data and survey sites

The research strategy represents a continuation of the long-term commitment of IO-BAS to investigate and map the spatial distribution and dynamics of marine litter along Bulgarian beaches and dunes (Bekova and Prodanov, 2023; Prodanov and Bekova, 2023). The total number of beaches surveyed in 2023 was 45, including 20 remote/natural, 18 semi-urban, and 7 urban beaches (Figure 1), according to the main characteristics of different beach typologies representing different levels of urbanization (Galgani et al., 2023):

- Urban Beaches are located in bustling urban centers with easy access via public and private transport; dense residential and tourist accommodations surround urban beaches and offer comprehensive services and facilities;
- Semi-Urban Beaches are situated on the periphery of cities near small coastal towns, are accessible, cater to moderate populations, and provide a moderate range of accommodations and fewer services than urban beaches;
- Remote/Natural Beaches are isolated, primarily accessed by private means, and are untouched by residential or commercial development, offering no services or facilities for visitors.

Collected litter data in 2023 for each category were standardized to account for the number of items per 100 meters of coastline following guidelines outlined in Commission Decision (EU) 2017/848, Galgani et al. (2023), and "*A Joint List of Litter Categories for Marine Macrolitter Monitoring*" (J-CODE list) by Fleet et al. (2021).

The beach macro litter surveys conducted in 2023 meticulously followed the most recent iteration of the "*Guidance on the Monitoring of Marine Litter in European Seas*" (Galgani et al., 2023). This guidance, developed by the MSFD Technical Group on

Section	Study sites (beaches)	Area, km²
NORTHERN	*(1) Durankulak – North (MSFD1)* (R)	2 542
	(2) Durankulak – South (R)	2 617
	(3) Durankulak - Kosmos (R)	2 916
	(4) Durankulak Lake (R)	2 003
	(5) Krapets - North (R)	2 147
	(6) Shabla – North (R)	2 371
	(7) Shabla – South (R)	1 926
	(8) Bolata (R)	3 091
	(9) Kranevo – Albena (S)	2 123
	(10) Asparuhovo (Varna) (U)	1 946
CENTRAL	*(11) Pasha Dere* (R)	2 582
	(12) Kamchiya (Mouth) (S)	2 329
	(13) Kamchiya - South (Novo Oryahovo Beach) (R)	1 699
	(14) Shkorpilovtsi (MSFD 4) (S)	1 941
	(15) Shkorpilovtsi – South (S)	1 676
	(16) Kara Dere - North (Byala) (MSFD 5) (R)	4 489
	(17) Kara Dere - South (Byala) (R)	2 009
	(18) Emine - North (R)	1 103
	(19) Emine - South (R)	1 281
SOUTHERN	*(20) Slanchev bryag* (U)	2 692
	(21) Nessebar – South (U)	2 773
	(22) Aheloy (S)	2 915
	(23) Pomorie Sand Spit (R)	3 208
	(24) Burgas Port Wall (U)	2 211
	(25) Vromos (R)	2 821
	(26) Campsite Gradina (U)	3 281
	(27) Harmani-Sozopol (U)	3 394
	(28) Kavatsite (U)	3 435
	(29) Alepu (MSFD 9) (R)	4 450
	(30) Arkutino (R)	1 767
	(31) Ropotamo (R)	1 786
	(32) Primorsko (Stamopolu) (S)	4 658
	(33) Primorsko (Mladost MMC) (S)	2 000
	(34) Atliman (S)	5 340
	(35) Dyavolska Mouth (S)	2 186
	(36) Koral (R)	2 613
	(37) Oazis (S)	2 353
	(38) Arapya (S)	2 278
	(39) Nestinarka (S)	1 541
	(40) Ahtopol (S)	2 617
	(41) Veleka Mouth (MSFD 10) (S)	2 453
	(42) Butamyata (S)	2 412
	(43) Lipite (R)	1 997
	(44) Silistar (MSFD A1) (R)	2 527
	(45) Kastrich (R)	1 017

FIGURE 1
Monitoring Survey sites of macro litter along Bulgarian Black Sea beaches in 2023.

Marine Litter, serves as an essential tool for enhancing harmonized monitoring of ML. Adherence to this guidance ensured that the surveys were conducted precisely and in line with established standards, facilitating accurate data collection and analysis for informed decision-making regarding ML management and conservation efforts. Notably, only ten of these beach systems are presently part of the monitoring initiatives mandated by the MSFD, overseen by the Ministry of Environment and Water of Bulgaria (BLKBG-D10-Marine litter, 2016).

The sampling unit comprises a 100-meter stretch of coast, extending from the water's edge to the back of the beach, measured along a curved line on curved beaches or a straight line on straight beaches. The width of the sampling unit (perpendicular to the shoreline) represents the distance between the water edge and the back of the beach (base of dunes, cliff, vegetation line, or human artifacts). Normalizing results to 100 m is imperative if the monitored stretch deviates slightly from the suggested length (Galgani et al., 2023).

Survey sites are ideally characterized by a minimum length of 100 m along the water's edge, consisting of sand or gravel, with a low to moderate slope, unobstructed access to the sea, and accessibility for survey teams throughout the year. Moreover, the selection of survey sites was spatially stratified to encompass diverse pressures and levels of litter exposure, such as proximity to river mouths, harbors/marinas, and tourist facilities. It should also consider various levels of development and urbanization, ensuring a balanced representation of urban, semi-urban, and remote/natural beaches. The total monitored beach area was evaluated at approximately 125,000 m^2, covering a coastline stretch of 4,000 m, equivalent to 0.9% of the shoreline length of 518.7 km (Figure 1). In 2023, the monitoring was conducted four times per season under the requirements of the MSFD (Galgani et al., 2023): winter – January and February; spring – April and May; summer – July and August; autumn – October and the first half of November (Figure 1).

2.2 Data methods

2.2.1 UAS data

Specialized Unmanned Aerial Systems (UAS) were applied to investigate the localization and spatial distribution of ML. The drones present a sustainable method for analyzing litter dynamics, providing valuable information for developing coastal litter models and parameters (Andriolo et al., 2023, 2024; Gonçalves et al., 2022). Through the application of UAS, researchers have implemented survey strategies to map and identify the abundance and distribution of macro litter items on sandy beaches, employing a combination of manual image screening and machine learning techniques (Deidun et al., 2018; Fallati et al., 2019; Gonçalves et al., 2020; Andriolo et al., 2021; Andriolo and Gonçalves, 2022; Bekova and Prodanov, 2023, 2022; Prodanov and Bekova, 2023).

The monitoring procedure began with UAS-photogrammetric surveys in each survey site before litter collection, using a DJI Phantom 4 RTK quadcopter equipped with a 20-megapixel camera following the standard procedure (Bekova and Prodanov, 2023; Prodanov and Bekova, 2023). The quadcopter ensured precise georeferencing by collecting ground control points with the Hi-Target V90 GNSS RTK System. Flight missions operated at a 20-meter altitude, capturing images with a resolution of 4000 × 3000 pixels and an overlapping rate of 90%. Post-processing using Agisoft Metashape to generate the orthophotomosaic (OM) with very high GSD between 0.3 and 0.5 cm/px. Another compelling reason for us to opt for drones in litter mapping was their efficiency in terms of both time and cost. Drones equipped with RTK (Real-Time Kinematic) mode can also significantly improve the accuracy of coastal macro-litter pollution assessments (Prodanov and Bekova, 2023).

