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A new deal between Science and Society through Citizen Science: the case study of sea-surface microplastics research

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In recent decades, environmental and public health crises have prompted discussions regarding the need to balance the right to work and the necessity of living in a healthy environment. A disconnect has arisen between scientific and civic societies due to communication breakdowns and a subsequent erosion of trust in the scientific community. Citizen Science serves to bridge this gap by fostering inclusion and promoting interaction as a democratic force for scientific processes. This article analyzes Citizen Science methodologies focused on monitoring sea-surface microplastics, assessing approaches to engage citizens in alignment with the principles established by the European Citizen Science Association. For this purpose, a literature review was conducted to identify eligible studies, utilizing three research databases with a specific focus on sampling methodologies. Furthermore, it examines sampling techniques and data management practices to ensure the integrity of data, in accordance with the European Union Marine Strategy Framework Directive. The findings indicate that Citizen Science initiatives aimed at monitoring sea-surface microplastics have emerged in academic literature in recent years but continue to be underutilized and/or under-published. The implementation of Citizen Science requires dedicated commitments and tools for straightforward adaptations or the development of new methodologies, with a focus on producing high-quality scientific data. Innovative approaches to Citizen Science can yield reliable data for research purposes and empower civil society to exchange knowledge with the scientific community, thereby promoting marine citizenship.

KEYWORDS

citizen science, data quality, microplastics monitoring, marine strategy framework directive, science democratization, plastic treaty

1 Introduction

After World War II, research increasingly resembled a factory-focused approach known as “Big Science”, until the 1980s, when neoliberalism prioritized market-oriented approaches that stressed measurable productivity, implying that all research should lead to innovation and economic growth (Jaeger et al., 2023). During the 20th century, society faced the environmental crisis (exacerbated by, i.e., rising chemical additives in agriculture, toxic waste, acid rains, residential close petrochemical facilities, and climate change) and global public health issues (i.e., Bovine Spongiform Encephalopathy), generating a debate between the right to work and the right to live in a healthy environment (Irwin, 1995). A disentangling between scientific and public communities arose, due to breakdowns in communication and loss of confidence in scientists (Irwin, 1995; Lippincott, 1971), and to environmental disasters (i.e., Seveso in 1976, Amoco Cadiz tank spill in 1978, Three Mile Island in 1979, Bhopal in 1984, and Chernobyl in 1986). This crisis was recently highlighted by the COVID-19 "infodemia" and lockdowns. New measures introduced by European legislation, as the Green New Deal (2019), ecological transition efforts, and initiatives for risk management and global warming, are perceived as having uncertain impacts on future personal and societal developments. This increasing misinformation stressed the relationship between science and society (Gentili et al., 2023), making scientific information ineffective (Domènech, 2017) and emphasizing the emergent need for transparency, democratization, broad participation, inclusion in decision-making, and a deeper understanding of science (Kurtulmus, 2021). The first-ever so far paper on "The Citizen's Science" (Lippincott, 1971) raises a crucial point: social problems require a science-enlightened citizenry to find informed solutions, starting with the growing importance and relevance of Citizen Science (CS) (Stilgoe, 2009; Hecker et al., 2018; Strasser et al., 2019). In the postmodern era, CS attends as a democratic force, promoting social diversity, inclusion, and interaction while ensuring enduring productivity (Haklay et al., 2023; Jaeger et al., 2023), resulting in participative and integrated strategies for scientific projects (Jaeger et al., 2023). The term "Citizen Science" was first legitimized in social science, addressing emerging societal needs in the 20th century (Irwin, 1995), and it has since become a central topic of discussion (Sprinks et al., 2021; Collins et al., 2022; Atias et al., 2023; Haklay et al., 2023). To date, numerous studies have explored CS across various research areas, and 35 different definitions of CS have been proposed (Haklay et al., 2023). In principle, CS involves collaboration between civil society and scientists at various stages, with both benefiting from new research outcomes and knowledge, promotes behavioral changes, influences policy-making, conveys the scientific process more democratically, enhances scientific literacy and awareness, and fosters both local and global policy changes. For CS to be legitimized, it must fulfill the criteria outlined for the European Community (EC) by the European Citizen Science Association (ECSA) (ECSA, 2015), including adherence to scientific methods, from formulating hypotheses to describing methods, gathering data, and generating new and broader knowledge by involving citizens.

Over the past 20 years, scientific discoveries and increased media coverage have drawn attention to one of the most widely discussed environmental issues: plastic pollution in the oceans, which is now recognized as an urgent threat (Keller and Wyles, 2021). Significant results have been obtained from the use of CS to monitor plastics on beaches, sediments, and debris (Hidalgo-Ruz et al., 2012; Hidalgo-Ruz and Thiel, 2013; Bergmann et al., 2017; Lots et al., 2017; Nelms et al., 2017).

Between the 19th and 20th centuries, plastics were exalted for their lightweight and multipurpose properties, profoundly transforming society and playing a central role in producing daily items (i.e., eating utensils, buttons, eyeglasses), previously inaccessible to the non-wealthy classes (Meikle, 1995; Fenichell, 1996). Plastics democratized a multitude of goods, steering the recently shaped and economically growing middle class by substituting scarce and expensive raw materials (Meikle, 1995). Plastics became synonymous with mass production and disposal cycles, captivating society with their affordability, durability, and safety. During the rigid post-war period, habits such as reusing objects, making do, and austerity became a daily attitude. The concept of "throwaway living" emerged 15 years after World War II, rising from a significant shift in political market decision-making. Consequently, the exponential growth of plastics production triggered an overwhelming presence of discarded plastic debris, littering every corner of the planet (Geyer et al., 2017; Love et al., 2021).

The term "microplastics" was first introduced in 2004, describing some granular fragments and fibrous materials with <20 μm in diameter (Thompson et al., 2004). It is now widely recognized that the term includes particles less than 5 mm (Arthur et al., 2009). Despite over 2 decades of research, many authors still describe the field of MPs research as "relatively young" and "emerging" with the need of future development on methods and impacts (Thompson et al., 2024), characterized by "an exciting and dynamic field" in "infancy", with "scientific immaturity" (Hartmann et al., 2019), "still in its infancy in many aspects" and with "major knowledge gaps" (Waldschläger et al., 2022), "emerging and challenging" and "the tip of a huge iceberg" (Hernández-Sánchez et al., 2021). Several authors underline the lack of standardized definitions, harmonized methodologies, and consistent analytical protocols (Frias and Nash, 2019; Rozman and Kalčíková, 2022; Rede et al., 2023). Cowger et al. (2020) identify MPs research as being at a "turning point", highlighting the need for a harmonized and transparent methodological framework. Actually, efforts aim to standardize methodologies, promote reproducibility, but since no single "right method" is at present practical, and will not be reachable soon (Rochman et al., 2017), the challenge of MPs research lies in future efforts to find widely shared, standardized protocols—ranging from experimental design and sampling methods to laboratory analytical definitions—to achieve a broad consensus. This includes terminology, classification, sampling matrices, and monitoring methods (Cowger et al., 2020). Several factors affect reliable data collection: the type and size of sampling devices, net mesh sizes, towing speeds, the volume of water filtered, and the use of flowmeters to determine actual filtered volume and sampling times (Frias and Nash, 2019; Hartmann et al., 2019; Lusher and Primpke, 2023). MPs monitoring has so far used various methods and protocols, making it hard to compare studies (Hidalgo-Ruz et al., 2012; Lusher et al., 2015; Syberg et al., 2015; Rochman et al., 2017). With the consistent intensification of studies, the lack of a wide consensus - from definitions, to categorization, and monitoring methods - leads to incomparable data (Frias and Nash, 2019; Hartmann et al., 2019; Lusher and Primpke, 2023), causing unclear communication among researchers worldwide, as well as between research and international and national governmental bodies. Accurately estimating the size, polymeric composition, categorization, prevalence, and distribution of MPs in the global ocean is fundamental for understanding their impact on marine ecosystems (Lindeque et al., 2020). Therefore, the important steps

