water

MDPI

Review

Citizen Science for Monitoring Plastic Pollution from Source to Sea: A Systematic Review of Methodologies, Best Practices, and Challenges

Corinne Corbau [1,*], Alexandre Lazarou [2], Oliver Bajt [3], Vlatka Filipović Marijić [4], Tatjana Simčič [3], Massimo Coltorti [1], Elisa Pignoni [1] and Umberto Simeoni [5]

1 Dipartimento di Scienze dell'Ambiente e della Prevenzione, UNIFE, Via Saragat 1, 44121 Ferrara, Italy; clt@unife.it (M.C.); pgnlse@unife.it (E.P.)
2 Zanassi and Partners, Via G. B. Amici 29, 41124 Modena, Italy; alexandros.lazarou@gmail.com
3 National Institute of Biology, Večna pot 121, SI-1000 Ljubljana, Slovenia; oliver.bajt@nib.si (O.B.); tatjana.simcic@nib.si (T.S.)
4 Ruđer Bošković Institute, Bijenička 54, 10000 Zagreb, Croatia; vfilip@irb.hr
5 Consorzio Universitario per la Ricerca Socioeconomica e per l'Ambiente, Via Sistina, 121, 00187 Roma, Italy; g23@unife.it
* Correspondence: cbc@unife.it

Abstract

Citizen science provides a valuable approach for tracking plastic pollution; however, its effectiveness is often limited by methodological inconsistencies, concerns about data quality, and a persistent gap between data collection and policy implementation. This systematic review addresses the key question: What constitutes a comprehensive set of best practices for addressing these issues and enhancing the scientific and societal impact of citizen science in monitoring plastic pollution from source to sea? Analyzing 84 studies, from beach cleanups to microplastic sampling, this review synthesizes best practices and identifies remaining gaps. It presents a structured framework designed to enhance data quality and volunteer participation. Key challenges include the 'microplastic analytical bottleneck,' the 'digital divide,' and notable geographical and demographic disparities that hinder the integration of policies. While citizen science is effective for large-scale data collection, its main challenge is translating data into actionable policies. The main contribution of this review is a series of practical recommendations aimed at improving methodological consistency, ensuring fair volunteer participation, and facilitating the transition from citizen data to evidence-based environmental management, thereby enhancing the effectiveness and impact of citizen science.

Keywords: public engagement; plastic pollution data quality; environmental monitoring; policy integration

check for updates

Academic Editor: José Luis Sánchez-Lizaso

Received: 24 July 2025
Revised: 27 August 2025
Accepted: 5 September 2025
Published: 9 September 2025

Citation: Corbau, C.; Lazarou, A.; Bajt, O.; Filipović Marijić, V.; Simčič, T.; Coltorti, M.; Pignoni, E.; Simeoni, U. Citizen Science for Monitoring Plastic Pollution from Source to Sea: A Systematic Review of Methodologies, Best Practices, and Challenges. *Water* **2025**, *17*, 2668. https://doi.org/10.3390/w17182668

1. Introduction

Plastic pollution is widely recognized as one of the most urgent environmental crises of the 21st century, with large amounts of macro- and microplastics accumulating in marine and freshwater ecosystems worldwide [1–4]. The scale of the issue is alarming. To put this into perspective, recent studies estimate that while only 9–10% of plastic produced has been recycled and 10–11% incinerated, roughly 80% has been disposed of in landfills or dispersed directly into the environment [5]. Plastics degrade slowly over centuries, persisting for centuries and breaking into meso-, micro- and nanoplastics. Their resistance to degradation, combined with river transport, makes them a major source of coastal and marine pollution [6,7]. For instance, a recent study identified the Zeta, Morača, and Bojana rivers as significant sources of microplastics to the Montenegrin coast in the Adriatic Sea [8]. This crisis threatens biodiversity, ecosystem services, and possibly human health, making it a key focus of global frameworks such as the United Nations Sustainable Development Goal 14 and the upcoming legally binding UN treaty on plastic pollution [9–12].