2.2.2 Manual collecting, visual census, and classification

The second step involved the manual collection and visual census of large BL over 2.5 cm. Ensuring accurate BL identification by observers was crucial. The goal was full coverage of the visual census and classification within the survey site. At least four IO-BAS observers conducted visual assessments using a consistent classification system based on ML categories listed in The Joint List of Litter Categories (Fleet et al., 2021), ensuring consistency in the classification and characterization of the identified litter. The litter was categorized into classes at J-CODE list: *Artificial polymer materials/Plastic, Rubber, Cloth/textile, Paper/Cardboard, Processed/worked wood, Metal, Glass/Ceramics, Chemicals, Food waste and Unidentified* (Fleet et al., 2021).

2.2.3 Manual image screening

To analyze macro litter distribution and dynamics, Beach and Density Litter Maps were created for each area using litter identified via manual image screening. Similar to Gonçalves et al. (2020), orthophotomosaics were gridded into 4 m squares for systematic analysis. Operators visually screened images, identified and classified litter items according to Fleet et al. (2021), marked item locations in GIS, and generated shapefiles for each area. These maps pinpointed BL hotspots, aiding in identifying fly-tipped areas, and could inform future surveys correlating litter density with beach and dune conditions.

2.3 Amount of beach macro litter

The assessment of beach litter abundance was based on *in-situ* manual collection and visual census. The unit of measurement for beach macro litter, as specified in Commission Decision (EU) 2017/848, is the amount (abundance) of litter per category, defined as the number of items per 100 meters along the coastline. The beach litter density was accounted for in items/sq.m.

2.4 Evaluation of CCI and PAI

The cleanliness of the studied beaches was assessed using the Clean Coast Index (CCI), developed by Alkalay et al. (2007). This index provides a comprehensive measure by considering both the abundance and density of macro litter pollution. Using the CCI, beaches can be categorized into five levels, ranging from "*very clean*" to "*extremely dirty*". These categories were calculated based on Formula (2) in Table 1.

The Plastic Abundance Index (PAI) is a valuable tool for the evaluation of plastic pollution (e.g., Rangel-Buitrago et al., 2021; Al Nahian et al., 2022; Bekova, 2023; Perumal et al., 2023; Sandaruwan et al., 2023; Ilechukwu et al., 2024; Mghili et al., 2024). The PAI was introduced to assess the presence of plastic on beaches by comparing the amount of plastic to the total litter collected (Rangel-Buitrago et al., 2021). For each of the 45 surveyed beaches, the PAI was calculated using the Formula (1) in Table 1. The PAI represents the number of plastic items per square meter, considering the relationship between plastics and the logarithm of all litter items collected across the sampling area. This index categorizes beaches based on plastic presence into five classes, ranging from "*very low abundance/absence*" to "*very high abundance*" (Rangel-Buitrago et al., 2021).

3 Results

The study presents the results from research conducted in 2023 across 45 beaches, analyzing the abundance, density, spatial distribution, and sources of ML. The survey sites were systematically categorized according to their cleanliness levels, as defined by the Clean Coast Index, and the categories of plastic pollution quantified through the Plastic Abundance Index. The average abundance of 760.51 items/100 m along the Bulgarian beaches showed moderate distribution of ML for 2023 (Table 2). This significant amount originates from pollution related to land-based sources (74.3%) and other maritime activities such as fishing and shipping. The PAI average of 2.34, classified under the "*moderate abundance*" category, emphasizes a considerable presence of plastic pollution. A CCI value of 7.61, categorized as "*moderate*", suggests that while the beaches are not in a critical condition, there is ample scope for improvement to achieve cleaner coastal environments (Table 2).

3.1 Abundance of ML, CCI, and PAI

On the Northern coast, a considerable variation in marine litter quantities exists, ranging from 189 items/100 m at (3) Durankulak - Kosmos to a substantial peak of 1 408 items/100 m at (8) Bolata. This fluctuation was attributed to disparities in beach accessibility and the intensity of their use. Clean Coast Index (CCI) values within this region extend from 2.16 to 12.34. A majority of the beaches are classified as "*clean*" except for (8) Bolata, which is distinctly categorized as "*dirty*" due to a pronounced accumulation of ML (Figure 2). Plastic Abundance Index (PAI) values vary from 0.70 to 4.33. While most sites in this region display "*low*" to "*moderate*" plastic abundance, Bolata shows a "*high abundance*" category of PAI, highlighting a critical demand for intensified plastic waste management strategies (Figures 3, 4).

Regarding ML distribution, the Central coast reports a generally lower abundance of ML, with quantities ranging from 113 items/100 m at (11) Pasha Dere to 452 items/100 m at (16) Kara Dere - North. This reduction may be correlated with decreased human activity or more effective waste management practices at the local level. Most of these sites maintain a "*clean*" status with CCI values varying between 1.20 and 5.35. Notably, (16) Kara Dere-North is characterized by a "*moderate*" rating, indicative of some visible litter (Figure 2). PAI values ranging from a low of 0.22 at (18) Emine-North to 2.31 at (16) Kara Dere-North suggest that the extent of plastic pollution is generally manageable across most locations in this region (Figures 3, 4).

The Southern coast exhibits the highest abundance of ML, particularly at urban locations such as (20) Slanchev bryag, (21) Nessebar – South, (24) Burgas Port Wall, and (28) Kavatsite, where figures surpass 2000 items/100 m, underscoring significant pollution challenges. The CCI in this region demonstrates extreme values, with several urban sites being designated as "*extremely dirty*". The minimum CCI recorded is 0.90 at (31) Ropotamo (Figures 2, 4). PAI reaches its zenith at 8.24 at (28) Kavatsite, classified as "*very high abundance*" (Figures 3, 4). Numerous sites manifest a "*high abundance*" of plastics,

TABLE 1 Values and categorization according to the PAI (Rangel-Buitrago et al., 2021) and CCI (Alkalay et al., 2007).

Plastic Abundance Index		Clean Coast Index	
$(1)\ \mathbf{PAI} = \dfrac{\dfrac{\sum \text{Plastic litter items}}{\log 10 \sum \text{Total litter items}}}{\text{Total area}} \times 20$		$(2)\ \mathbf{CCI} = \dfrac{\text{Total number of macro litter (items)}}{\text{Total area (100 m x width)},\ (m^2)} \times 20$	
Values	Abundance[1]/*Description*[2]	Values	Cleanliness[1]/*Description*[2]
0	**Very Low Abundance/Absence**[1] (*No plastics are seen*)[2]	**0 – 2**	**Very clean**[1] (*no litter is seen*)[2]
0.1 - 1	**Low Abundance**[1] (*Some plastics are in the sample area*)[2]	**2 - 5**	**Clean**[1] (*no litter is seen over a large area*)[2]
1.1 - 4	**Moderate Abundance**[1] (*A considerable amount of plastics are seen*)[2]	**5 – 10**	**Moderate**[1] (*a few pieces of litter can be detected*)[2]
4.1 - 8	**High Abundance**[1] (*A lot of plastics are in the sample area*)[2]	**10 – 20**	**Dirty**[1] (*a lot of waste on the shore*)[2]
> 8	**Very High Abundance**[1] (*Most of the sampling area is composed of plastics*)[2]	**20+**	**Extremely dirty**[1] (*most of the shore is covered with plastic debris*)[2]

TABLE 2 Generalized data of marine litter distribution on Bulgarian beaches in 2023 (detailed version of the table see in Appendix 1).

