Marine Pollution Bulletin 185 (2022) 114250

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

COVID-19-related litter pollution on Greek beaches and nearshore shallow water environments

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ARTICLE INFO

Keywords:
COVID-19
Personal protective equipment (PPE)
Plastic pollution
Beach
Benthic litter
Greece

ABSTRACT

COVID-19 pandemic has led to an increase in certain types of litter, many of which are expected to end up in the marine environment. The present study aimed to monitor the pandemic-related litter pollution along the Greek coastal environment. Overall, 59 beach and 83 underwater clean-ups were conducted. Litter was categorized as: PPE (face masks and gloves), COVID-19-related, single-use plastic (SUP) and takeaway items. PPE, dominated by face masks (86.21 %), accounted for 0.29 % of all litter. The average PPE density was 3.1×10^{-3} items m^{-2} and 2.59 items/ 100 m. COVID-19-related items represented 1.04 % of the total. Wet wipes showed higher densities (0.67 % of all litter) than in the pre-COVID era, while no increase in SUP and takeaway items was observed. Benthic PPE, dominated by gloves (83.95 %), represented 0.26 % of the total. The mean PPE density was 2.5×10^{-3} items m^{-2}.

1. Introduction

Since December 2019, the world has been affected by a new strain of coronavirus, known as Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) (Wang et al., 2020). Due to the severity and the high contagiousness of the disease, the World Health Organization decided to declare the outbreak of SARS-CoV-2 a pandemic on March 11, 2020 (World Health Organization, 2020a). In an attempt to contain the transmission, many nations have implemented several precautionary measures, such as lockdowns or movement restrictions at different stringencies, social distancing, and closure of non-essential businesses (Bansal and Sharma, 2021). Subsequently, many changes occurred in the use and purchase of materials, such as personal protective equipment (PPE) and single-use plastics (SUP).

The use of PPE, such as disposable gloves, surgical masks, N95 facepiece respirators, etc., can reduce the risk of infection from contagious diseases and has significantly improved public health. At first, PPE was explicitly recommended for healthcare workers (World Health Organization, 2020b). However, as COVID-19 continued to spread rapidly, the general population started to use PPE as a protective gear against the infection. The production of disposable face masks in China, a country among the ones with the highest production rates worldwide, increased to 116 million per day in February of 2020 (Adyel, 2020). Prata et al. (2020) estimated that the pandemic will lead to a monthly global consumption and disposal of 129 billion face masks and 65 billion gloves. In early 2020, >240 tons of medical residues from hospitals in Wuhan were

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https://doi.org/10.1016/j.marpolbul.2022.114250
Received 1 September 2022; Received in revised form 7 October 2022; Accepted 9 October 2022
Available online 14 October 2022

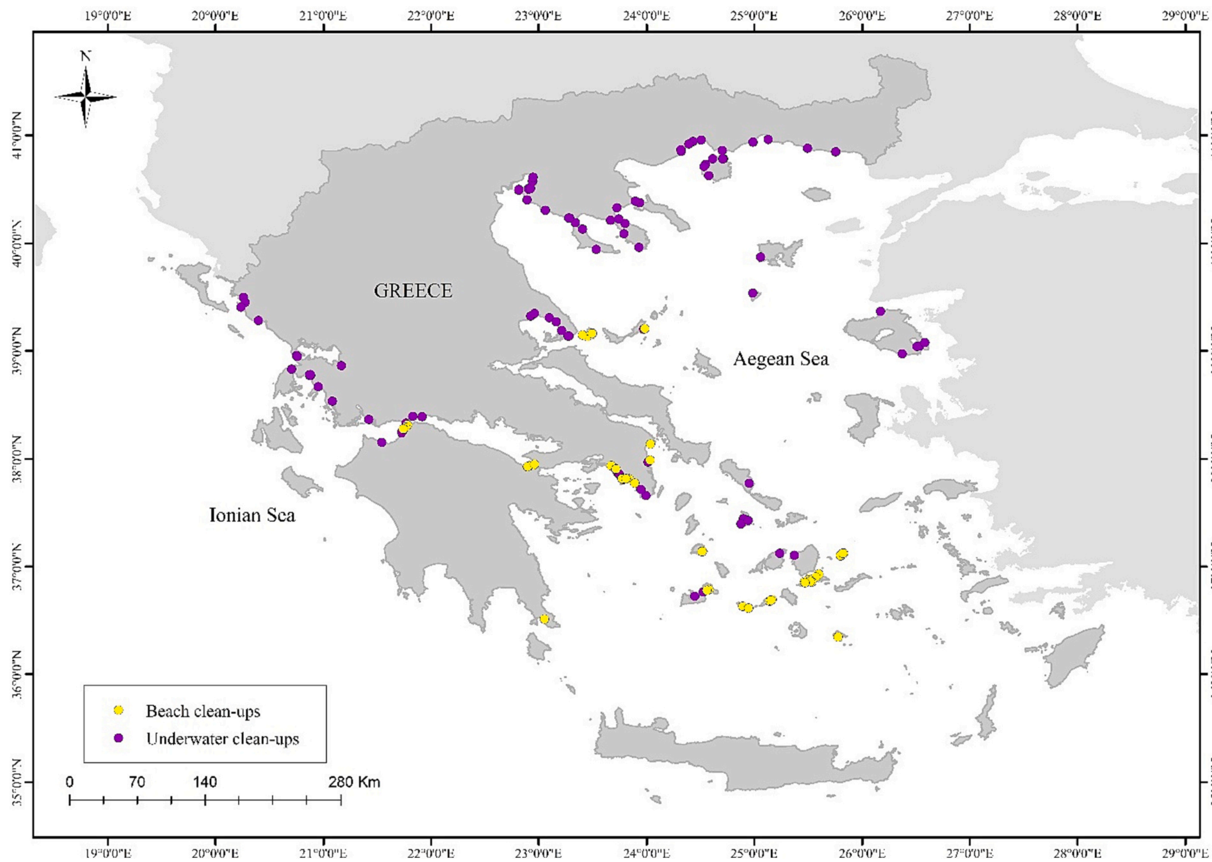

Fig. 1. Map of sampling sites on Greek beaches (yellow) and underwater locations (purple). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reported daily, i.e., six times the usual amount (Adyel, 2020). Most PPE is primarily made of plastic materials (Kutralam-Muniasamy et al., 2022). The exponential increase in the production and use of these types of plastics, in combination with poor management or improper disposal, will potentially promote an explosion of plastic pollution, with many negative consequences for terrestrial and aquatic environments (De-la-Torre and Aragaw, 2021).