The effects of plastic debris are widespread and varied. Plastics are classified by size, ranging from megaplastic (>50 cm) to microplastics (MPs, <5 mm) and nanoplastics (<1 µm) [13,14]. Due to their small size, MPs are particularly harmful. In aquatic systems, the most abundant forms are often fibers and fragments made of common polymers, such as polyethylene (PE) and polypropylene (PP) [8]. They are ingested by a vast range of organisms, including zooplankton, bivalves, fish, turtles, and marine mammals, often mistaken for food [15]. While ingestion can cause physical damage or other physiological disturbances, MPs also serve as carriers for other pollutants and microorganisms [16]. Their high surface area-to-volume ratio and hydrophobic character allow them to absorb and concentrate heavy metals and persistent organic pollutants, which can then be released into the tissues of organisms, bioaccumulating along the food chain [17,18].

Effectively addressing this complex issue requires comprehensive, frequent, and widespread monitoring across different regions. However, traditional scientific methods, while necessary, encounter practical limitations due to high costs, logistical challenges, and limited spatial reach, which makes it hard to manage a pollutant as active and widespread as plastic [19]. In addition, achieving comprehensive monitoring at fine spatial and temporal scales, as required for tracking marine litter dynamics, often exceeds the capacity of conventional field research methods [20]. In response, citizen science (CS) has become a valuable complementary approach for environmental monitoring.

Citizen science is defined as the active involvement of the public in scientific research, with citizens contributing their knowledge, effort, or resources alongside professional scientists [21,22]. These projects vary from contributory projects, where volunteers collect data through activities such as beach cleanups and water sampling, to more collaborative models in which citizens help design, interpret, and share research findings [23]. Such programs produce valuable large datasets and also raise environmental awareness, encouraging pro-environmental behavior. A notable example is the 2019 Danish project, where 57,000 students conducted the country's first national plastic waste survey, generating essential data while also exploring participants' perceptions and intentions related to plastic use [24]. The initiative demonstrated how CS projects can produce valuable data, drive behavioral change, and increase environmental awareness. Similarly, marine ecosystem monitoring efforts, like SeagrassSpotter and Seagrass-Watch, demonstrate how citizen science can facilitate the collection of Big Data by involving numerous volunteers to monitor seagrass habitats across various countries [25]. These initiatives demonstrate how citizen science can meet the requirements of Big Data (volume, velocity, and variety) even in challenging areas, such as marine and coastal zones.

Despite its potential, the widespread use of citizen science faces several challenges, including variations in methods, concerns about data quality, spatial and demographic participation biases, and a tendency to incorporate findings into official policy frameworks [26,27]. To improve its effectiveness, it is essential to understand best practices, identify gaps, and explore future opportunities. While existing reviews have summarized trends (e.g., [27,28]), this paper provides a concise and critical synthesis of the full project lifecycle (methodology, gaps, and policy) into an actionable framework for future work. Specifically, it offers the first comprehensive source-to-sea overview of citizen science methods for tracking plastic pollution. This review aims to identify and categorize methodologies used in citizen science projects for monitoring macro- and microplastic pollution in marine and freshwater environments. It also compiles and evaluates best practices for designing, implementing, managing data, and communicating these initiatives to enhance their scientific accuracy and societal impact. Furthermore, the review analyzes current research literature to identify key geographical, thematic, and methodological gaps that need further exploration. It concludes with evidence-based recommendations to improve the effectiveness, scalability, and policy relevance of citizen science efforts in tackling plastic pollution.

This review analyzes the strengths, weaknesses, and opportunities of existing citizen science experiences for monitoring plastic pollution. The aim is to provide insights to inform future research, support project development, and enhance policy integration, ultimately contributing to more effective global initiatives to tackle this critical environmental challenge. The following sections will detail specific methodologies, highlight established best practices, examine current challenges, and conclude with actionable recommendations.

While traditional citizen science efforts have mainly focused on marine litter, this review adopts a source-to-sea perspective. It examines how citizen science techniques are employed to track plastics from their sources, including rivers, urban runoff points, industrial zones, and watersheds, through freshwater and terrestrial systems, ultimately reaching coastal and marine areas. Although there is no dedicated section on "source monitoring," the source-to-sea approach is present throughout the methodology analysis. This comprehensive strategy improves our understanding of plastic pollution pathways and supports the development of effective interventions at every stage of the pollution cycle.

2. Materials and Methods

This review combines current insights on citizen science approaches for monitoring plastic pollution, highlights effective strategies, and identifies research gaps. A systematic approach was used to identify and select relevant literature to achieve these goals.

Literature Research Strategy

The database utilized for the literature search was Scopus, chosen for its extensive coverage of peer-reviewed literature across diverse scientific disciplines, including environmental science. Its strong indexing of keywords and abstracts enhances its appropriateness for targeted inquiries.