Year	Parameter	Unit	Average (mean) values	Categorization	Seasonal variation
2023	**Abundance**	Items/ 100 m	753 ± 97	–	Spring: 877
					Autumn: 629
	D_{av}	Items/m^2	0.38 ± 0.05	–	Spring: 0.44
					Autumn: 0.31
	PAI_{av}	Values	2.34 ± 0.32	Moderate Abundance	Spring: 2.55
					Autumn: 2.12
	CCI_{av}	Values	7.61 ± 1.00	Moderate	Spring: 8.93
					Autumn: 6.29

accentuating the grave issue of plastic pollution prevalent in the region. This analysis underscores the urgent need for targeted plastic waste reduction and management initiatives on the Southern Coast to mitigate the environmental impacts observed.

3.2 Composition of ML

The values show that *Artificial polymer materials* constituted the predominant component, accounting for 86.62% of the total litter observed (Figure 5A). This significant proportion underscores plastic pollution's persistent and prevalent nature in the sites. Despite concerted efforts to mitigate this issue, the data indicates limited variability in the prevalence of plastic polymer litter over the preceding five years. This finding highlights the exigency for developing and implementing more efficacious strategies and interventions aimed at curbing *plastic litter* in the area. A worrying trend emerged during the research concerning the presence of *Paper/cardboard litter* along the Bulgarian beaches. Over time, the proportion of *Paper/cardboard litter* gradually increased, reaching 5.72% of the total waste detected along the coast. This trend warrants further investigation into the underlying factors contributing to the rising prevalence of *Paper/cardboard* waste in the marine environment.

In contrast, *Metal* and *Glass/ceramics* were identified as relatively rare constituents of beach litter, comprising modest proportions of 2.12% and 2.30% of the total litter amount, respectively. These materials tend to exhibit localized concentrations in specific hotspots rather than being evenly distributed along the coastline. Conversely, *Processed/worked wood, Rubber*, and *Cloth/textile* were the least frequently encountered types of litter throughout the monitoring period, constituting proportions of 1.38%, 0.86%, and 0.66%, respectively (Figure 5A).

3.3 Sources of ML

Beach litter, particularly along the Bulgarian coast, primarily originates from *land-based sources*, accounting for approximately 74.3% of ML. This high percentage is dominated by public litter, constituting 71.1% of the total litter amount. This suggests that littering by tourists at the beaches (Recreational Public litter - 86.1% from Public litter) and nearby areas is the most significant

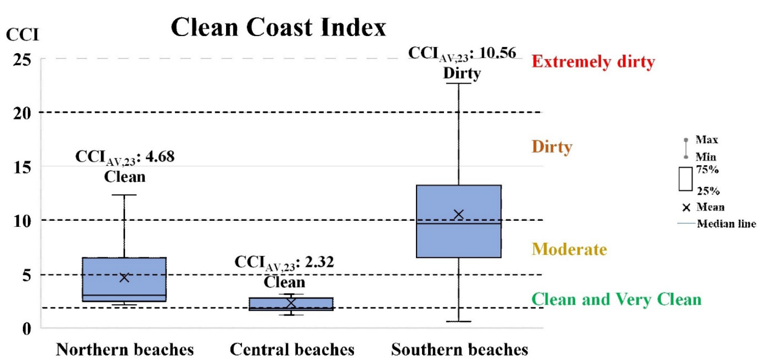

FIGURE 2
Distribution of Clean Coast Index at the surveyed Bulgarian beaches in 2023.

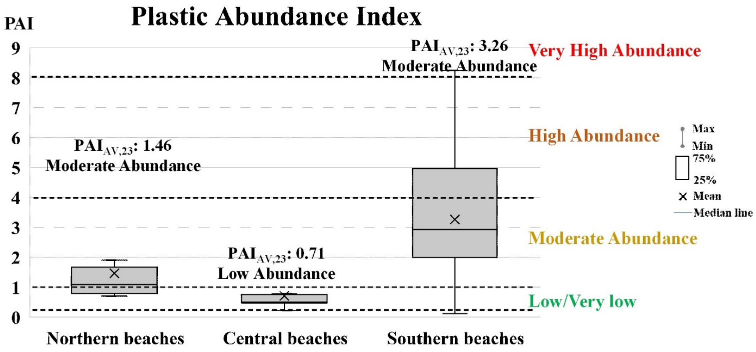

FIGURE 3
Distribution of Plastic Abundance Index at the surveyed Bulgarian beaches in 2023.

contributor to marine pollution in this region of the Black Sea (Figure 6).

In contrast, *sea-based sources* contribute to 25.7% of the ML. This category includes various specific sources: *fishing litter* (4.9%), which likely includes discarded fishing gear such as nets and lines; *sewage and sanitary waste* (2.7%), possibly from boat discharges or coastal sewage outputs; shipping litter (4.1%), which can involve garbage thrown overboard from ships; *fly-tipped waste* (7.2%), which refers to large items illegally dumped into the sea; and *medical waste* (4.3%), likely discarded from ships or coastal facilities. In 2023, a category termed "*non-sourced*" makes up 5.7% of the marine litter, indicating unidentified or mixed-origin debris (Figure 6).