Since the beginning of the pandemic, several experts have suggested the use of SUP and packaging to control the transmission of SARS-CoV-2. The temporary closure of restaurants and shops may have limited the spread of the virus, but it has changed people's habits leading to an increase in takeaway and delivery services, and subsequently in SUP. A lot of people have turned to packaged food, takeaway coffee and disposable utensils. Also, the growth of e-commerce leads to the use of more packaging materials (Bansal and Sharma, 2021). A survey in South Korea showed an increase in online food purchases and other daily necessities by 92.5 % and 44.5 %, respectively (Hyun, 2020). According to Greek eCommerce Association (GRECA), the growth rate of e-commerce in Greece increased up to 107 % in May 2020, four times more than at the beginning of 2020 (GRECA, 2020). The global plastic packaging market is expected to grow by $ 63.73 billion, with an annual increase of 5.89 % over 2021–2025 (Technavio, 2021).

Mass testing is one of the most significant aspects of controlling the spread of SARS-CoV-2, according to the World Health Organization (World Health Organization, 2020c). The standard diagnostic techniques are (1) detection of viral RNA by molecular methods, typically a reverse transcription-polymerase chain reaction (RT-PCR), and (2) antigen rapid diagnostic tests (Ag-RDT) via lateral flow assays (LFIAs). A lot of plastic waste is generated from the RT-PCR tests. According to reports by Celis et al. (2021), approximately 15,439 tons of plastic waste for diagnostics had been produced by August 2020. Such plastic wastes include nasopharyngeal swabs, falcon tubes, tips, single-use Pasteur pipettes, bottles for buffer solutions, 96-well PCR plates, Eppendorf tubes, etc. It is estimated that RT-PCR generates 37 g of plastic residues per sample (Celis et al., 2021). COVID-19 test kits could also create a huge plastic waste problem. The highly transmissible new variants of the virus and the mandatory weekly testing for unvaccinated people in Greece have increased the demand in rapid test kits, as they are more affordable and the turnaround time for results is usually very fast.

It is well known that plastic pollution can directly impact wildlife. There are documented records of either entanglement in and/or ingestion of plastics for >200 species, including marine mammals, sea turtles, and birds (Kühn et al., 2015). Neto et al. (2021) recently discovered a dead Magellanic penguin (*Spheniscus magellanicus*) who had ingested an FFP-2 face mask. In addition, various deleterious effects are generated from the breakdown of PPE into microplastic particles and fibers and the release of hazardous chemicals from PPE exposure to UV radiation (Silva et al., 2021). In the study of Kutralam-Muniasamy et al. (2022), some of the effects of ingestion of microfibers by marine organisms are mentioned. Furthermore, De-la-Torre et al. (2021) reported red algae colonization of two face masks, therefore PPE can act as an artificial substrate for algae and marine invertebrates. The association of marine organisms with benthic litter items has been previously described by Ioakeimidis et al. (2015). Moreover, depending on the buoyancy, PPE can become vectors of non-native and invasive species (García-Gómez et al., 2021), thereby modifying the composition of the bio community (Werner et al., 2016). Finally, the disposal of PPE in the environment also raises health risks. As coronaviruses remain contagious for several days on surfaces, there are concerns about the transmission of SARS-CoV-2 through contact with discarded PPE (Urban and Nakada, 2021).

Many estimates have been made about the amount of PPE used on average in several countries (Chowdhury et al., 2021; Haque et al., 2021; Prata et al., 2020; Torres and De-la-Torre, 2021). Recently, the first data that have emerged from in situ monitoring activities are being published. These studies have examined various environments providing an overview of the PPE pollution caused by the ongoing COVID-19 pandemic, including cities and urban environments (Ammendolia et al., 2021; Fadare and Okoffo, 2020; Okuku et al., 2021; Prata et al., 2020), water bodies, such as rivers (Aragaw, 2020; Cordova et al., 2021) and lakes (Aragaw et al., 2022), as well as coastal environments (Akhbarizadeh et al., 2021; Ardusso et al., 2021; De-la-Torre et al., 2021; Okuku et al., 2021; Rakib et al., 2021; Thiel et al., 2021). Ever since the first COVID-19-related litter was detected on the coast, there has been significant interest in determining the extent and rate this waste accumulates in the coastal environment. There is currently no internationally accepted protocol for PPE waste research. As a result, sampling methods differ between surveys depending on the environment (marine or urban) and the survey's objectives (Kutralam-Muniasamy et al., 2022). In general, comparisons between surveys are based on density values of PPE (items/m^2, items/100 m) to reduce the influence of various methodological factors, such as the area sampled, weather conditions, the number of samplings, etc. It is also necessary to identify COVID-19-related plastic litter other than PPE (e.g., wet wipes).

Information concerning PPE pollution in the Mediterranean Sea is largely lacking. The objective of the present study is to report the abundance, composition, spatial distribution, and density of PPE and COVID-19-related litter in general, on the beaches and seafloor of Greece, based on a critical amount of data collected through volunteer campaigns on 55 beaches and 83 underwater locations. Four of the beaches were visited twice, consequently a total of 59 beach samplings were conducted. To the best of our knowledge, this is the first PPE monitoring carried out in Greece and we present the first data regarding underwater cleanups, thus providing valuable information concerning the extent of pollution caused by the ongoing pandemic. In March 2020, the Greek authorities announced restrictions on all nonessential movements throughout the country, and face masks became mandatory in all public spaces. However, movement outside the house was permitted for exercising or taking one's pet out, so many people gathered on beaches and other coastal public spaces. In addition, the use of SUP increased during the curfew due to the turn to takeaway and delivery services. These events may have led to increased plastic pollution in Greek coastal environments.