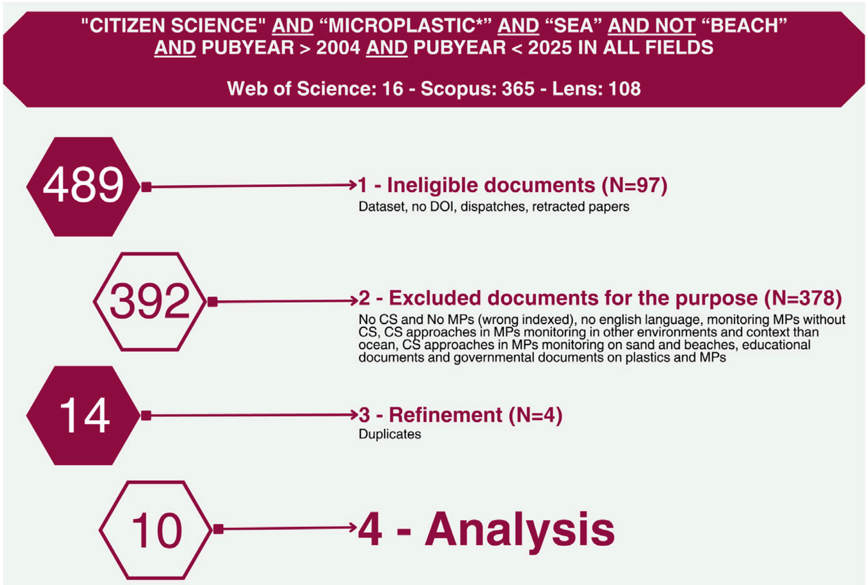


FIGURE 1
The flow diagram for the conducted review, based on the chosen criteria, and the number of documents analyzed at each cascading stage.

actually are to ensure accuracy and practicality when customizing sampling protocols, maintain technical and scientific rigor on one hand, and ensure the accessibility and usability of methods and data on the other, including also CS applications, and social and behavioral research (Rochman et al., 2017).

The EU Marine Strategy Framework Directive (MSFD) (European Commission, 2008) was among the first efforts to establish a standardized approach for MPs data, setting criteria for EU Member States to achieve Good Environmental Status (GES). Descriptor 10 specifically addresses plastic debris and MPs, highlighting potential threats to the marine environment. It offers sampling guidelines for data collection across Europe (GESAMP, 2019).

In this context, we reviewed the current state of integrating CS applications for monitoring MPs in surface marine waters. The goal was to evaluate: 1) how many CS approaches have been used in MPs surface marine waters, 2) whether these CS approaches follow ECSA's 10 principles, and 3) whether these approaches follow MSFD monitoring guidelines.

2 Materials and methods

A literature review was conducted using three research engines: Web of Science and Scopus, two traditional scientific platforms, and Lens, an open-access and freely available engine. The review was performed on January 9, 2025, across all three engines. The search employed the following: the two key terms of the research, "Citizen Science" and "microplastic*", connected by the logical operator AND. The asterisk included both singular and plural forms of the term. Additionally, the operator AND was appended with "sea" to ensure that the search results were specific to marine environments. The operator NOT was used to exclude any documents focused on CS and MPs found on beaches or within terrestrial sandy areas. The temporal range for the search was set from 2004, the year in which the term "microplastics" was first introduced (Thompson et al., 2004), up to 2025. The research was conducted by selecting "IN ALL FIELDS" as the query parameter. The resultant queries yielded 16 outcomes for Web of Science, 365 for Scopus, and 108 for Lens. For the purposes of this review, subsequent to the initial query, the following criteria were employed to identify eligible articles (Figure 1):

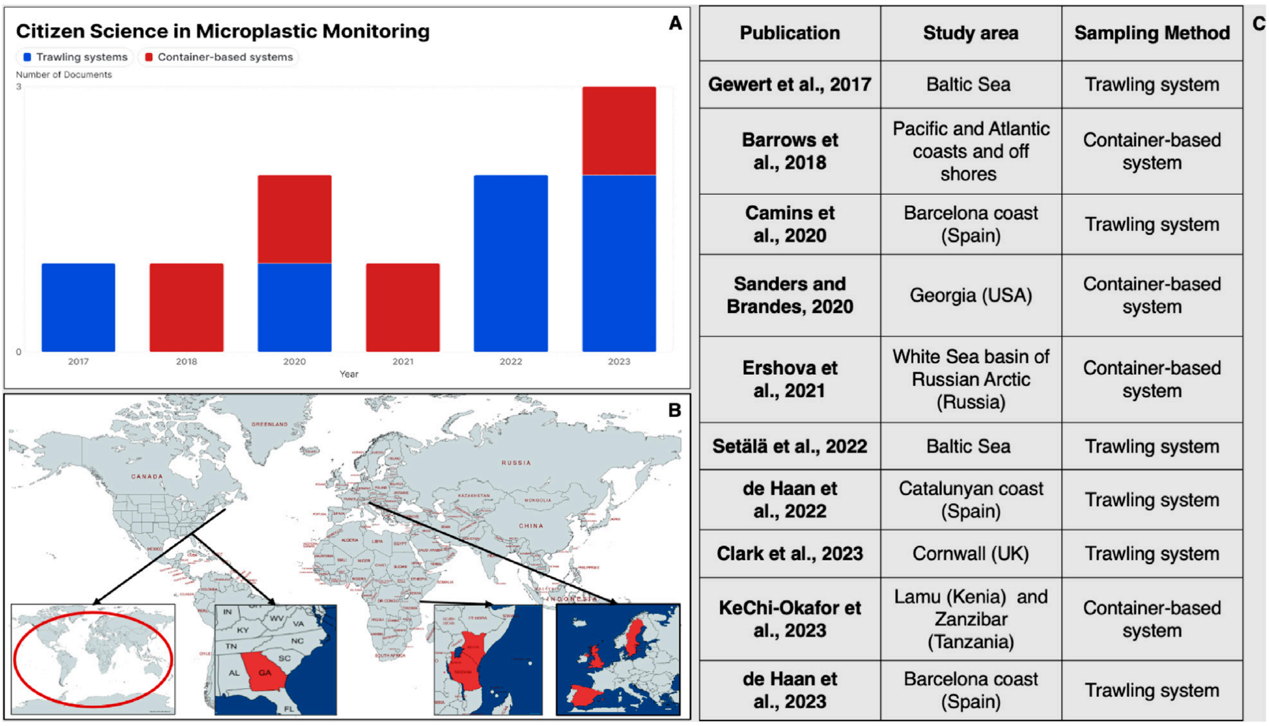
- exclusion of ineligible documents, such as datasets, documents without a DOI or not indexed in selected scientific database scientific engines, and those that are retracted articles;
- exclusion of documents incorrectly indexed by the selected databases, such as those without contributions to CS or MPs, and those pertaining to CS studies conducted in other contexts such as archeology and historical contexts, agriculture and rural areas, urban environments, riverine environments, soil matrix, laboratory chemical analysis, waste management, food, bottled, and tap water analysis, bird nesting, and as well as those documented related to CS and macroplastics research, and MPs conducted on sand, sediments, and beaches;
- duplicates were thoroughly checked, and review articles were excluded.