The initial search string employed was: "plastic" and "citizen science" as keywords. This extensive search returned 206 documents, including different types such as articles (165), conference papers (14), reviews (14), book chapters (7), books (3), notes (2), and a single short survey.

To improve the search and target citizen science applications related to plastic pollution more precisely, the search was refined to include only publications where the terms "citizen" and "science" appeared together in the abstract and were indexed with either "Citizen Science" or "Plastic" as standardized keywords.

In the final selection step, results were filtered to include only those within environmental sciences, agriculture and biological sciences, or earth sciences. This resulted in a final dataset of 126 documents, consisting of 119 scientific articles and 7 review papers. We employed Web of Science (WoS) using the same keywords as in our main Scopus search. Although the number of papers was fewer, the overlap confirmed the dataset's thoroughness and consistency, increasing confidence in its representativeness.

The number of publications has increased over the past decade, peaking in 2022 and 2023 with 25 documents each. This trend continues strongly into 2024 (20) and 2025 (10).

Most research is concentrated in the fields of Environmental Science (122 documents), Agricultural and Biological Sciences (52), and Earth and Planetary Sciences (46), which highlights a significant focus on environmental and ecological issues. Important sources of publication include journals Marine Pollution Bulletin (32 documents), Science of the Total Environment (15), and Sustainability (8), along with other key outlets such as Water (Figure 1a).

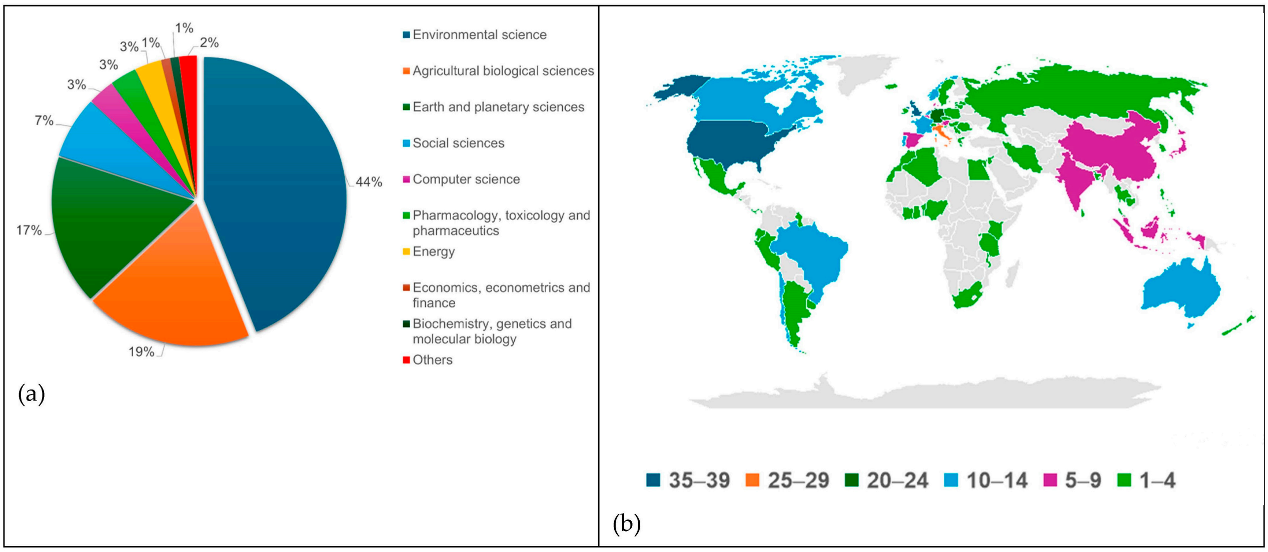

Figure 1. Distribution of the 84 peer-reviewed studies included in this review: (**a**) subject categories of publications (percentage), and (**b**) geographical distribution of research efforts by region.

The geographical distribution of the research papers is varied (Figure 1b), with the most significant contributions from the United Kingdom (26), Italy (19), and the United States (18). The main authors include Thiel, M. (10 documents), Knickmeier, K. (7), and Syberg, K. (6), suggesting a dedicated group of researchers involved in this field.