2. Materials and methods

2.1. Study area and sampling strategy

Greece is located in Southeastern Europe and is the country with the longest coastline in the Mediterranean Basin and the 11th longest coastline in the world. From June 2021 to March 2022, between the 3rd and 4th coronavirus pandemic wave, 59 beach samplings were conducted along the Greek coastline (Fig.1). The geographic distribution of the sampling points covered a wide range of coastal environments spanning island coasts (in the Aegean and Ionian Seas), open gulfs (i.e., the Saronikos and Thermaikos Gulfs), and semi-enclosed gulfs (i.e., the Gulf of Corinth). The total surveyed area was approximately 316,000 m^2 and the total length was 11,814 m. Depending on the total length of the beach, some beaches were cleaned entirely, while on very long beaches, a specific part (≥100 m transect) of the beach was cleaned. In most of the locations the area surveyed was estimated in the field, but in five beaches, Google Earth Pro, 2022 was used for this purpose. In addition, the following information regarding the beaches was recorded: beach activity (recreational or non-recreational) and the presence of regular bins or infrastructure for proper disposal of COVID-19-related litter (informative signposts or specific bins). In total, twelve non-governmental organizations, foundations, and universities of about 300 volunteers participated in the data collection. The observers covered the whole area from the strandline to the back of the beach by moving along 5 m separated transects parallel to the coastline. While moving along the transect, volunteers removed, sorted, classified and counted all marine litter items >2.5 cm. The classification of litter items by type was carried out according to a modified list from the protocol for the monitoring of marine debris of the European Commission (Galgani et al., 2013), appropriately amended to include PPE. In order to roughly estimate the temporal trend of PPE litter accumulation, four beaches in the city of Corinth were visited twice. The first clean-up campaign on these four beaches took place in December 2021 and the second in March 2022.

Table 1
PPE densities (items/m^2, items/100 m).

Beach clean-ups	
Beaches	55
Beach samplings	59
Area (m^2)	315,928
Total litter items	69,219

	Mean	Range
PPE Density (items m^{-2})	3.1×10^{-3}	$0.00–7.50 \times 10^{-2}$
PPE Density (items/100 m)	2.59	0.00–18.8

Furthermore, 83 underwater cleaning surveys were conducted with SCUBA in 2020, 49 in 2020 and 34 in 2021, in selected coastal locations, mainly ports (Fig. 1). The locations were selected based on litter load (e.g., fishing points) and accessibility for the divers. The maximum depth of the dives was 10 m and the trained divers moved in two line transects for each site. The divers swam along the transect line, recorded and collected (in sacks) litter items above ~2.5 cm, depending on water column visibility, and categorized them based on the proposed list of macro litter items by the Marine Strategy Framework Directive (Galgani et al., 2013). The total seafloor area surveyed was 408,000 m^2. The following litter items were recorded: face masks, gloves, and wet wipes.

2.2. Data processing

For the purposes of this study, pandemic-related litter was categorized into four sub-groups. In particular:

1) PPE litter, represented by single-use and reusable face masks and gloves.
2) COVID-19-related litter, including PPE. This category includes items that protect against the virus or help diagnosis, namely disinfectants and sanitizer packaging, materials related to sanitary waste (e.g., nasopharyngeal swabs), disinfectant wipes (wet wipes), and unspecified COVID-19-related litter. Wet wipes are included in this category because their densities are thought to be increased due to the pandemic, but they had been a common litter in coastal environments well before COVID-19.
3) SUP takeaway, according to the categorization followed by Vlachogianni et al. (2018) (straws and stirrers, bottle caps and rings, plastic bags and bag pieces, disposable cups and their lids, food packaging, water/soft drink bottles) to determine if and in what extent the pandemic increased SUP litter.
4) Takeaway items (SUP and additional non-plastic takeaway items, such as paper straws, paper food/beverage packaging, aluminum soft drink/beer cans, and metal bottle caps, lids & pull tabs).

The databases of the LIFE DEBAG (2019) and MELTEMI (2020) EU projects were used as baseline information, to compare the percentages of SUP and takeaway litter items before and during the pandemic and to determine any temporal trend. The density of PPE items on each beach (items per m^2) and the density per 100 m of beach length were calculated. Results were eventually expressed using the average PPE density

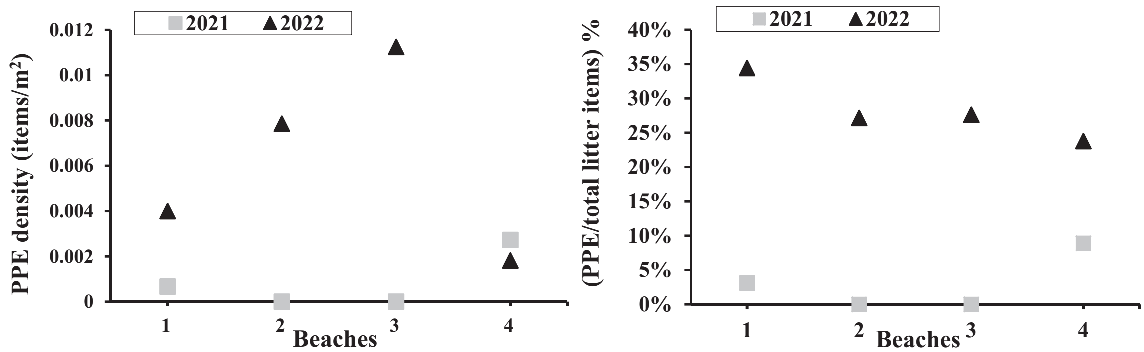

Fig. 2. Temporal variation of PPE density (left) and PPE percentages over the total litter items (right) in the four monitoring beaches.