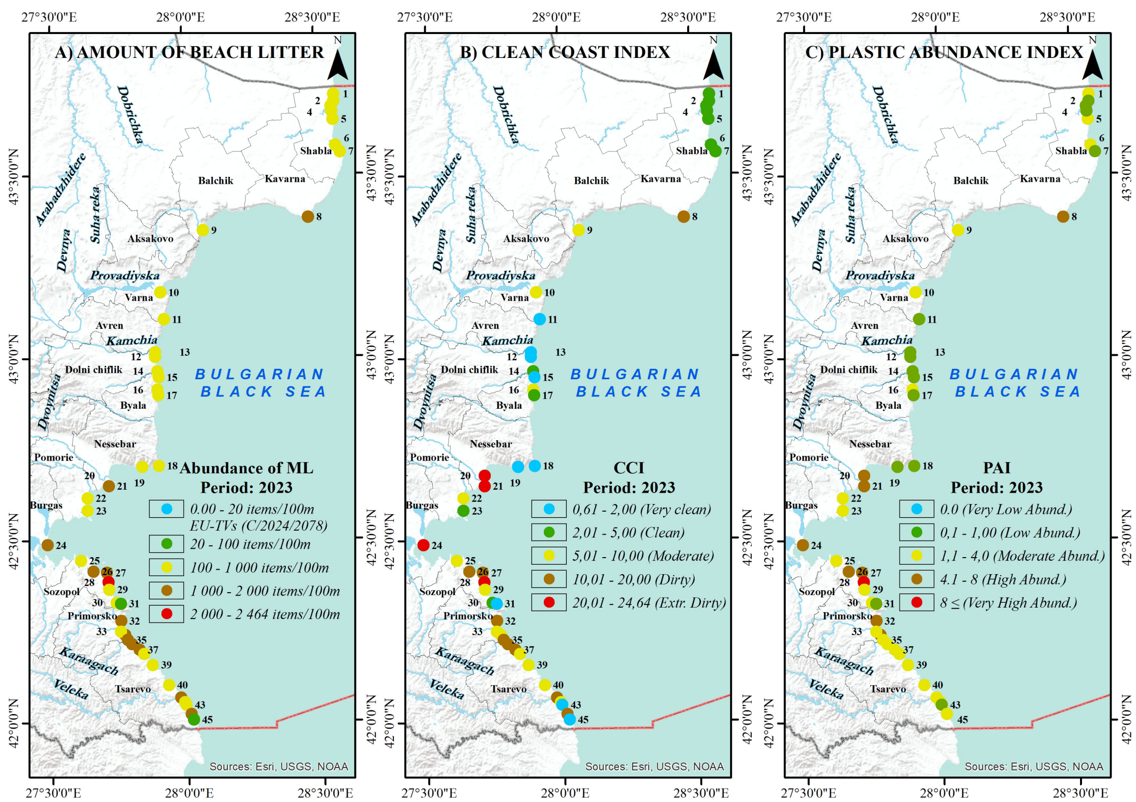

FIGURE 4
Results of monitoring surveys in 2023 at the Bulgarian Black Sea beaches; **(A)** Amount of beach litter (*abundance – items/100 m*); **(B)** Evaluation of Clean Coast Index; **(C)** Categorization by Plastic Abundance Index.

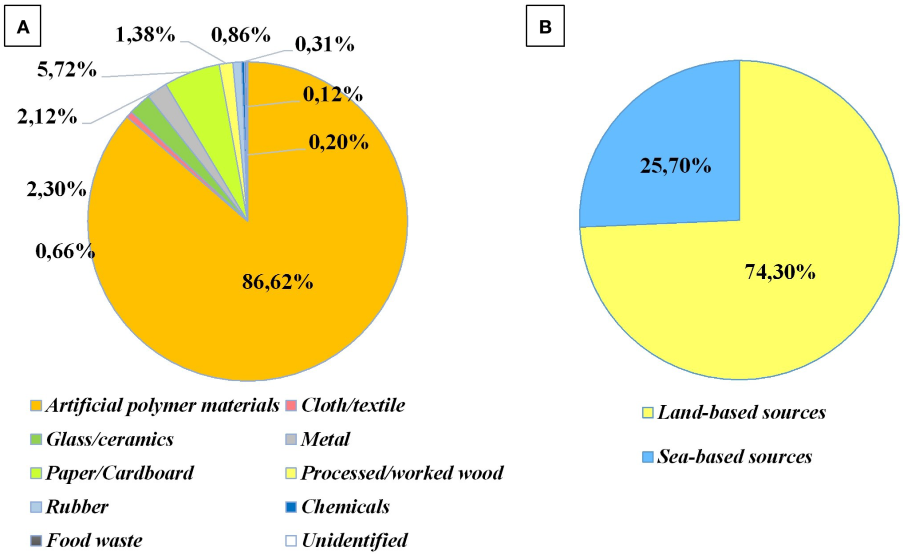

FIGURE 5
Composition **(A)** and main sources **(B)** of ML on Bulgarian beaches in 2023.

4 Discussion

4.1 Variation of ML composition and sources

The Bulgaria coastline on the western Black Sea coast consistently shows a high density of floating marine litter (ML) distribution across all numerical scenarios (Castro-Rosero et al., 2023). On the other hand, both floating and seafloor ML are major contributors to overall marine litter (BSC, 2007; Ioakeimidis et al., 2014; Lechner et al., 2014; Suaria et al., 2015; Moncheva et al., 2016; Öztekin and Bat, 2017; Slobodnik et al., 2018; Stanev and Ricker, 2019; Aytan et al., 2020; Berov and Klayn, 2020; Doncheva et al., 2020; Miladinova et al., 2020; Raykov et al., 2020; Slabakova et al., 2020; Terzi et al., 2020; Panayotova et al., 2021; Erüz et al., 2022, 2023; González-Fernández et al., 2020; González-Fernández et al., 2022; Demetrashvili et al., 2022; Bobchev et al., 2023; Castro-Rosero et al., 2023; Pogojeva et al., 2023). However, land-based sources remain primary, with varying estimates of beach litter accumulation along the southern and western coasts of the Black Sea ranging from 62% (Aytan et al., 2020), 74.13% (Bat et al., 2022) to 77.4% (Bekova and Prodanov, 2023). In 2023, *Land-based litter* again dominated at

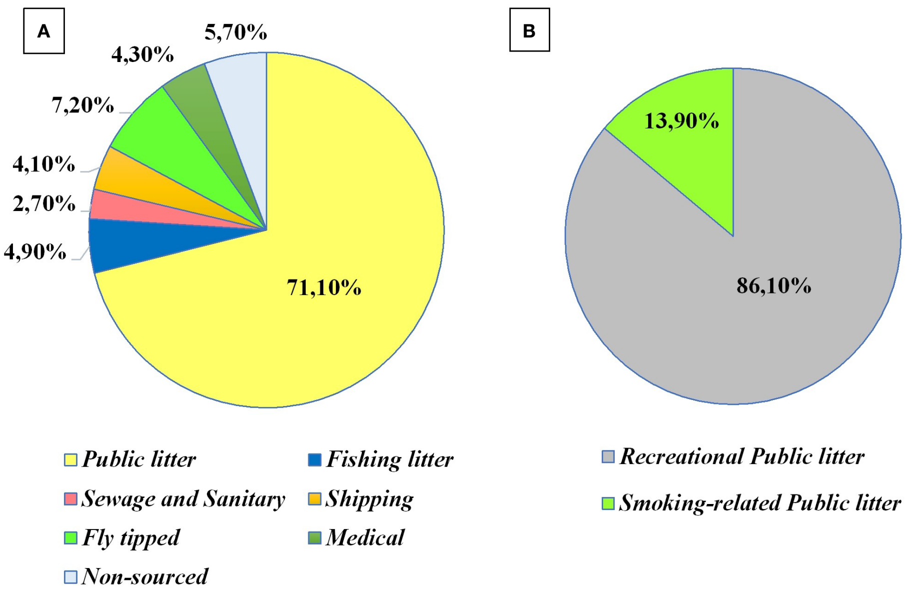

FIGURE 6
ML sources **(A)** and Public-related sources of ML **(B)** along Bulgarian beaches in 2023.

74.3% compared to *Sea-based litter* at 25.7%, primarily due to recreational activities along the Bulgarian coast.

High plastic pollution has been documented on remote/semi-urban situated beaches such as Bolata, Kamchiya-Shkorpilovtsi, Veleka Mouth, and Alepu (Bekova, 2023; Bekova and Prodanov, 2023), with efforts must be aimed at reducing such high values to the range of 60.2%-64.9% during the period 2017–2018 (Simeonova et al., 2020).

Despite a decrease in concentration from 87.06% in 2018 (Bekova and Prodanov, 2023) to 86.62% in 2023, *Artificial polymer materials* continue to dominate beach litter, emphasizing the persistent challenge of plastic pollution. This sustained dominance underscores the ongoing difficulties in managing plastic pollution despite some improvement ($PAI_{AV,18\text{-}23}$: 2.35 "*moderate abundance*"). Furthermore, there was a slight increase in *Cloth/textile* waste from 0.63% in 2018 to 0.66% in 2023. While this percentage rise may seem modest, it warrants attention due to the environmental challenges posed by textile waste, including microfiber pollution and biodegradability issues (Figure 5A).