In the final refinement stage, the eligible documents were reviewed to ensure that all monitoring activities were described, including sampling methods, specifications for the devices used, accessibility of the activities, which documents assure CS activities during the sampling period, and how the data and results were treated.

Significant focus has been directed toward the CS implementation of methodologies and protocols and whether it ensures adherence to ECSA's 10 Principles (ECSA, 2015) (Table 1).

TABLE 1 List of the 10 principles reported by the European Citizen Science Association as a best practice guideline on what constitutes good Citizen Science. These guidelines were presented at the European Citizen Science Association General Assembly 2015 in Barcelona.

Number of ECSA's principle	European Citizen Science Association's principles
1	Citizen Science projects actively involve citizens in scientific endeavour that generates new knowledge or understanding Citizens may act as contributors, collaborators, or as project leader and have a meaningful role in the project
2	Citizen Science projects have a genuine science outcome
3	Both the professional scientists and the Citizen Scientists benefit from taking part
4	Citizen Scientists may, if they wish, participate in multiple stages of the scientific process
5	Citizen Scientists receive feedback from the project
6	Citizen Science is considered a research approach like any other, with limitations and biases that should be considered and controlled for
7	Citizen Science project data and meta-data are made publicly available and where possible, results are published in an open access format
8	Citizen Scientists are acknowledged in project results and publications
9	Citizen Science programs are evaluated for their scientific output, data quality, participant experience and wider societal or policy impact
10	The leaders of Citizen Science projects take into consideration legal and ethical issues surrounding copyright, intellectual property, data sharing agreements, confidentiality, attribution, and the environmental impact of any activities



Publication	Study area	Sampling Method
Gewert et al., 2017	Baltic Sea	Trawling system
Barrows et al., 2018	Pacific and Atlantic coasts and off shores	Container-based system
Camins et al., 2020	Barcelona coast (Spain)	Trawling system
Sanders and Brandes, 2020	Georgia (USA)	Container-based system
Ershova et al., 2021	White Sea basin of Russian Arctic (Russia)	Container-based system
Setälä et al., 2022	Baltic Sea	Trawling system
de Haan et al., 2022	Catalunyan coast (Spain)	Trawling system
Clark et al., 2023	Cornwall (UK)	Trawling system
KeChi-Okafor et al., 2023	Lamu (Kenia) and Zanzibar (Tanzania)	Container-based system
de Haan et al., 2023	Barcelona coast (Spain)	Trawling system

FIGURE 2
Number of scientific documents with Citizen Science approach in surface microplastics monitoring through the years after the literature review **(A)**, the geographical area where the Citizen Science was undertaken **(B)**, the final list of publications of Citizen Science with authors, geographical areas, and systems used **(C)**. In **(B)**, maps were created with www.mapchart.net.

Consequently, an analysis was conducted to verify whether these approaches ensure outcomes and data quality for integration in scientific research and whether they adhere to the MSFD to ensure policy impact.

This in-depth analysis covers the sampling devices used, their categorization into "Container-based systems", which use graduated or calibrated containers to sample specific seawater volumes (such as buckets, bottles, or jugs), and "Trawling

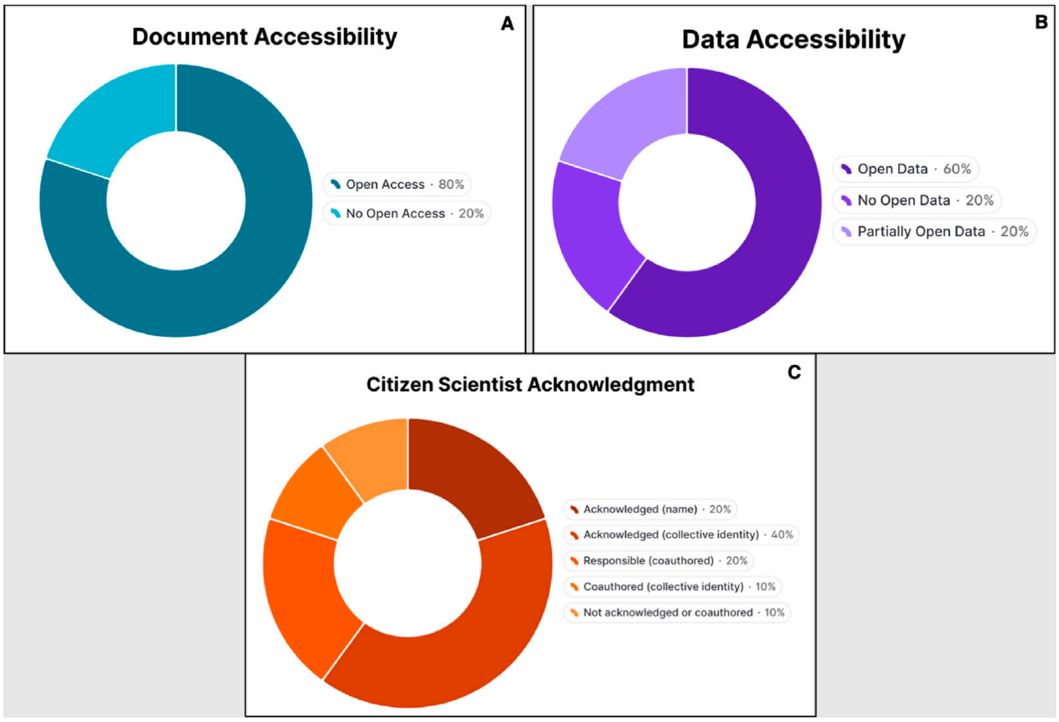


FIGURE 3
Documents outlining the European Citizen Science Association's requirements: accessibility of documents **(A)**; accessibility of data **(B)**; types of Citizen Scientists' acknowledgment **(C)**.

systems", which employ trawled devices equipped with nets to capture MPs over defined spatial and/or temporal scales (such as Manta and its revisitations). The categorization highlights sampling devices and their characteristics, as well as the data collected during the sampling period, regardless of the supporting structures (such as paddles, boats, or other equipment) or the method used to trawl the systems.

3 Results

3.1 Literature survey

The initial literature search identified 489 documents. Subsequently, after applying the above-selected criteria, 10 documents were considered for this review, all of which are articles published in the selected scientific journals (see Supplementary Material, Supplementary Table S1).

3.2 The Citizen Science approach for the study of sea-surface microplastics

CS methods for tracking MPs in surface seawaters have been introduced recently, with the first publication appearing in peer-reviewed articles in 2017 (Figures 2A,C).