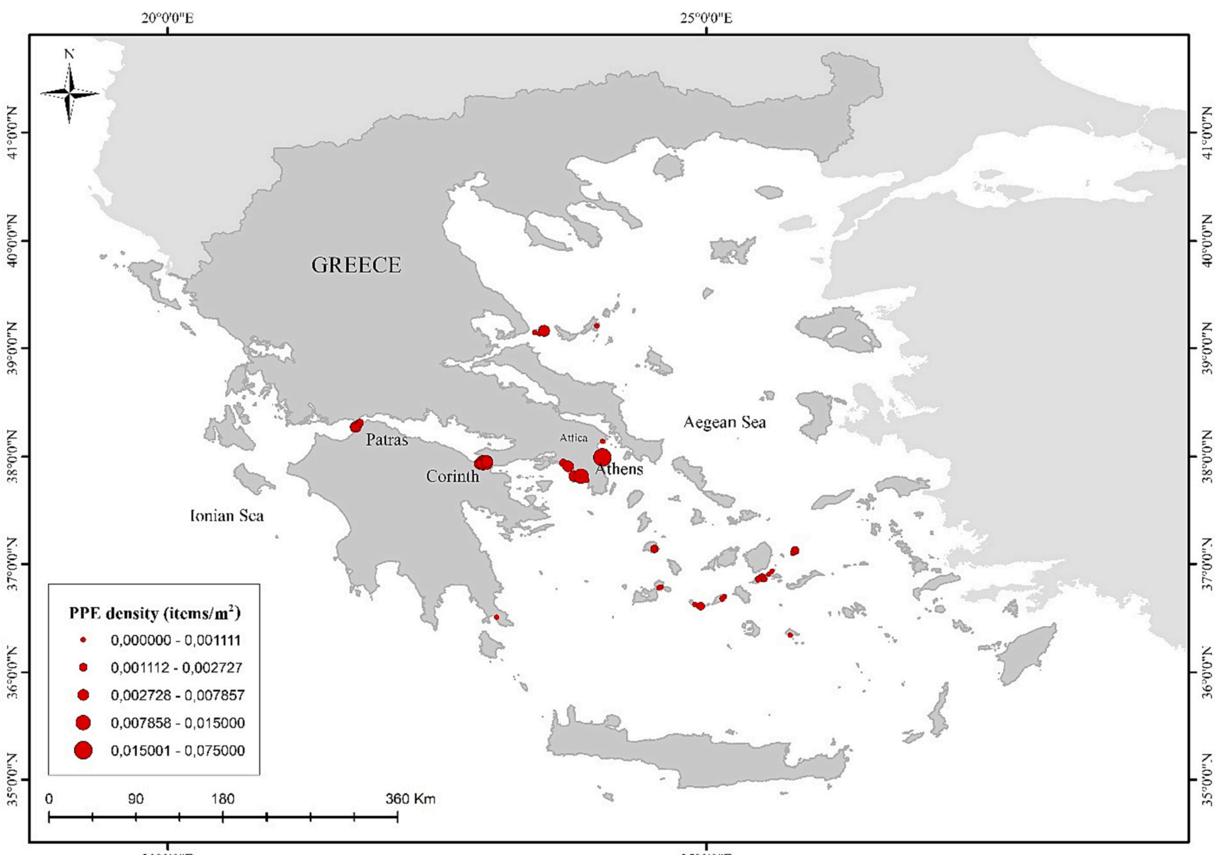

Fig. 3. Map of spatial distribution of PPE densities on Greek beaches.

(items m^{-2}).

3. Results

3.1. Beach clean-ups

A total of 69,219 litter items were collected on Greek beaches (Table 1). PPE were observed on 37 out of the 59 surveyed locations (63 %). The PPE items found were disposable or reusable face masks and gloves. A total of 203 PPE items were found, representing 0.29 % of all litter items. Face masks were the most abundant type of PPE (86.21 %) on the beaches. The mean PPE density was 3.1 × 10^{-3} items m^{-2} (ranging between 0 and 7.5 × 10^{-2} items m^{-2}), and the mean PPE density per 100 m of beach was 2.59 items/100 m (ranging between 0 and 18.8 items/100 m). In addition, 721 COVID-19-related items were counted, accounting for 1.04 % of the total. COVID-19-related litter was dominated by wet wipes (64.4 %), followed by face masks (24.3 %). SUP accounted for 17.2 % of the total and were dominated by bottle caps and rings (32.1 %), followed by straws and stirrers (27.9 %). Finally, take-away items accounted for 19.3 % of the total (Table 3).

Regarding the temporal variations of PPE litter, three of the four monitored beaches showed an increase of PPE densities in spring 2022 compared to winter 2021 (Fig. 2). Similarly, the PPE/total litter items percentage was higher in 2022 compared to 2021 in all four beaches (Fig. 2).

Concerning the spatial distribution of PPE litter, highest densities were observed in urban beaches near metropolitan centers of Attica (Athens), the city of Patras and the city of Corinth (Fig. 3).