Additionally, *Glass/ceramics, Metal, Paper/cardboard, Processed/worked wood*, and *Rubber* exhibited stable percentages or marginal increases over the analyzed period. While these materials may not comprise the majority of beach litter (< 2.5%) like plastics, their persistence highlights the necessity for comprehensive waste management strategies that address diverse types of litter. Moreover, in 2023, a small percentage of *Chemicals* (0.31%) and *Food waste* (0.20%) were recorded (Figure 5A). Although these categories currently represent a minor fraction of beach litter, their emergence signals evolving patterns of pollution that require proactive measures to prevent their escalation. This underscores the importance of four seasons of monitoring and addressing emerging sources of pollution to ensure the health and sustainability of coastal ecosystems.

Both the Turkish coast and Bulgarian beaches demonstrate a persistent trend of high *land-based sources* of macro ML. In Turkey, studies by Aytan et al. (2020) and Bat et al. (2022) reported percentages of 62% and 74.13%, respectively. Meanwhile, Bulgarian beaches maintained consistently high values of *Public litter* from 2018 to 2023: 74.1% (2018), 72.3% (2019), 78% (2020), 91% (2021), 74.1% (2022) (Bekova and Prodanov, 2023) and 71.1% (2023) - (Figure 6). The rise in public litter is particularly notable in recreational areas, where it accounts for 86.1% of the total, compared to 13.9% attributed to *Smoking-related public litter*. This increase aligns with the escalating tourist activity along the coastline. However, it also highlights a concerning long-term issue: the proportion of public waste has risen from 48.3% in previous years (Chuturkova and Simeonova, 2021) to an average of 68% in 2023. Notably, specific beaches such as Kavatsi, Nesebar, Sunny Beach, and Bolata, among others, witness debris directly left by tourists exceeding 90%. This underscores the urgent need for targeted interventions to address littering behaviors and improve waste management infrastructure in popular tourist destinations.

While *Public litter* remains a significant concern, there have been slight improvements in other areas. *Fishing litter*, for instance, saw a marginal decrease from 5.10% in 2018 (Bekova and Prodanov, 2023) to 4.90% in 2023 (Figure 6). Though modest, this decline suggests the potential effectiveness of efforts to promote responsible fishing practices and implement regulations to curb marine debris resulting from fishing activities. *Sewage and sanitary sources* maintained a consistent presence at 2.70% throughout the analyzed period. This stability may indicate efficient sewage management practices, yet it also highlights the need for ongoing evaluation and enhancement of wastewater treatment systems to prevent marine pollution from sewage discharge. Similarly, *Shipping* and *Fly-tipped sources* exhibited stability, with concentrations remaining at 4.10% and 7.20%, respectively, in 2023 compared to 2018 (Bekova and Prodanov, 2023). While these sources did not undergo significant changes, addressing *Shipping-related litter* may require international collaboration and regulatory measures. Addressing *Fly-tipped litter* necessitates local enforcement and improvements in waste disposal infrastructure (Figure 6).

One notable positive trend is the decrease in *Medical waste* from 13.00% in 2018 (Bekova and Prodanov, 2023) to 4.3% in 2023. This decline can be attributed to reduced usage of single-use personal protective equipment following the COVID-19 pandemic. However, remnants of these items persist on beaches, indicating the ongoing need for intensity in waste management practices.

4.2 Spatial patterns of litter distribution along Bulgarian beaches

Mean values have surged from 428 ± 47 items/100 m in 2018 (Bekova and Prodanov, 2023) to 753 ± 97 items/100 m in 2023, with notable peaks of 240% at 1462 ± 147 items/100 m in 2021, before stabilizing documented in this study (Figure 7; Appendix 1). While the increase of over 200% may appear impressive at first glance, it is crucial to consider the broader context. Our research confirms that Bulgarian beaches experienced the most significant pollution with macro litter in 2020 and 2021 within all types of beaches. The COVID-19 pandemic and associated travel restrictions abroad played a pivotal role in exacerbating this issue. These measures led to a significant influx of local tourists to Bulgarian beaches, overwhelming both the public recreational sources and local authorities. Evidence of the scale of the indirect impact of COVID-19 measures is evident in the sharp increase in medical waste from 0.8% in 2021 (Chuturkova and Simeonova, 2021) to 16% in 22% (Bekova and Prodanov, 2023). However, following the end of the pandemic in 2021 and the subsequent exponential increase in the use of single-use personal protective equipment, our research observed a long-term normalization (decreasing) trend regarding medical waste, reducing it to 6% (Figure 7B).

As the World moves away from the COVID-19 pandemic and its consequences, the article directs our discussion to whether there has been an improvement in litter distribution. Bekova and Prodanov (2023) report a significant reduction in litter distribution from 1462 ± 147 items/100 m in 2021 to 609 ± 70 items/100 m in 2022. Encouragingly, current data for 2023 show 753 ± 97 items/100 m, indicating a stabilization at these pollution levels (Figure 7A). The mid-term analysis showed that the situation has stabilized to normal levels for the Bulgarian coastline over the

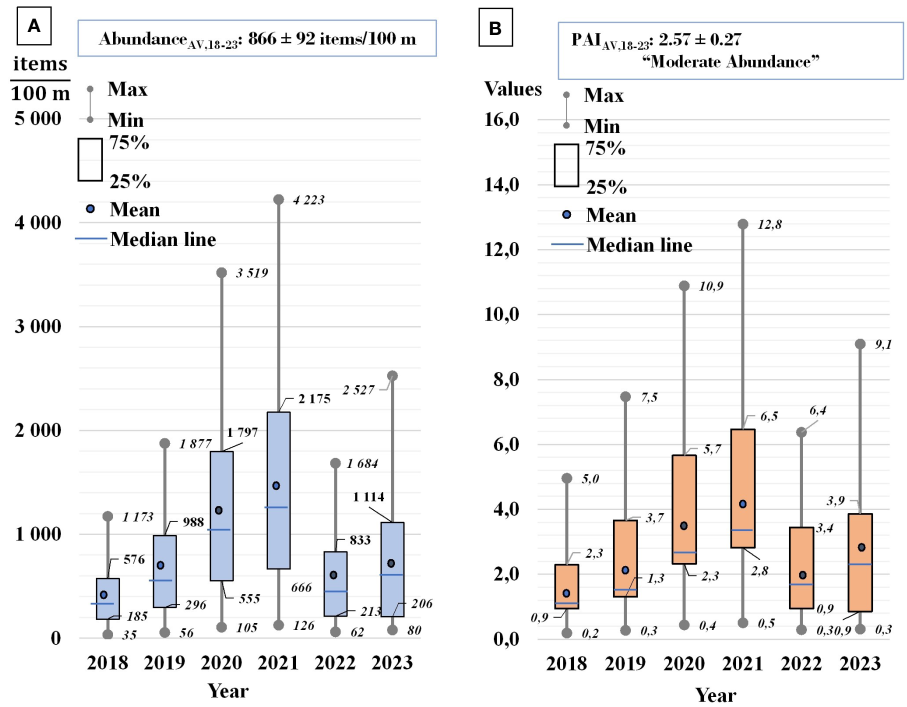

FIGURE 7
Temporal variation in the distribution of marine litter along the Bulgarian Black Sea beaches in the period 2018 - 2023; **(A)** Amount/abundance of ML in items/100 m; **(B)** Plastic Abundance Index (PAI).

past three years. The reduction in litter quantity was estimated at 48%, from 1462 ± 147 items/100 m in 2021 (Bekova and Prodanov, 2023) to 753 ± 97 items/100 m in 2023 (Figure 7A). Although the improvement appears sustainable, the Bulgarian coastline varies significantly regarding anthropogenic pressure and recreational beach use. Geomorphological conditions and wave exposure are primary factors determining marine litter distribution conditions. In addition to geographical distinctions, three sections of beaches were defined according to cleanliness: northern (1–10), central (11–19), and southern (20–45) – Figure 5; Appendix 1).