Europe, which includes the United Kingdom in this geographical context, has produced six publications, the United States has contributed two, and Russia and Africa have each contributed one. One of the American publications (Barrows et al., 2018) covers a broad region studying the Atlantic and Pacific zones, whereas the other documents are related to specific geographically restricted areas (Figure 2B).

80% of the articles (eight) are in open access (ECSA's point 7; Figure 3A) (ECSA, 2015). Regarding data accessibility (ECSA's point 7), these records are low at 60% (six), with 20% (two) being partially accessible or with no data available, as requests to the authors were considered not open access (Figure 3B). Regarding the CS engagement methodologies, 80% (eight) of the studies have relied on territorial environmentalism associations, while 20% (two) involved individual volunteers. Information regarding the number of Citizen Scientists (CSist) — serving as a measure of societal engagement and impact (ECSA's point 9) — is present in 50% (five) of the documents. Conversely, 40% (four) of the articles reported the term "hundreds" or a similar term, and 10% (one) do not provide any information. The monitoring training processes of the involved CSist are assured in all the articles. Outcome feedback and dissemination (ECSA's point 5) were given back in 40% (four) of the studies (Table 2, 3). CSist acknowledgement (ECSA's point 8) is reported in 90% of the articles and is divided into subcategories: CSist acknowledged by name (20%), under collective identity (40%), CSist are credited as coauthored by naming the association or organization responsible (20%), or under collective identity (10%) (Ward-Fear et al., 2020; Sandin et al., 2024) (Figure 3C).

TABLE 2 Summary of "Container-based systems" used in Citizen Science approaches, with the results of microplastics and fibers per volume, geographical areas and Citizen Science activities enrolled. Bold text in the "Sampling protocol" column indicates the mesh size used for seawater filtering. Bold text in the "MPs or fibers/volume" column indicates the different methods used to evaluate microplastics concentration.

Publication	Device	Sampling protocol	MPs or fibers/volume	CS engagement, numbers of CSist, and feedback	CS training
Barrows et al. (2018)	Bottle	• Samples collected up-current or using a bucket, bottles were capped underwater, closed, packed and mailed to a laboratory • Different sampling platforms (wading and watercraft) and sampling locations (rocky and sandy shorelines, offshore, estuaries, remote and urban) • Recorded field sampling data (smart phone app and on a hard copy data sheet) • In laboratory samples vacuumed filtered over a gridded - **0.45 µm** filter • 1628 samples • Atlantic and Pacific coastal and open ocean areas	• **Fibers/L** 11.8 ± 0.6 particles L^{-1}	• NGO Adventure Scientists • "Hundreds" CSist • No info about feedback	yes
Sanders and Brandes (2020)	Buckett	• Four-liter samples of water collected in steel buckets • Poured through a series of stainless steel sieves of varying sizes: **355 µm–106 µm** - **63 µm** • Three locations for each group, sampled monthly during outgoing tide • 145 samples monthly, filtered in site • Georgia intracoastal waterway	• **MPs/4 L** Total MPs for site, no average, concentration varied from none to >80 particles per 4 L	• UGA MAREX volunteer program, the Satilla, Altamaha and Ogeechee Riverkeepers • 16 volunteers • Feedback and territorial activities	yes
Ershova et al. (2021)	Buckett	• Calibrated aluminum 10 L bucket, metal sieves with **100** and **500 µm** mesh size • 500 L of water filtered through sieves for each sample • 13 samples, one sample for site, filtered in site • In laboratory water samples were filtered through **50 µm** pore size stainless steel mesh • White Sea basin coastal waters, rivers, and lakes	• **MPs/volume** 1.14 MPs m^{-3}	• NGOs Clean North-Clean Country, Ecopatrol • 200 volunteers • Online dissemination	yes
KeChi-Okafor et al. (2023)	Jug	• Constructed from a coffee AeroPress®, nylon filters - **50 µm** mesh size • 2 L plastic jug used to draw water from the surface down to a maximum depth of 100 mm below the surface. Process repeated three times sampling, a total of 6 L of water • 37 replicates: 2 replicates in Lamu County, 3 in Tana River County, 13 replicates in Kilifi County, 6 Kwale County, 13 Zanzibar Archipelago	• **Fibers/L** 0.73 ± 1.99 fibres L^{-1}	• Flipflopi Project sailing expedition • No CSist engaged number • No info about feedback	yes

Four studies focus on integrating CS research with "Container-based systems" (40%), which do not comply with the MSFD guidelines and correspond to the non-European study areas. Conversely, the six studies (60%) that utilize "Trawling systems" are all in the European area (Figure 4C). "Container-based systems" use buckets, bottles, and jugs for sampling water; instead, "Trawling systems" use customed nets or replicates of Manta (Figures 4A,B).

3.3 Container-based sampling methods in Citizen Science projects for sea-surface microplastic monitoring

Four studies are included in the "Container-based systems" category, with two focusing on CS approaches for monitoring synthetic microfibers in the marine environment and two addressing

TABLE 3 Summary of the "Trawlings systems" used in Citizen Science approaches, with results of microplastics and fibers per volume, geographical areas, and Citizen Science activities enrolled. Bold text in the "Sampling protocol" column highlights the mesh size and the eventual use of flowmeter. Bold text in the "MPs/Estimated Volume or MPs/Surface" column indicates the different approaches used to estimate microplastics concentration.