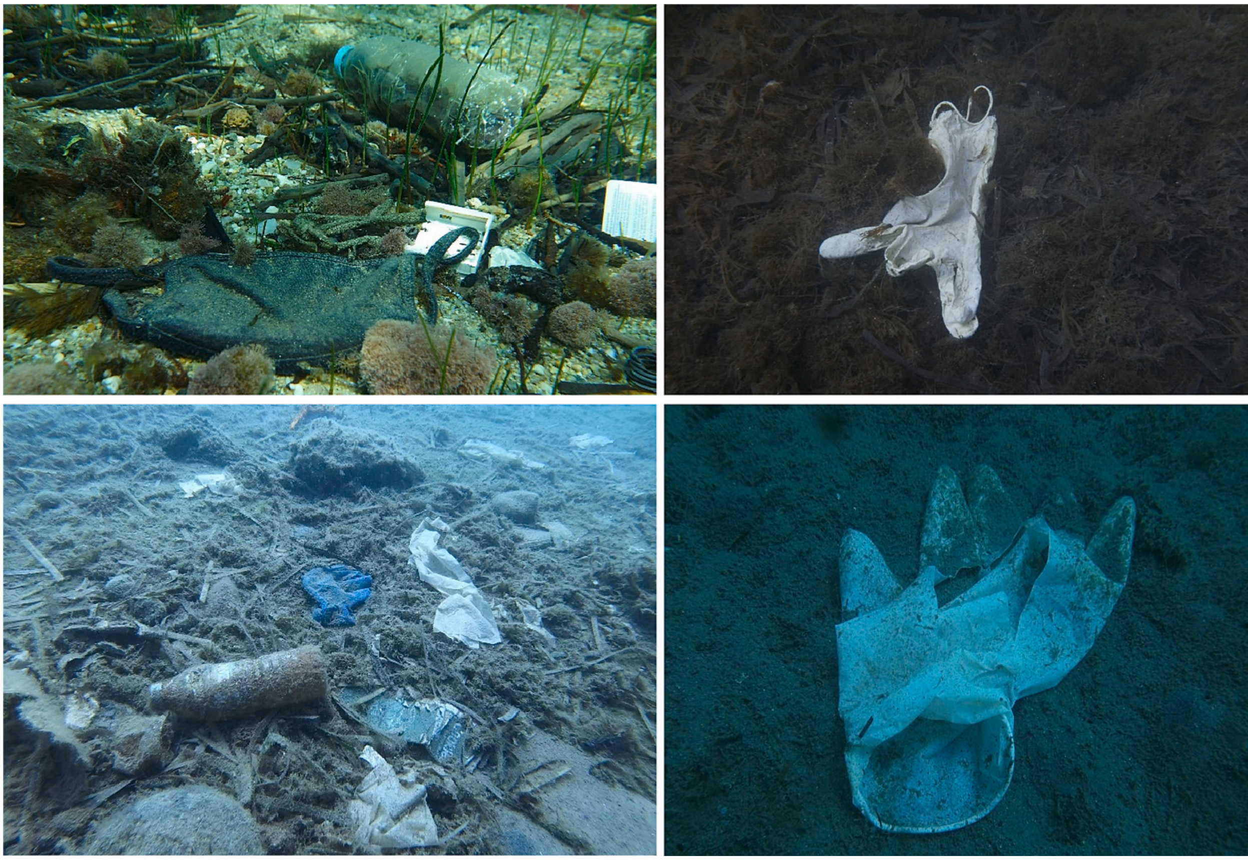

Fig. 4. Examples of PPE found in underwater clean-ups in Northern Greece in 2021 (photos by iSea).

3.2. Underwater clean-ups

Table 4 summarizes the results from the underwater clean-ups. A total of 30,941 litter items were collected during the study and 81 PPE items were recorded (Fig. 4), representing 0.26 % of all litter items. Gloves were the most abundant type of PPE (83.95 %). The mean PPE density was 2.5×10^{-3} items m^{-2} (range of 0.0–1.4×10^{-1} items m^{-2}). In addition to PPE, 30 wet wipes were counted during the cleaning campaigns. The occurrence of PPE seems to increase over time as COVID-19-related litter was found in 33 % of the sites surveyed in 2020, while in 2021, the corresponding percentage has reached 51 %.

The spatial distribution of PPE litter densities in underwater locations is presented in Fig. 5. The higher densities are observed in Northern Greece, and especially in Thermaikos Gulf, Chalkidiki peninsula, and Makri, a village close to the city of Alexandroupoli.

4. Discussion

The data collected for this research allowed for the first time the assessment of the polluting footprint of the pandemic in the coastal marine environment of Greece. PPE, especially face masks, are being used in massive quantities to limit the spread of the coronavirus. The presence of PPE waste (0.29 %) on Greek beaches is attributed exclusively to the pandemic because this type of litter had never been recorded before in coastal environments (Kordella et al., 2013). PPE has been used as an indicator of plastic pollution caused by the COVID-19 pandemic. Table 5 provides a comparison of the mean and the range of PPE densities on beaches across published studies. The mean PPE density reported on Greek beaches (3.1×10^{-3} items m^{-2}) is 274 times higher than the density (1.13×10^{-5} items m^{-2}) reported in Agadir, Morocco (Haddad et al., 2021), 48 times higher than the density (6.42×10^{-5} PPE m^{-2}) registered in Lima, Peru (De-la-Torre et al., 2021), and half the density (6.29×10^{-3} PPE m^{-2}) of Cox's Bazar, Bangladesh (Rakib et al., 2021). Akhbarizadeh et al. (2021) reported that PPE density ranged between 7.71×10^{-3} - 2.70×10^{-2} items m^{-2} along the coastline of Iran. On Kenyan beaches, PPE densities reached up to 5.6×10^{-2} PPE m^{-2} (Okuku et al., 2021). Differences in the methodology of each survey may have influenced the measured values, and therefore the comparison is indicative.

Face masks dominate PPE (86.2 %) in Greece in accordance with other studies (96.81 % in Agadir, 87.7 % in Lima, and 97.9 % in Cox's Bazar). Face masks were the most abundant PPE category even in two rivers in Indonesia and the urban areas of Toronto (Ammendolia et al., 2021; Cordova et al., 2021). The results show that this new type of litter has now entered the coastal and marine environment of Greece, at a percentage of 0.25 %, which may seem low, however, as the systematic use of mask began only two years ago, it is expected to increase in the coming months. Moreover, face masks are important sources of microplastics, in the form of fibers, in coastal environments. Recent studies confirmed that micro- and nanoplastics can be released from different types of face masks due to UV radiation and mechanical abrasion (Saliu et al., 2021). Face masks may also pose a threat for the coastal environment due to their specific design and to the fact that they can act as fomites. The elastic chords of masks may cause entanglement of coastal avifauna (Silva et al., 2021; Mghili et al., 2022) and sea turtles. Face masks could also carry the SARS-CoV-2 virus and consequently could be a pathway for zoonotic transmissions. In this context, the ability of wild birds to be zoonotic spreading conduits of the new coronavirus has been suggested (Rahman et al., 2021).