4.2.1 Northern beaches

The "Clean" Dobrudzha subsection encompasses the northernmost beaches stretching from Durankulak-North to Bolata, classified as Remote (Figures 2–4; Appendix 1). Given its proximity to the Romanian border, the coastline of Durankulak, in particular, faces the risk of marine litter (ML) influx from offshore areas. This susceptibility is attributed to the influence of the Black Sea current, circulating the entire basin counterclockwise, potentially aiding the spread of plastic ML across the Romanian basin (Stanev and Ricker, 2019; Chuturkova and Simeonova, 2021; Castro-Rosero et al., 2023). However, in the long term, this subsection boasts clean beaches with variations in values in the range of 3.92 ≤ $CCI_{AV,18\text{-}23}$ ≤ 4.48. The situation regarding *Artificial polymer materials/Plastic* pollution has remained at a "*moderate*" level over the past six years, with values of 1.08 ≤ $PAI_{AV,18\text{-}23}$ ≤ 2.9. *Land-based litter* accounts for 64%, while *Public litter* contributes 56%. However, it is worth noting that the surveyed beach areas are lightly visited. The beaches of Dobrudzha maintain their cleanliness in the long term, with a $CCI_{AV,18\text{-}23}$ categorizations of 4.25 "*clean*" and potential for soon improvement to "*very clean*" (Figures 2, 3).

An exception was identified at (8) Bolata, where pollution from tourists registers exceptionally high levels despite state conservation efforts. After years of extreme dirtiness, in 2023, the beach was categorized as "*dirty*" with a $CCI_{AV,23}$ of 12.34. Maintenance issues persist, and in the plastic pollution ranking, (8) Bolata stands second in long-term beach pollution with a $PAI_{AV,18\text{-}23}$ of 5.73, following Kavatsi. The long-term categorization of $CCI_{AV,18\text{-}23}$: 19.19, is "*dirty*", with a prospect of further pollution due to the beach's small area, increasing tourist influx, and infrastructure degradation (Figures 2, 3).

Turning attention briefly to the Varna subsection, it comprises two beaches: (9) Kranevo – Albena (semi-urban) and (10) Asparuhovo – Varna (urban), both experiencing a significant tourist flow. Despite the thousands of tourists, sporadic clean-up efforts, and summer maintenance by local authorities, they maintain a moderately acceptable level of cleanliness. Pollution levels also remain in "*moderate abundance*", with 1.81 ≤ $PAI_{AV,18\text{-}23}$ ≤ 1.90. The long-term categorization $CCI_{AV,18\text{-}23}$ evaluates at 10.91 "*dirty*" with potential for improvement to moderate pollution beaches (Figures 2, 3).

4.2.2 Central beaches

The coastline stretching between (11) Pasha Dere and (19) Emine–South forms a pristine beachfront with a $CCI_{AV18\text{-}23}$: 3.89 "*clean*" (Figures 2, 3). This area includes the extensive Kamchiya-

Skorpilovtsi coastal strip and Kara Dere, which, due to lower visitation rates, remain minimally affected by human activity, including plastic pollution. Similar to the northern beaches, camping is prevalent here, and the issue of plastic pollution exists within moderate boundaries, with values ranging between 1 and 3.

The long-term categorization of $CCI_{AV,18\text{-}23}$ was assessed at 3.34 "*clean*" with room for improvement, indicating that measures aimed at regulating camping and beach usage are proving effective. These efforts contribute to maintaining the beaches' cleanliness and mitigating the impact of human activities on the coastal environment.

4.2.3 Southern beaches

While the northern coast boasts long-term "*clean*" beaches, to the south of Cape Emine, there are localized major resort centers such as (20) Slanchev bryag, (21) Nessebar – South, and (24) Burgas Port Wall and areas south of Sozopol. Here, a distinction must be made between urban and semi-urban beaches and remote/natural beaches. Predominantly, beaches were categorized as "*dirty*" and "*moderate*," with a $CCI_{AV,18\text{-}23}$ value of 10.52 for the southern coastline (Figures 2, 3; Appendix 1). These beaches are highly exposed to wave action (Valchev et al., 2023), and their gently sloping profiles facilitate the accumulation, removal, transportation, and relocation of debris across various locations or beaches.

This region encompasses the vast beach of the resort center (20) Slanchev bryag, and the southern beach of Nessebar. During the COVID-19 epidemic, there was a significant influx of macro debris, but over the past two years, local authorities have managed to reduce this waste through regular cleaning initiatives. Concurrently, plastic waste has been reduced ($6.88 \leq PAI_{AV,18\text{-}23} \leq 16.86$).

During the summer, tourist traffic along the southern coastline is concentrated south of Sozopol, where over 90% of beaches are concessioned and maintained. However, a significant portion of the coastal strip remains unregulated outside the summer season. During the COVID-19 epidemic and travel restrictions abroad, resorts' beaches struggled to accommodate a large number of tourists, leading to significant overcrowding of beaches along the Strandzha mountain. Bekokva and Prodanov (2023) reported exceptionally high levels of pollution along the southern coastline, with a $CCI_{AV,20\text{-}21}$ of 16.74 "*dirty*", accompanied by a peak in high abundance of plastics pollution $PAI_{AV,20\text{-}21}$: 5.85 "*high abundance*". The proliferation of personal protective equipment (PPE) such as face masks, gloves, and wet wipes during the pandemic significantly contributed to plastic pollution, with face masks being the predominant PPE items found in the marine environment. With the easing of the COVID-19 epidemic, there has been a decrease in the use of single-use plastics, reflected in a long-term reduction of plastic pollution along the southern coastline with a PAI value of 3.86 "*moderate abundance*" (Figures 2, 3).

Although there is a noticeable improvement in the pollution situation along the southern coastline, a clear trend regarding waste reduction is still elusive. In 2022 and 2023, there was extensive construction along the coastline south of Sozopol. Apart from tourism, there has been an increase in permanent residents, inevitably leading to increased anthropogenic waste and pressure on the ecosystem. The situation within the Kavatsite coastal sector is particularly concerning, where construction is mere meters away from the beach-dune system, contributing to waste transfer.