Publication	Device	Sampling protocol	MPs/Estimated Volume or MPs/ Surface	CS engagement, numbers of CSist, and feedback	CS training
Gewert et al. (2017)	Designed trawling net	• Special designed trawl: round opening diameter 10 cm; mesh size: **80 µm** • Trawl net on the water surface behind the paddleboards • 4 replicates, one for day; sampling time: 30, 80, 50, 35 min • Locations: Visby Gotska Sandön Nämdö Fjärden Stockholm • **No flowmeter**	• **MPs/Estimated volume** range: 0.11 MPs m^{-3}–0.87 MPs m^{-3} • **MPs/surface** range: 9×10^3 MPs km^{-2}– 6.86×10^4 MPs km^{-2}	• Scientists contacted by paddle volunteers • volunteers • No info about feedback	yes
Camins et al. (2020)	Revisitated Manta "The Paddle Trawl"	• Revisitated Manta: mouth 38 cm × 30 cm; length of the net: 1.35 m; diameter cod 10 cm; rope length 3 m; mesh size: **330 µm** • Net towed on the water surface with paddleboards; smartphone for geolocation • Costal parallel transects • 6 samples, one for day; sampling time: 30 min - 1 hour • Locations: Barcelona and Prat • **No flowmeter**	• **MPs/Estimated volume** no • **MPs/surface** 11.2×10^4 MPs km^{-2}	• Surfrider Europe - Barcelona Chapter • Generical info about engaged CSist number • Feedback in festivals	yes
de Haan et al. (2022)	Revisitated Manta "The Paddle Trawl"	• Revisitated Manta: see Camins et al. (2020) • Coastal parallel transects or concentric transects in locations bounded by breakwaters or harbors; sampling time: 1 h • 129 samples, one for day • Locations: Ametlla de Mar, Arenys de Mar, Barceloneta, Castelldefels, Comarruga, Llança, Llevant, Mar Bella, Montgat, Nova Icaria, Palamos, Sant Sebastia • **No flowmeter**	• **MPs/Estimated volume** no • **MPs/surface** mean: 0.41 ± 0.81 MPs m^{-2}	• Surfrider Europe - Barcelona Chapter-Surfing for Science project • Generical info about engaged CSist number • No info about feedback	yes
Setälä et al. (2022)	Revisitated Manta "Mini Manta"	• Revisitated Manta: mouth 460 mm × 133 mm; mesh size: **0.3 mm** • Sailing boat; travel speed: 1.5 knots; sampling time: 30 min • 1 sample per location • 7 locations: Northern Baltic proper, Arkona Basin, Bothnian Sea, Bothnian Bay, Åland Sea, and Gulf of Finland • **No flowmeter**	• **MPs/Estimated volume** range: 0.45 m^{-3}–1.98 MPs m^{-3} • **MPs/surface** no	One sailor No info about feedback	yes
Clark et al. (2023)	HSMT High Speed Manta Trawl	• High Speed Manta Trawl; mouth 10 cm × 60 cm; length of the net: 4 m; mesh size: **333 µm** • Catamaran; average speed 6 kts; sampling time: 60–185 min • 28 samples in 5 route • Locations: Newquay Marine Conservation Zone, Padstow and Surrounds • **No flowmeter**	• **MPs/Estimated volume** no • **MPs/surface** mean: 8,515 MPs±6,383 MPs km^{-2} range: 1,350–26,875 MPs km^{-2}	• Cornwall Marine Microplastic Coalition, Polzeath Marine Conservation Group, the Cornwall Seal Group Research Trust, St Agnes Marine Conservation Group, Newquay Sea Safaris and Fishing, Cornwall College Newquay • 84 CSist • Feedback in local outreach events	yes
de Haan et al. (2023)	Revisitated Manta "The Paddle Trawl"	• Revisitated Manta: see Camins et al. (2020) • Other revisited Manta: mouth 0.34 × 0.26 m; length of the net 1.35 m; mesh size: **335 µm** • Sampling protocol: de Haan et al., 2022 • Net towed on the water surface with	**Research focus: Artificial Turf Fibers (AT)** • **AT/Estimated volume** mean: 0.03 AT m^{-3} range: 0–0.82 AT m^{-3} • **AT/surface** mean: 9,500 AT km^{-2} range: 0–213,200 km^{-2}	• Surfing for Science project • Generical info about engaged CSist number • No info about feedback	yes

(Continued on following page)

TABLE 3 (*Continued*) Summary of the "Trawlings systems" used in Citizen Science approaches, with results of microplastics and fibers per volume, geographical areas, and Citizen Science activities enrolled. Bold text in the "Sampling protocol" column highlights the mesh size and the eventual use of flowmeter. Bold text in the "MPs/Estimated Volume or MPs/Surface" column indicates the different approaches used to estimate microplastics concentration.

Publication	Device	Sampling protocol	MPs/Estimated Volume or MPs/Surface	CS engagement, numbers of CSist, and feedback	CS training
		paddleboards and kayaks • 152 replicates • 13 locations: coastline of Catalonia • **No flowmeter**			

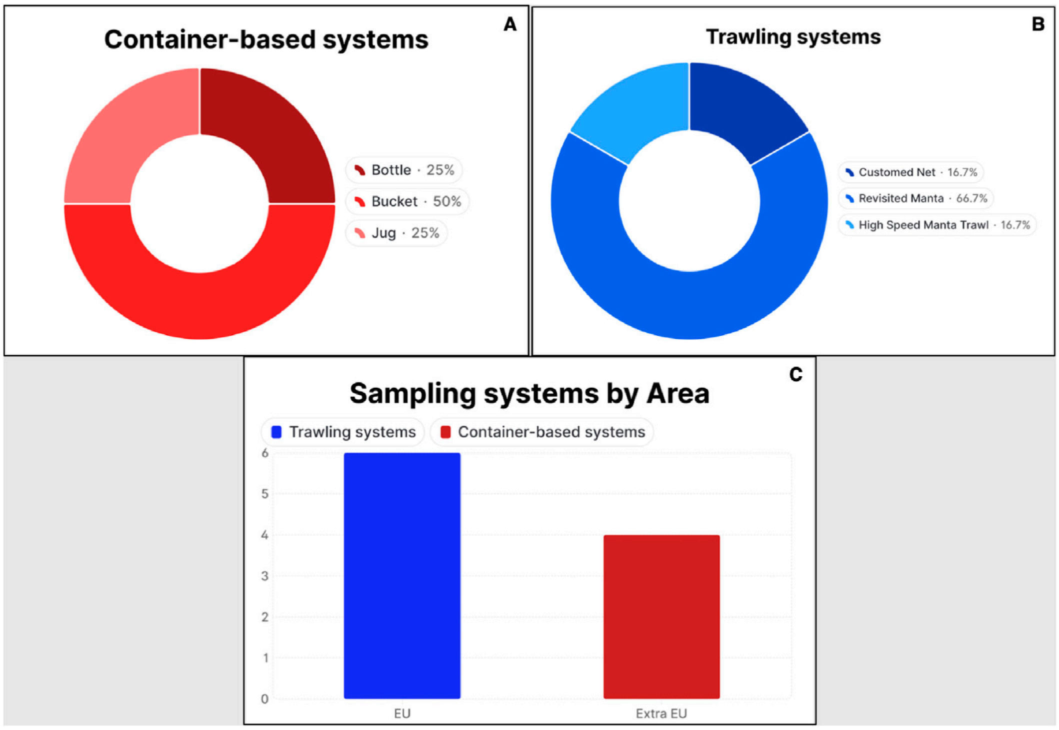


FIGURE 4
Documents outlining the categorization of sampling systems used: "Container-based systems" **(A)**; "Trawling systems" **(B)**; and the geographical distribution of sampling systems **(C)**.

microplastics (MPs) more generally (Table 2). The four studies varied in their strategy, protocol, sampling device, number of samples (n = 13–1628), spatial coverage (from coastal regional area to worldwide sample campaigns), sample filtered volumes (liters: 1–500), and CSist engaged (n = no info – "hundreds"). Each of them reported CSist training activities. All the details are reported in Table 2.

Barrows et al. (2018) present the first dataset on global microfiber distribution, describing CS sampling with 1-L bottles over 5 years along Atlantic and Pacific coasts, including rocky, sandy, offshore, estuarine, remote, and urban sites. Citizens were recruited via *Adventure Scientists*, a non-profit guiding community members on a mission to collect data for conservation in hard-to-reach locations.

KeChi-Okafor et al. (2023) focus on monitoring microfibers in CS *Flipflopi Project*, an East African initiative that promotes a circular economy by reducing and eliminating single-use plastics, encouraging alternative waste uses, and supporting regional legislation. To involve local communities in data collection, the project developed an affordable sampling method using a coffee AeroPress®, enabling community members to participate in surface water sampling.

Sanders and Brandes (2020) and Ershova et al. (2021) incorporate CS into their research on MPs' monitoring activities. Sanders and Brandes (2020) conducted CS activities specifically to enhance public understanding through education, along the Georgia (United States) intracoastal waterway. The document is in open access, but it does not include supplementary data related to monitoring activities. Ershova et al. (2021) conducted MPs monitoring in the White Sea basin of the Russian Arctic during the summer of 2020, focusing on coastal waters, rivers, and lakes. Due to the extreme remoteness of the area—no access roads, limited transportation—volunteers were required to walk distances exceeding 20 km to reach sampling sites. Under these conditions, conventional sampling methods like Manta or neuston nets and pumped filters were impractical. As a result, the CS activities utilized lightweight, cost-effective, and user-friendly filtration tools to collect water samples efficiently.