Disposable gloves show a relatively small percentage (13.80 %) of the total PPE and only 0.04 % of the total litter items (Table 2) on the beaches. The low occurrence of single-use gloves is probably a result of the mandatory use of face masks after the first wave of the pandemic and the decrease in the use of gloves because of the wider use of wet wipes

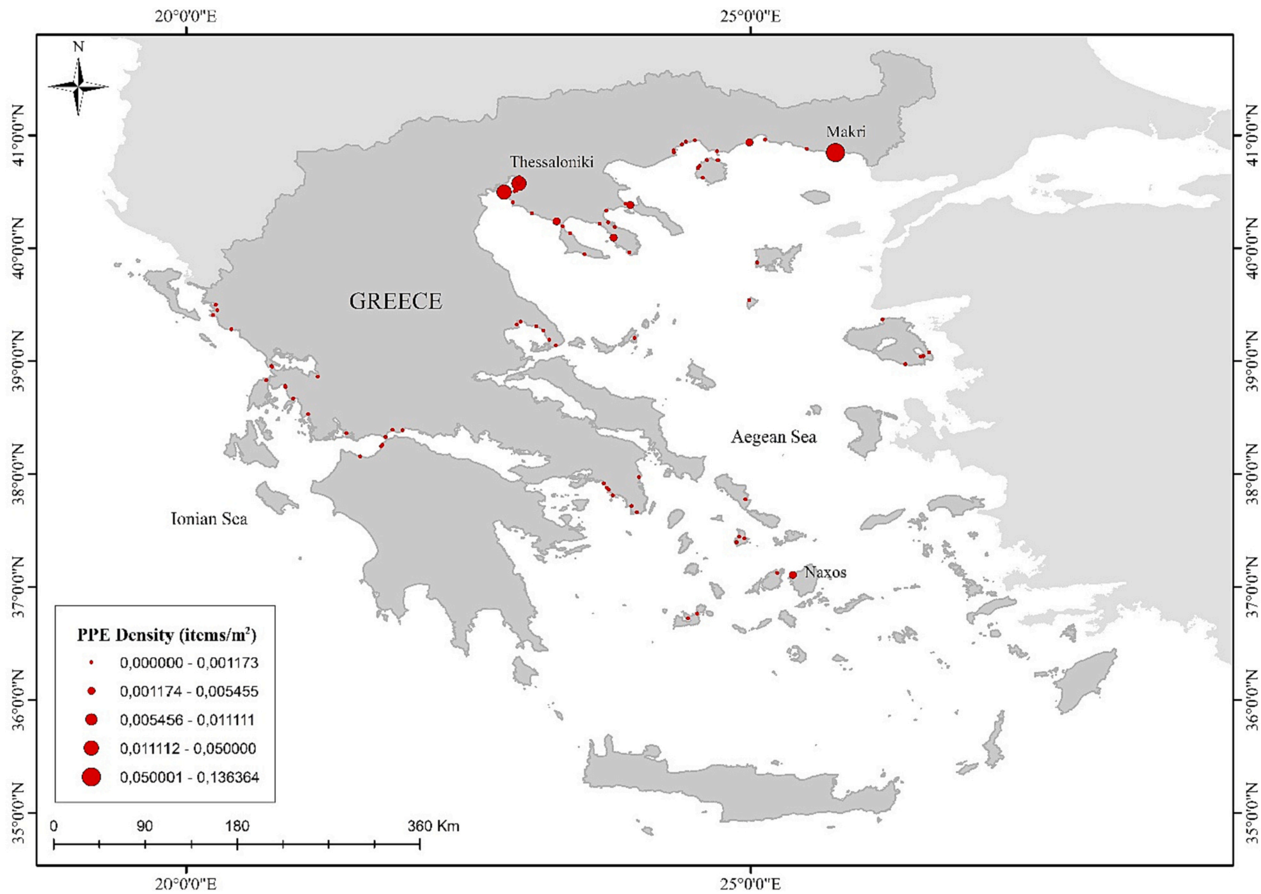

Fig. 5. Map of spatial distribution of PPE densities in underwater locations.

Table 2
COVID-19-related litter percentages from beach clean-ups.

	Items	% PPE	% COVID-19-related	% Total
Face masks	175	86.2 %	24.3 %	0.25 %
Gloves	28	13.8 %	3.88 %	0.04 %
Total PPE	203	–	28.2 %	0.29 %
Other COVID-19-related plastics (e.g., self-test)	26	–	3.61 %	0.04 %
Wet wipes	464	–	64.4 %	0.67 %
Sanitizers packaging	6	–	0.83 %	0.01 %
Unspecified	22	–	3.05 %	0.03 %
Total COVID-19-related litter	721	–	–	1.04 %

Table 3
SUP and Takeaway litter percentages from beach clean-ups.

	Items	% SUP	% Takeaway	% Total
Straws and stirrers	3329	27.9 %	24.9 %	4.81 %
Bottle caps and rings	3828	32.1 %	28.6 %	5.53 %
Plastic bags and bag pieces	1758	14.8 %	13.2 %	2.54 %
Disposable cups and their lids	691	5.80 %	5.17 %	1.00 %
Food packaging (sweets, yogurts, chips etc.)	1571	13.2 %	11.8 %	2.27 %
Water/soft drink bottles	737	6.19 %	5.51 %	1.06 %
Total SUP	11,914	–	89.1 %	17.2 %
Paper straws	27	–	0.20 %	0.04 %
Paper food/beverage packaging	903	–	6.76 %	1.30 %
Aluminum soft drink/beer cans	261	–	1.95 %	0.38 %
Bottle caps, lids & pull tabs	264	–	1.98 %	0.38 %
Total Takeaway	13,369	–	–	19.30 %

for cleaning surfaces and hands. Recent large-scale research (Roberts et al., 2021) found that gloves represented 0.20 % of total landfill solid waste before the pandemic, which increased to 2.4 % in the first months and then decreased back to 0.20 %, indicating the decrease of extensive use of gloves as a means of protection.

In the Greek coastal areas, wet wipes (0.67 %) show more than twice the percentage of face masks and seventeen times the percentage of gloves in the total waste. Wet wipes dominate the COVID-19-related litter at 64.4 %, compared to 24.3 % of face masks and just 3.88 % of gloves. In Canada and Peru wet wipes accounted for 8 % to 46 % of total COVID-19-related litter (Ammendolia et al., 2021; De-la-Torre et al., 2021). In addition, in the research of Okuku et al. (2021), wet wipes were the second most common litter type on the streets and beaches after the face masks. There is also photographic evidence of wet wipes on beaches in Chile (Ardusso et al., 2021). However, many recently published articles focus on PPE as a pandemic-driven pollution and either do not mention wet wipes or discuss them only slightly (Chowdhury et al., 2021; Mghili et al., 2022; Walker, 2021).