4.3 Urban proximity and tourist impact on beach litter distribution

4.3.1 Remote/natural beach

Beaches outside populated areas are concentrated along the central and northern coastlines: (1) Durankulak – North, (2) Durankulak – South, (3) Durankulak – Kosmos, (4) Durankulak Lake, (5) Krapets – North, (6) Shabla – North, (7) Shabla – South, (8) Bolata, (11) Pasha Dere, (13) Kamchiya – South (Novo Oryahovo Beach), (16) Kara Dere - North (Byala), (17) Kara Dere - South (Byala), (18) Emine – North, (19) Emine – South, (23) Pomorie Sand Spit, (29) Alepu, (30) Arkutino, (31) Ropotamo, (43) Lipite, and (45) Kastrich (Figures 4, 8, 9). In some of these locations, a reverse proportionality between PAI and CCI has been observed. Plastics remain highly prevalent even after the calming of the COVID-19 situation. For the most part, they range between "*clean*" and "*very clean*" $0.87 \leq CCI_{AV,18\text{-}23} \leq 12.95$ (Figures 4, 8, 9). Their relatively clean nature is primarily due to the relatively

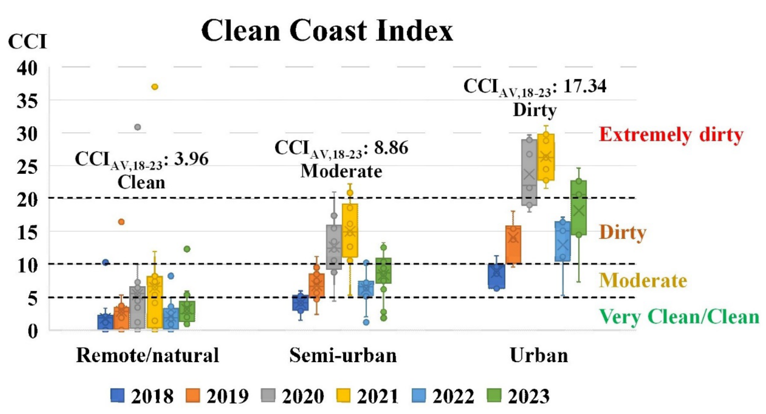

FIGURE 8
Temporal variation of the CCI by different types of beaches in 2018–2023.

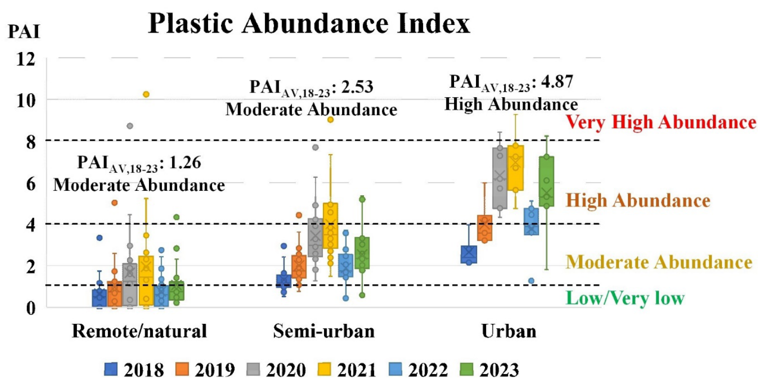

FIGURE 9
Temporal variation of the PAI by different types of beaches in 2018–2023.

low tourist visits. The beaches are long and far from concession activities, which does not make them attractive to a large number of tourists. In 2023, a significant decrease in anthropogenic pressure regarding litter distribution $CCI_{AV,23}$: 4.81 "*clean*", albeit still retaining plastic waste within acceptable limits $PAI_{AV,23}$: 1.26 "*moderate abundance*", has been observed. More concerning are the beaches along the southern coast. However, despite their distance from populated areas, they maintain a constant and concentrated influx of tourists. Given their small areas, waste tends to concentrate, thus raising their CCI to "*moderate*" values. Despite all these beaches, the situation with marine debris has improved over the last two years, and no alarming events pose a risk of increasing waste concentration. This year, measures have been taken against illegal camping along the Black Sea coast, which mainly contributes to anthropogenic waste on remote/natural beaches (Figures 4, 8, 9).

4.3.2 Semi-urban beaches

The semi-urban beaches encompass locations such as (9) Kranevo – Albena, (12) Kamchiya (Mouth), (14) Shkorpilovtsi, (15) Shkorpilovtsi – South, (22) Aheloy, (25) Vromos, (32) Primorsko (Stamopolu), (33) Primorsko (Mladost MMC), (34) Atliman, (35) Dyavolska Mouth, (36) Koral, (37) Oazis, (38) Arapya, (39) Nestinarka, (40) Ahtopol, (41) Veleka Mouth, (42) Butamyata and (44) Silistar (Figure 1). Among them, beaches are experiencing high tourist traffic, reflected in over 100% more waste accumulation - $CCI_{AV,23}$: 4.81 (Figures 4, 8, 9). Although 75% of them exhibit $PAI_{AV,23}$: 3.28 "*moderate abundance*", plastics reach concerning levels around the popular Primorsko and Tsarevo areas at beaches (32) Primorsko (Stamopolu), (33) Primorsko (Mladost MMC), (34) Atliman, (37) Oazis. Compared to remote beaches, plastics at semi-urban ones show over 95% more accumulation in a long-term perspective $PAI_{AV,23}$: 2.29 "*moderate abundance*" (Figures 4, 8, 9). In 2020 and 2021, they recorded their lowest levels of cleanliness and, respectively, their highest levels of plastic pollution (Bekova and Prodanov, 2023). During COVID-19, these beaches were affected by the use of protective medical gear. Long-term improvement has been observed, and with proper maintenance, the proximity of these beaches to resorts would not be a factor in increasing plastic and other waste pollution (Figures 4, 8, 9).

4.3.3 Urban beaches

These beaches number only seven but attract significant tourist traffic along the Bulgarian coastline: (10) Asparuhovo (Varna), (20) Slanchev bryag, (21) Nessebar – South, (24) Burgas Port Wall, (26) Campsite Gradina, (27) Harmani-Sozopol, and (28) Kavatsite (Figures 4, 8, 9). Despite the survey sites being located on the periphery of these beaches and not undergoing summer mechanical cleaning, they still "collect" the highest amounts of waste $CCI_{AV,18-23}$: 17.34, a fact that also applies to plastic pollution $CCI_{AV,18-23}$: 6.04. Finding trends for these beaches is difficult as they are subjected to constant anthropogenic pressure. While Bekova and Prodanov (2023) noted improvement in 2022, a drastic increase in waste was observed in 2023, reminiscent of levels during COVID-19. Plastic pollution has persisted at a stable "*high abundance*" level over the past six years, $3.67 \leq PAI_{AV,18-23} \leq 8.37$ (Figures 4, 8, 9). For these beaches, an explanation for the high pollution levels lies in the failure of local authorities to maintain the beaches outside the summer tourist season. They are no exception to the general rule that waste quantities are higher during winter and spring (Panayotova et al., 2020; Bekova and Prodanov, 2023), and this should be a focus when devising strategies for beach cleanliness maintenance.

4.4 Kakhovka crisis footprints

In 2023, no significant increase in the distribution of marine litter (ML) was observed in the study sites (1) Durankulak - North, (2) Durankulak - South, (3) Durankulak - Kosmos, (4) Durankulak Lake, (5) Krapets - North, (6) Shabla - North and (7) Shabla - South (Figure 4). In the monitoring campaigns after the Kakhovka dam crisis, no beach litter originating from Ukraine was found to be transported and deposited along the Bulgarian coast.

4.5 Achieving clean beaches

The ongoing issue of pollution remains deeply concerning, with the ambitious target of 20 litter items per 100 meters seeming unattainable in the near future for Bulgarian beaches. In the long term, benchmark beaches for cleanliness such as (18) Emine – South (68 items/100 m), (19) Emine – North (104 items/100 m), (31) Ropotamo (80 items/100 m), and (43) Lipite (114 items/100 m) appear closest to achieving an element of GES with proper beach management in 2023.