3.4 Trawling sampling systems in Citizen Science for sea-surface microplastics monitoring

Six documents are associated with "Trawling systems" methods. None of the studies utilized the Manta traditionally used by research and environmental agencies for MSFD monitoring; instead, they employed variations of it or alternative trawling sampling methods (Table 3). The six studies varied in their strategy, protocol, sampling device, number of samples (n = 4–152), spatial coverage (coastal area campaigns), and CSist engaged (n = from one to a generic number). Each of them reported CSist training activities. All the details are reported in Table 3.

Revisited Manta designs were explicitly created for four studies (Camins et al., 2020; De Haan et al., 2022; 2023; Setälä et al., 2022). Three studies (Camins et al., 2020; De Haan et al., 2022; 2023) utilized a design called "The Paddle Trawl", inspired by the Low-tech Aquatic Debris Instrument (LADI) (Coyle et al., 2016), which is a smaller, less expensive, and easier-to-build alternative to the standard Manta. The fourth study used a custom-made version called the "Mini Manta" (Setälä et al., 2022). Another type of Manta used for CS integration in MPs studies is the High-Speed Manta Trawl (HSMT) (Clark et al., 2023). Occasionally, a lightweight trawl for paddle trawling was developed (Gewert et al., 2017).

Gewert et al. (2017) detail a surface water sampling campaign conducted in an urbanized area of the Stockholm Archipelago, Baltic Sea, aligning with MSFD guidelines. During this campaign, two Swedish volunteers collected surface water samples while on stand-up paddleboards in June 2015 to raise awareness about plastic pollution in the Baltic Sea. Researchers designed a lightweight trawl to facilitate sampling that could be towed behind the paddleboards.

Camins et al. (2020), De Haan et al. (2022), and De Haan et al. (2023) implemented a modified Manta trawl, referred to as "The Paddle Trawl", which is specifically designed to be towed by paddleboards, kayaks, and rowing vessels. This approach aimed to address the scarcity of data on MPs in nearshore environments by enabling sampling in locations typically inaccessible to larger research vessels. De Haan et al. (2023) further incorporated CS initiatives to investigate artificial turf particles in both riverine and marine contexts. Public engagement was facilitated through the *Surfing for Science* project, in collaboration with *Surfrider Spain* and various local social, environmental, and athletic organizations. Similarly, Setälä et al. (2022) conducted a CS experiment during the summer of 2018 to collect marine MPs samples from the surface waters of the Baltic Sea. They utilized a custom-designed Manta, called "Mini-Manta", which is towed behind a sailing vessel operated by a volunteer. The objective of this campaign was to replicate the MSFD sample line protocols, thereby assessing the effectiveness of CS methods in monitoring marine MPs.

For monitoring activities along the coast of Cornwall (United Kingdom), Clark et al. (2023) used a High-Speed Manta Trawl (HSMT). These activities were conducted on a catamaran, involving volunteers from the *Cornwall Marine Microplastic Coalition (CMMR), Polzeath Marine Conservation Group, The Cornwall Seal Group Research Trust, Newquay Sea Safaris and Fishing,* and *Cornwall College Newquay.*

4 Discussion

In 1956, Lloyd Stouffer, editor of the US magazine "Modern Packaging", during the Society of the Plastics Industry meeting in New York City, said: "*The future of plastics is in the trash can . . . It is time for the plastics industry to stop thinking about 'reuse' packages and concentrate on single-use. For the package that is used once and thrown away, like a tin can or a paper carton, represents not a one-shot market for a few thousand units, but an everyday recurring market measured by the billions of units*" (Stouffer, 1963; Liboiron, 2021). Since then, plastic has become one of the most popular threats to the marine environment. Continuous, harmonized, and standardized quality-quantitative monitoring data of marine MPs is necessary to appropriately inform international bodies, policymakers, stakeholders, and local administrations, enabling them to implement effective measures to mitigate the environmental risks associated with MPs (Lusher and Primpke, 2023).

Here, a comprehensive systematic review was conducted to evaluate the advancements in CS methodologies for monitoring MPs on the sea surface. In recent years, CS has been extensively employed in the study of macroplastics and MPs found on beaches and within sediments, as well as in the monitoring of floating plastics (Hidalgo-Ruz et al., 2012; Hidalgo-Ruz and Thiel, 2013; Bergmann et al., 2017; Lots et al., 2017; Nelms et al., 2017). This approach has gained significant attention in international research with numerous citizen engagements and has produced robust findings. The outcomes of this review indicate that the integration of CS into the monitoring of MPs on the sea surface is still in its nascent stages of development, with a scarcity of literature (only 10 documents) suggesting it remains a relatively underexplored research domain (Hidalgo-Ruz and Thiel, 2015; De Haan et al., 2022). While the number of peer-reviewed publications has increased for both CS (63909 in Web of Science, 46485 in Scopus, and 114661 in Lens) and MPs (25040, 86031, and 40678 respectively), only ten studies have used CS methods for MPs monitoring in the past 20 years. This gap shows a countertrend compared to the separate growth of these expanding fields (Figure 5).

This challenge may stem from the dual obstacles associated with the accessibility of Marine Citizen Science (MCS) applications and the absence of harmonization and standardization in conventional MPs research (Rochman et al., 2017; Lusher and Primpke, 2023), both of which are critical factors influencing data quality and broader citizen participation. Nevertheless, the reviewed papers indicate that the obstacles can be overcome by reorganizing traditional protocols and devices, refining sampling methods, and enhancing experimental designs through dedicated efforts and time investment to ensure simultaneous data quality, standardization, accessibility, and, ultimately, facilitating comprehensive spatial-temporal monitoring data provision. These points oppose the dominant notion that CS is intrinsically a low-cost scientific approach or frugal science for large-scale spatial and temporal