In Greece, the importance of personal hygiene and the use of face masks has been emphasized by several advertising campaigns. Since there is not always access to water, people use wet wipes as a tool for

Table 4
COVID-19-related litter densities and percentages from the underwater clean-ups.

Underwater clean-ups		
Dives	84	
Area (m^2)	408,185	
Total litter	30,941	
	Mean	Range
PPE density (items m^{-2})	2.5×10^{-3}	$0.0–1.4 \times 10^{-1}$

	Items	% PPE	% COVID-19-related	% Total
Face masks	13	16 %	11.7 %	0.04 %
Gloves	68	84 %	61.3 %	0.22 %
Total PPE	81	–	73 %	0.26 %
Wet wipes	30	–	27 %	0.10 %
Total COVID-19-related litter	111	–	–	0.36 %

sanitizing counters, doorknobs, and hands. Wet wipes may be used for several reasons besides the protection against viruses (e.g., regular cleaning, nursing homes, baby wipes) and it is not possible to distinguish between the multiple uses, however, their increased densities are largely related to the current pandemic. People who did not use wet wipes before, have started using them now. To meet the global increase in demand, many manufacturers have increased the production of wipes. According to a recent report, Clorox increased its production from 1 million wipes per day in 2020 to 1.5 million in the first quarter of 2021 (Stankiewicz, 2021). The size of the global wipes market is estimated at $ 23.9 billion in 2020 and is expected to expand at a compound annual growth rate (CAGR) of 2.4 % from 2021 to 2028 (Grand View Research, 2021). We suggest that wet wipes' occurrence increased in marine environments, because of COVID-19. In order to strengthen the above statement, we compared the percentages of wet wipes in the present study with data from the European funded projects MELTEMI and LIFE DEBAG available before the outbreak of the pandemic. The sampling and classification method followed in these research projects was the same with the current survey. Before the pandemic, wet wipes made up 0.37 % (MELTEMI) and 0.05 % (LIFE DEBAG) of total litter, while in the current survey the corresponding percentage increased significantly (0.67 %).

Wipes are a common wastewater litter because they are flushed into the toilets. After an overflow in the sewage system caused by heavy rainfall events, wipes can end up in marine environments through surface runoff or river supplies (Asensio-Montesinos et al., 2019, 2020). Another reason for the accumulation of wipes in coastal environments is that many people do not seem to know that most wipes are made of synthetic fibers of polyester, polypropylene and nylon (Shruti et al., 2021) and so they are not biodegradable. As a result, they throw them away in the environment after each use, just like paper tissues. Wet wipes, however, can remain for up to 100 years in the environment, where they are easily degraded into micro- and nanoplastics under the influence of various factors (Munoz et al., 2018). They constitute an important source of white microplastic fibers in the marine environment that can act as vectors for potentially harmful contaminants (Galafassi et al., 2019). The problem of microplastics has been categorized as the second largest scientific problem in the field of environmental sciences (Horton et al., 2017). Also, many citizens chose to visit remote areas during the pandemic, where bins were not established yet.

The data from the present study show that wet wipes are being found in higher densities than PPE, while also showing higher densities than in the pre-COVID era. Based on these findings, we support that these two types of litter, PPE (face masks, gloves) and wet wipes, are reliable indicators of pandemic-driven plastic pollution. This observation is in line

Table 5
Summary of the reports and evidence of PPE pollution in marine environments in different countries.

			PPE density (items m^{-2})			
Country	City	Sampling campaigns	Mean	Range	% PPE	Reference
Greece	Nationwide	59 beach samplings	3.1×10^{-3}	$0.00–7.50 \times 10^{-2}$	86.21 % masks 13.79 % gloves	This study
Morocco	Agadir	11 sampling points: 2 periods (Before and after the lockdown)	1.13×10^{-5}	$0.00–1.21 \times 10^{-4}$	96.81 % masks 2.76 % face shields 0.44 % gloves	(Haddad et al., 2021)
Peru	Lima	11 beaches: 12 samplings in 12 consecutive weeks	6.42×10^{-5}	$0.00–7.44 \times 10^{-4}$	87.7 % masks 6.5 % face shields 4.3 % gloves 1.5 % other	(De-la-Torre et al., 2021)
Peru	Nationwide	36 sampling points	6.60×10^{-4}	$0.00–5.01 \times 10^{-3}$	94.5 % masks 2.9 % face shields 2 % gloves	(De-la-Torre et al., 2022)
Argentina	Nationwide	15 sampling points	7.21×10^{-4}	$0.00–5.60 \times 10^{-3}$	48.8 % masks 48.8 % gloves	(De-la-Torre et al., 2022)
Bangladesh	Cox's Bazar	13 sampling points in 12 consecutive weeks	6.29×10^{-3}	3.16×10^{-4}-2.18×10^{-2}	97.9 % masks 1.3 % gloves 0.79 % bouffant caps	(Rakib et al., 2021)
Kenya	Kwale, Kilifi	25 beaches	–	$0.00–5.6 \times 10^{-2}$	–	(Okuku et al., 2021)
Chile	Nationwide	32 beaches	6.00×10^{-3} [a]	–	–	(Thiel et al., 2021)
Iran	Bushehr	9 sampling points: 4 samplings at each point in 40 days	–	7.71×10^{-3}-2.70×10^{-2}	66 % masks 34 % gloves	(Akhbarizadeh et al., 2021)
Morocco	Tetouan	16 samplings at 5 beaches (3 samplings at each beach)	1.2×10^{-3}	$0.00–3.67 \times 10^{-3}$	100 % masks	(Mghili et al., 2022)
India	Pondicherry, Tamil Nadu	6 sampling stations for 3 months	1.08×10^{-3}	$2.81 \times 10^{-4}–2.80 \times 10^{-3}$	98.39 % masks 1.61 % gloves	(Gunasekaran et al., 2022)
Brazil	Santos Bay	13 sampling points: 2 periods	7.46×10^{-5}	$0.00–3.89 \times 10^{-4}$	90.85 % masks 5.2 % gloves 3.95 % other	(Ribeiro et al., 2022)

[a] Only face masks were counted.

with the research conducted in urban environments in 11 countries, including the United States and Australia, which used these three types of litter as "guides" for the pandemic-driven pollution, as the percentages of face masks, gloves, and wipes in the total litter, before the onset of the pandemic and health measures, were only <0.01 %, 0.2 % and 0.2 %, respectively and increased sharply as the pandemic was spreading (Roberts et al., 2021).