Criterion D10C1 from D10 Commission Decision (EU) 2017/848 of 17 May 2017 is imperative to ensure that the composition, quantity, and spatial arrangement of litter along the coastline, within the surface layer of the water column, and on the seabed remain within acceptable limits that safeguard the integrity of coastal and marine ecosystems Commission Decision (EU) 2017/848 (2017). To achieve this, Member States are tasked with collaboratively setting threshold values at the Union level. These values must be carefully tailored to accommodate regional or subregional variations, thereby addressing the unique environmental characteristics of different areas. Doing so aims to mitigate the adverse impacts of marine litter and uphold the health of our coastal and marine environments for generations to come. The D10C1 ensures that ML amount, composition, and distribution across beaches, water surfaces, and seabed are environmentally safe. It utilizes data primarily focused on litter abundance (Werner et al., 2020). The precautionary principle guides the selection of the 15th percentile level from the 2015/2016 baseline as the threshold values (TV) for EU coastlines. This TV, set at 20 litter items per 100 meters of coastline, was established in 2020 (Hanke et al., 2019; Van Loon et al., 2020; C/2024/2078, 2024). However, achieving this ambitious target may require multiple implementation cycles. Intermediate measurable targets are under development by TG ML and RSCs, considering regional variations and transboundary impacts (Macias et al., 2019, 2022). During the 2018 MSFD reporting, only 10 out of 22 Member States reported some quantitative TVs for D10C1, mostly at regional or national levels (Ruiz-Orejón et al., 2021).

Only four beaches currently have prospects of achieving the goal of less than 20 items/100 m. We must discuss: Are Bulgarian Black Sea beaches effectively managed and maintained for cleanliness? The Black Sea Coast Spatial Development Act of the Republic of Bulgaria assigns responsibility for cleanliness to concessionaires utilizing the beaches (BSCSDA, 2008). The Regulation on the Categorization of Beaches (RCB, 2005) only introduced requirements for maintaining concession beaches. While maintained beaches around significant tourist centers are cleaned before, during, and after the summer season, in remote and semi-urban beaches is lower control and, in some places, the absence of maintenance, particularly on natural beaches such as those between Durankulak - Krapets, Kamchiya-Shkorpilovtsi, or Vromos.

The results indicate that conditions and the influx of ML along the northern and central beaches are manageable by local authorities and NGOs to keep the beaches clean/very clean with low to moderate plastic abundance. In contrast, more significant efforts are needed to limit pollution along the southern coast. The lack of cleaning activities outside the summer tourist season, irregular volunteer campaigns, high-energy storm events during the winter and spring seasons, and the concentration of floating marine litter facilitate the accumulation of beach litter during these periods. This dependency is evident in the density of beach waste, with 24 out of 26 beaches along the southern coast showing higher ML densities in spring compared to autumn (Table 2).

Furthermore, the difference between clean beaches within concession activities with tourist influx (remote/natural or semi-urban) and *dirty/extremely dirty* beaches, concentrated in the urban beaches, demonstrate the disparity between them and highlight the need to intensify cleaning activities around urban and semi-urban areas. While costly, campaigns for cleaning after every storm are deemed necessary to reduce waste relocation and decrease pollution, especially considering that beach litter accounts for over 90% of the anthropogenic litter found in adjacent wetland areas and dune systems along the Bulgarian Black Sea Coast (Prodanov and Bekova, 2023).

5 Conclusion

This study represents a spatiotemporal analysis of macro ML along Bulgarian beaches for 2023, aligned with the MSFD guidelines (Galgani et al., 2023). The beach framework is evenly distributed along the coastline, aiming to cover a more significant number of beaches - 45, including 20 remote/natural, 18 semi-urban, and 7 urban beaches.

Over the past two years, there has been an improvement in marine macro litter pollution along Bulgarian beaches. Following the high pollution values reported by Bekova and Prodanov (2023) in 2020 and 2021 due to travel restrictions abroad during the COVID-19 epidemic, the situation has stabilized, with a gradual decrease in litter amount. Litter distribution registered has significantly improved, decreasing by 48% from an abundance of 1462 ± 147 items/100 m in 2021 (Bekova and Prodanov, 2023) to 753 ± 97 items/100 m in 2023. The improvement in beach pollution resulted in a decrease in the overall CCI category from 14.61 "dirty" in 2021 (Bekova and Prodanov, 2023) to 7.61 ± 1.00 "*moderate*" in 2023. In a long-term six-year monitoring period, the "*moderate*" categorization of pollution on Bulgarian beaches is maintained - $CCI_{AV,18-23}$: 8.81.

Artificial polymer materials/Plastic litter distribution remains within *moderate* ranges – $PAI_{AV,23}$: 2.35 ± 0.32, with the "*very high abundance*" of plastics found at Kavatsite - $PAI_{AV,23}$: 8.24. In the long term, there has been an overall reduction in plastic macro litter - $PAI_{AV,18-23}$: 2.57 ± 0.27. However, it remains a severe problem for the southern coastline, especially concerning *public recreational-related sources* of ML: *cigarette butts and filters, plastic caps/lids, drinks, and cups/cup lids*.

Remote and natural beaches along the central and northern coastlines are noted for their low pollution levels, with cleanliness ratings ranging from "*clean*" to "*very clean*" ($0.87 \le CCI_{AV,18-23} \le 12.95$). The minimal pollution is due to their remote locations, fewer tourist visits, and distance from commercial activities. Although there is still some presence of plastic waste, it remains within acceptable limits ($PAI_{AV,23}$: 1.26, *moderate abundance*").

Semi-urban beaches such as Primorsko and Veleka attract more tourists and consequently suffer from significantly higher levels of ML, particularly plastic ($PAI_{AV,23}$: 2.53 "*moderate abundance*"). Despite improvements, these areas require ongoing maintenance to prevent worsening pollution ($CCI_{AV,23}$: 8.26 "*moderate*").

Urban beaches experience the highest litter accumulation due to significant tourist impact and recreation activity ($CCI_{AV,23}$: 17.34 "*dirty*"; $PAI_{AV,23}$: 4.87 "*high abundance*"). Despite clean-up efforts, persistent anthropogenic pressure and inadequate off-season maintenance pose challenges. Predicted future scenarios for these beaches include increasing plastic pollution driven by higher tourist numbers and inadequate waste management, as well as potential exacerbation from climate change impacts such as sea level rise and extreme weather, which could increase ML amount and complicate clean-up campaigning.

In General, the pollution of ML shows improvement, but it remains fragile. To continue the pursuit of achieving a good ecological status with threshold values under 20 items/100 m (Van Loon et al., 2020; C/2024/2078, 2024), significant improvements in cleanliness policy at the state level are necessary for the maintenance of the depositional coast. Simple and easily implementable actions include significantly increasing tourist waste collection facilities and focusing on urban and semi-urban beaches (out of concession), which, unfortunately, have been neglected by the local authority thus far. Increasing the activity of local authorities, supported by NGOs, for systematic actions, prioritizing those following winter and spring storm events that accumulate a larger number of macro ML items on beaches, is essential. Beaches, dunes, and wetlands should be considered interconnected vessels regarding waste distribution, and cleanliness measures in the coastal zone should apply fully to the sensitive coastal ecosystem.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

RB: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. BP: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2024.1416134/full#supplementary-material

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