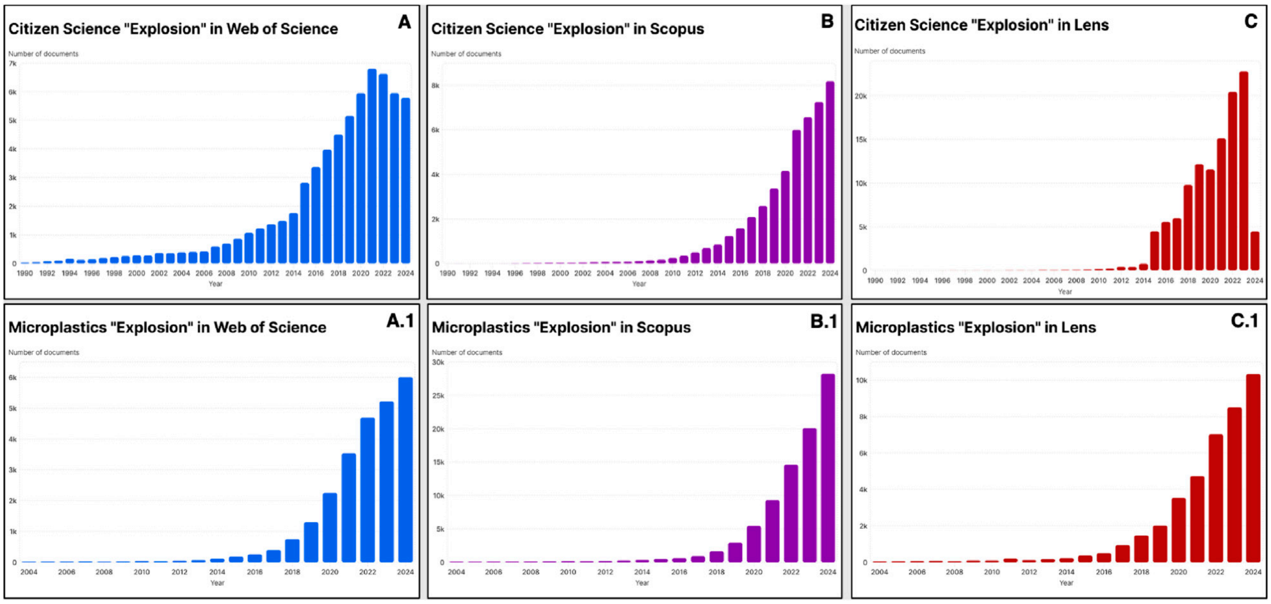


FIGURE 5
The "Citizen Science Explosion" in peer-reviewed publications through the three-engine used for the present review: Web of Science **(A)**, Scopus **(B)**, and Lens **(C)**, from 1990 to 2025, and "Microplastics Explosion" in peer-reviewed publications with the same engines Web of Science **(A.1)**, Scopus **(B.1)** and Lens **(C.1)**, from 2004 to 2025.

monitoring (Vasantha Raman et al., 2023). The discrepancy in the literature between MCS and its terrestrial counterparts has been underlined several times and is inherent to the complex and distinctive marine environment research, as well as to the traditional scientific context, presenting compelling challenges, especially in terms of accessibility and difficulty (Roy et al., 2012; Thiel et al., 2014; Sandahl and Tøttrup, 2020). Notwithstanding this, MCS is experiencing continual growth as a scientific methodology, with 1,267 initiatives documented to date. A notable surge in popularity occurred at the conclusion of the 1990s, featuring enduring projects that extend beyond 30 years (i.e., the "Conchological Society of Great Britain and Ireland's Marine Mollusc Recording Scheme" which commenced in 1876, is presently in its 147th year; the "Recreational Spearfishers for Collecting Marine Data in South-Eastern Australia" established in 1960, and the "Cooperative Shark Tagging Program" established in 1962, both still active) (Wehn et al., 2025). The extensive potential of MCS across time and space is essential for advancing marine understanding and conservation (Thiel et al., 2014; Cigliano et al., 2015). Engaging citizens as active stakeholders can enhance the effectiveness of marine governance strategies and ensure better conservation outcomes (McKinley and Fletcher, 2010). As marine citizenship can facilitate effective conservation of the environment by promoting active participation of the public in policymaking and implementation processes, it is imperative to rethink and ease the accessibility to scientific processes. The literature here underlines that MCS facilitates access to shallow coastal areas where monitoring vessels cannot operate (Gewert et al., 2017; Barrows et al., 2018; Camins et al., 2020; Sanders and Brandes, 2020; Ershova et al., 2021; De Haan et al., 2022; KeChi-Okafor et al., 2023; De Haan et al., 2023). Conducting CS in coastal waters can reveal spatial discrepancies in the distribution of MPs, offering valuable insights into their potential sources and pathways.

The pioneering studies have highlighted key aspects to outperform when using CS to monitor surface MPs. For example, on cruises with tight schedules and limited space for citizen sampling, it is advisable to adjust the sampling conditions and optimize the use of instruments (Setälä et al., 2022; Clark et al., 2023). Therefore, making such activities more accessible to a broader audience is only feasible through the use of "Container-based systems" (Barrows et al., 2018; Sanders and Brandes, 2020; Ershova et al., 2021; KeChi-Okafor et al., 2023). However, these approaches avoid replicating the methodology of the MFSD and do not ensure that the data produced are comparable with scientific and governmental data within the European Union context.

The tool used to assess MPs in the EU sea surface is the Manta Trawl Net (Manta, according to the MSFD), adapted from zooplankton and neuston studies (Tranter and Smith, 1968; Hidalgo-Ruz et al., 2012; Eriksen et al., 2013; Lusher et al., 2015). The complexity of using the Manta, even in its various adaptations, limits a significant portion of society from engaging in inclusive and participatory science activities. For example, paddleboarding and surfing may only be accessible to individuals with the necessary sporting skills, who are better equipped to handle prolonged sampling durations with surfboards, which typically last over 30 min (Gewert et al., 2017; Camins et al., 2020; De Haan et al., 2022; 2023). This situation ultimately undermines one of the main benefits of CS: broad participation and improved spatial sampling coverage.

Replicating the Manta in CS presents several estimation challenges that have also been noted in traditional research. These challenges include inaccuracies in estimating the filtered volume and limitations in sampling specific ranges of MPs. "Trawling systems" in these CS approaches routinely do not employ flowmeters to evaluate the filtered volume. Some studies assess MPs based on estimated surface area rather than on estimated filtered volume (Camins et al., 2020; De Haan et al., 2022). When filtered volume is considered, it is typically estimated by multiplying the net's mouth opening by the distance trawled (Gewert et al., 2017; Setälä et al., 2022), in accordance with the MSFD guidelines. Clark et al. (2023) applied a correction factor to evaluate only the lower half of the trawl opening. Except for Camins et al. (2020) De Haan et al. (2022), and De Haan et al. (2023), which employed the same modified Manta ("LADI") (Coyle et al., 2016) in the same monitored area, all other "Trawling systems" utilized different modified Mantas with varying mouth openings. Additionally, Gewert et al. (2017) used a custom-designed trawl with an 80 μm mesh size, while all other studies aimed to comply with the mesh size standards defined by the MSFD guidelines (330–335 μm). Lastly, trawling durations varied across different studies, and even within individual studies (Gewert et al., 2017; Camins et al., 2020; Clark et al., 2023).

Except for KeChi-Okafor et al. (2023), which does not mention any references to the CSist involved, all the documents report information about the engagement of citizens in various activities, mainly sampling. The available data show a range from 1 participant (Setälä et al., 2022) to "hundreds" of participants (Barrows et al., 2018). Aside from Setälä et al. (2022), whose study verified that data collected by CSist are comparable to traditional data obtained with the MSFD guidelines, the other studies were designed to involve citizens in scientific activities. When the exact number of involved citizens is reported, participation was consistent, with 200 CSists (Ershova et al., 2021) and 84 (Clark et al., 2023). For Barrows et al. (2018), the "hundreds" CSist participation in data collection enabled the creation of the first dataset worldwide on global microfiber distribution, demonstrating the power of civil society participation in producing large datasets that would otherwise be impossible for individual researchers. Most studies employed positive and strong collaborations with local environmental associations or NGOs to engage citizens, emphasizing the importance of establishing broad connections outside the traditional academic environment to connect with society and harness the positive interest in civil society to participate in scientific research. The collected and analyzed data are uploaded to open repositories linked in the papers for those articles that are published with data available. While there are many applications for data sharing and presence reporting among citizens and between citizens and researchers, particularly for documenting presence and gathering information on macro- and mesoplastics for CS research (e.g., Marine Debris Tracker, Litterati, JRC Floating Litter Monitoring App, EEA Marine LitterWatch), no similar applications are known, publicly available, or advertised specifically for CS approach focused on MPs monitoring.