In order to examine whether the SUP and takeaway litter categories are reliable indicators of pandemic driven plastic pollution, the results of the present study were compared with those collected before the pandemic. The comparison showed that there is currently no increase in the percentage of SUP. Before the pandemic, in MELTEMI project it was estimated that SUP accounted for 17.4 % of total litter items, in LIFE DEBAG for 24 % and in Vlachogianni et al. (2018) for 19 %, while after the onset of the pandemic, in the current survey, it was estimated that SUP occupy 17.2 %. Similar results are obtained for takeaway waste: 19.3 % (current survey), 18.5 % (MELTEMI) and 25 % (LIFE DEBAG).

The temporal variations of PPE were beyond the scope of this paper and need further research. Nonetheless, the increase of PPE abundance over time (Fig. 2) in the four beaches studied, likely indicates the accumulation of this type of waste due to continued use as the pandemic progresses.

Although the spatial coverage of the studied beaches is not representative of the variability of Greece's coastal environment, some few general hypotheses can be made. Most of the beaches surveyed (90 %) are used for recreational purposes. In addition, higher PPE densities were found in recreational beaches close to big cities, whereas the higher total litter densities were spotted in non-recreational beaches. Furthermore, in the majority of the beaches there were bins for general waste, but none had specific litterbins for PPE or signposts to inform the visitors for the proper disposal of COVID-19-related litter. High PPE densities on recreational beaches close to big cities suggest that the inappropriate disposal of face masks, single-use gloves, and wet wipes in the urban environment, and especially in public places, along with the absence of measures and management, are the main contributors of pandemic-related waste. Thus, beachgoers, during the period of social distancing and lockdown, are a significant source of litter. On the other hand, face mask litter in the urban fabric can be also washed onto beaches and the coastal environment through surface runoff.

So far, no scientific articles have been published on underwater surveys associated to COVID-19-related litter. Only indirect indications of seafloor pollution from COVID-19 have been published. Thiel et al. (2021) mentioned that some masks in Chilean beaches had been rolled along the seafloor due to their entanglement with thalli of several species of seaweeds. In the present study, the increase in less than one year (2020–2021) of the number of underwater locations polluted by COVID-19-related litter (from 33 % to 51 %), strengthens the hypothesis of the increase of seafloor pollution caused by the pandemic. This finding is in accordance with the increase of PPE litter densities in 2022 compared to 2021.

Most published research on the plastic-associated environmental burden of COVID-19 is theoretical and does not include data from in-situ surveys (Alfonso et al., 2021; Benson et al., 2021; Gorrasi et al., 2021; Torres and De-la-Torre, 2021). Those that include primary data are limited and cover specific and relatively small areas, and as a result the problem is not effectively highlighted.

5. Conclusion

The present study showed that the ongoing COVID-19 pandemic is exacerbating the plastic pollution of Greek coastal marine environments. PPE (face masks, gloves) and wet wipes are reliable indicators of this type of pollution, as their presence in the marine environment increased sharply with the spreading of the pandemic. PPE represented 0.29 % of all litter items and dominated by face masks (86.21 %). In addition, COVID-19-related items accounted for 1.04 % of the total litter items. Wet wipes showed higher densities (0.67 % of all litter) than in the pre-COVID era. No increase in SUP and takeaway items was observed. In underwater clean-ups, 81 PPE items were recorded, representing 0.26 % of all litter item and dominated by gloves (83.95 %).

Our study is expected to fill several gaps, since information concerning PPE pollution in the Mediterranean Sea was lacking. To the best of our knowledge, we also provide, for the first-time, data of pandemic-driven pollution from underwater clean-ups. COVID-19 pandemic is not over yet and unless drastic measures are taken, we can only wait for marine pollution to worsen. In order to gather a sufficient amount of data that will cover a wide spatiotemporal range and will be strong evidence of the effects of pollution on the environment, the cooperation of many different organizations, foundations, institutions and even citizens (citizen scientists) is considered necessary. It is recommended that the indicators listed above be included in the recording protocols so that data can be compared between different countries and response measures can be planned on a global scale.

CRediT authorship contribution statement

Konstantina Kouvara: Data curation, Methodology, Writing – original draft, Writing – review & editing. **George Papatheodorou:** Conceptualization, Supervision, Methodology, Writing – original draft, Writing – review & editing. **Angeliki Kosmopoulou:** Sampling, Writing – review & editing. **Ioannis Giovos:** Sampling, Writing - review & editing. **Anastasia Charitou:** Sampling, Writing – review & editing. **Anastasios Filippides:** Sampling, Writing – review & editing. **Helen Kaberi:** Sampling, Writing – review & editing. **Loukia Kalaitzi:** Sampling. **Filippos Kyrkitsos:** Sampling, Writing - review & editing. **Phoebe Koundouri:** Sampling, Writing - review & editing. **Constantinos Triantafyllou:** Sampling, Writing – review & editing. **Miltos Gletsos:** Sampling, Writing – review & editing. **Elias Fakiris:** Data curation, Methodology, Writing – review & editing. **Maria Geraga:** Data curation, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

Authors would like to thank the members of the Collaboration Network for Marine Environment (https://diktyogiatithalassa.gr/, https://www.aclcf.org/sea/cooperation-network-for-the-marine-environment/), the Athanasios C. Laskaridis Charitable Foundation and the many volunteers who have participated in the clean-ups.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2022.114250.

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