All outcomes from the reviewed papers originate from various treatments, including different protocols, devices, and net meshes used to detect MPs, as well as the evaluation of filtered water volume, sampling duration, and data treatment (see Tables 2, 3). Except for Camins et al. (2020) De Haan et al. (2022), and De Haan et al. (2023), who used the same device design and protocol, allowing for data evaluation and comparison between them, the other data could only be compared with studies employing the same sampling protocols. For example, the diverse net mesh used in "Container-based" sampling methods permits comparison only with research that uses the same net mesh. These discrepancies hinder the standardization of data on MPs (Hidalgo-Ruz et al., 2012; Lusher et al., 2015; Rochman et al., 2017; Lusher and Primpke, 2023) and impact the robustness of data in the application of CS, ultimately reducing its influence on policymaking.

Standly, the new deal of sea surface MPs research with citizens' inclusion lies through the adoption of new user-friendly devices with standardized, easily deployable protocols, with harmonized experimental designs across CS initiatives. Those steps could enable CS applications to make regional comparisons and ensure integration, validation, and calibration with scientific and governmental monitoring frameworks, including the MSFD. A new deal would complement wider accessibility by reducing the cost of sampling efforts and infrastructure, permitting sampling in areas otherwise not included in MSFD monitoring (i.e., such as coastal areas, estuarine areas, and others), promoting long-term citizen engagement, and enabling monitoring through broader spatial and temporal data coverage. CS can achieve reliability, transparency, and scientific robustness through data empowerment—transforming citizen-generated data into credible, decision-relevant evidence that could support environmental governance, inform policymaking, and ultimately contribute positively to the advancement of MPs traditional scientific research and monitoring.

5 Future perspectives of Citizen Science as a bridge between Science and Society

Monitoring MPs using the CS approach poses a dual challenge in generating robust and standardized data. Assuming the large-scale needs for monitoring MPs and the necessity to gather new data, it is ideal to conceive cost-effective strategies to boost the current knowledge. Additional information through CS approaches can be used to establish comprehensive monitoring strategies to track the global distribution of MPs (Sherman and van Sebille, 2016). This initiative requires commitment, innovation, and determination to enhance research methodologies and practices. The field of CS holds a yet-to-be-fully-estimated potential for innovating and revitalizing environmental sciences (Hecker et al., 2018; ERC, 2022; Schmidt et al., 2022; von Gönner et al., 2023). New instruments are needed to successfully engage and implement CS initiatives for monitoring MPs; this should be carefully designed to enhance the guidelines used in the MSFD, with simple and accessible adaptations for CSist. Its primary goal should be to gather MPs and robust data through flowmeters and tracking systems that monitor distances traveled, which modern smartphone applications can facilitate.

Utilizing innovative tools and methodologies in CS could bridge the knowledge gap and provide a valuable data compendium for scientific research and monitoring. This, in turn, would help address solutions for both national and international governing bodies and create broad opportunities for advancing marine understanding and conservation (Thiel et al., 2014; Cigliano et al., 2015). This attempt is significant for the challenging task of the United Nations Decade of Ocean Science for Sustainable Development, an initiative by UNESCO's Intergovernmental Oceanographic Commission aimed at creating a collaborative framework and promoting ocean literacy.

It is fundamental to recognize that active participation in CS creates opportunities for individuals who might otherwise be marginalized due to social and economic barriers. By raising awareness of opportunities beyond their daily struggles, citizens can explore a broader range of cultural and professional paths than those typically available in their everyday lives. These experiences provide educational opportunities, especially for youth, women, and others who are often deprived of their right to knowledge in a world characterized by the ongoing creation of "discarded people" (Armiero, 2021), communities, and spaces influenced by unequal socio-ecological dynamics. These initiatives permit those society fragments identified such as "societal discards" (i.e., from marginalized areas), to make strides in scientific, civic, and political participation. CS projects enclose the potential to align with the 2030 Agenda's Sustainable Development Goals (SDG), which emphasize the critical need to ensure that no individual is left behind in accessing knowledge and resources. This includes: i. SDG 4 (ensuring inclusive and equitable quality education and promoting lifelong learning opportunities for all), ii. SDG 5 (achieving gender equality and empowering all women and girls), and iii. SDG 10 (reducing inequality within and among countries) (Fritz et al., 2019; Fraisl et al., 2020; Sprinks et al., 2021; United Nations, 2021; Gacutan et al., 2023). For these future commitments, it is essential to acknowledge the right of scientific citizenship, which ensures individuals' active and informed participation in the democratic process within a knowledge-based society. Public decisions are increasingly complex and necessitate highly common and shared specialized expertise.

Scientific citizenship necessitates open, data-driven dialogue and collaboration among institutional actors, the scientific community, business entities, and civil society. Given the postponement of talks on the UN Plastic Treaty to 2025, initiated in 2022, it is crucial to gather standardized and accessible scientific data on (micro)plastics pollution through CS, by securing funding and including diverse societal perspectives, separating opinions from data facts, and promoting global alignment (Oturai et al., 2023).

In addition, CS possesses the capacity to directly address the "Extinction of Experience", referring to the diminishing occurrence of first-hand field experience in ecological research within the scientific community (Soga and Gaston, 2016). The erosion of a broad empirical field experience is particularly troubling, as direct interaction with natural phenomena is integral to science in general and is vital for ecological and environmental studies, transforming personal observations into meaningful data-driven insights (Soga and Gaston, 2016).

Finally, CS permits the repositioning of the scientist in society, rearranging Gramsci's concept of the "organic intellectuals" (Gramsci, 2014), who emerge from particular social classes, advocating their interests while staying linked to the economic and political structures of those classes, unlike "traditional intellectuals", who perceive themselves as separate from class relations. Implementing this model in the "scientific intellectuals" space is indispensable, avoiding a neutral or detached standpoint from society. Scientists should engage with diverse social classes and participate in social and political matters to enhance scientific awareness while dedicating themselves to transformative actions addressing upcoming challenges. Actually, denialism, revisionism, discredit towards scientific evidence rise, and rush to delete common shared data. Irrational political measures, led by the swift political and economic consensus, struck through economic instabilities and future uncertainties, are taken without considering the consequences. Rebuilding communication bridges between science and society is essential for the present and future global agenda, as democracy is in a state of slow disintegration, and science is under attack, even in countries considered pillars of the world's democratic system. Science - and its shared data - needs democracy, and democracy needs science to regain its rightful place for science and society (Greco, 2018; Mantovani, 2023).

Author contributions

RB: Conceptualization, Methodology, Data curation, Formal Analysis, Supervision, Visualization, Writing – original draft, Writing – review and editing SB: Conceptualization, Methodology, Data curation, Formal Analysis, Supervision, Visualization, Writing – original draft, Writing – review and editing.

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Conflict of interest

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Supplementary material

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