Furthermore, review papers were excluded, and their abstracts were carefully examined. Specifically, review papers that limited their scope to general summaries were excluded from the main analysis, whereas reviews that contributed significant methodological insights were retained and used in synthesizing best practices and identifying gaps. The main inclusion criterion required that the paper include significant information relevant to the review's objectives, especially regarding citizen science methods for monitoring plastic pollution, including their implementation, strengths, weaknesses, or potential improvements.

A total of eighty-four research papers were selected for this review. The studies, published between 2013 and 2025, demonstrate a significant increase in publications starting in 2019 and cover a wide geographic area, with major contributions from countries such as the United Kingdom, Italy, and the United States, as well as many others worldwide. The journals with the most frequent publications are Marine Pollution Bulletin and Science of Total Environment.

For all 84 chosen papers, data were systematically collected regarding:

- The citizen science methodologies used for monitoring macro- and/or microplastics.
- The environmental context (e.g., marine, freshwater, coastal, riverine).
- Reported strengths and weaknesses of the methodologies.
- Aspects of scalability.
- Quality assurance and quality control (QA/QC) measures employed.
- Technological integrations and their effectiveness.

- Challenges, biases, and gaps found in existing practices.
- Suggested solutions or directions for future research.

The information collected was organized into thematic tables (Tables 1–3), focusing on key methodologies and main features; best practices; gaps; and opportunities. This review primarily synthesizes insights from the analysis of the selected literature to produce a structured overview and critical assessment that directly aligns with the review's objectives.

3. Citizen Science Methodologies for Plastic Pollution Monitoring

Citizen science projects use a wide range of methodologies to monitor plastic pollution in both marine and freshwater environments. These methods aim to address both macroplastics and microplastics, and their selection often depends on the study environment, available resources, and the expertise of participating volunteers. Table 1 summarizes key methodologies, their main features, and representative examples from the literature.

3.1. Macroplastic Monitoring Methods

Citizen science initiatives to track macroplastics (>5 mm) are varied but generally fall into a few common methodological approaches. These methods are popular because macroplastics are visible and simpler for volunteers to identify and categorize. According to the reviewed literature, these approaches can be organized into the following groups:

- Shoreline surveys and clean-ups (more than 10 studies): The most common method involves volunteers collecting and recording litter along specified transects, often following international protocols like OSPAR or MSFD [29]. Items such as bottles, bags, and fishing gear are categorized with data cards or apps. These efforts produce valuable datasets and also help remove pollutants, with the results already supporting policy assessments and management [30,31].
- Visual Estimation Methods (more than 10 studies): Volunteers assess litter density by direct observation, typically using standardized scales like items per 100 m [32]. Although less detailed than itemized surveys, this approach delivers quick insights across large areas and helps prioritize cleanup efforts.
- Technology-driven approaches (5–10 studies): Smartphone apps allow citizens to report litter sightings using photos, GPS data, and standard classifications [33–35]. These tools expand geographic coverage and enable nearly immediate reporting, although challenges related to inclusivity persist.
- Specialized monitoring that generally requires more specialized training or equipment:
    - Fishing for Litter (between 5 and 10 studies): This initiative engages fishers to collect marine litter items as bycatch during regular fishing operations. The litter is then brought ashore for recording and analysis, providing insights into the types and quantities of debris on the seafloor, which is typically inaccessible via shoreline surveys [36].
    - Underwater Surveys (more than 5 studies): Volunteer divers assess litter on the seabed in marine environments through visual census methods or photo and video documentation, providing data on litter accumulation in benthic ecosystems [37].
    - Policy and planning-driven strategies (around 5 to 10 studies) involve citizens and stakeholders more actively in the decision-making and planning processes related to marine litter [24,38,39]. These approaches promote collaboration among citizens, researchers, policymakers, local businesses, and other relevant groups. Participants engage in co-creating knowledge through workshops, interviews, or mapping exercises, identify local pollution sources and impacts, and develop management strategies like recycling initiatives or campaigns to reduce specific

litter types [29,38]. For instance, citizen-collected beach cleanup and brand audit data have been used to evaluate the impact of single-use plastic policies [40].

3.2. Microplastic Monitoring Methods

Monitoring microplastics (<5 mm) requires more complex methods, as detection and confirmation necessitate specialized analysis. Despite these challenges, citizen science has played a significant role in various environmental systems, often through hybrid models in which volunteers collect samples for laboratory testing.

Citizen science methods for monitoring microplastics include:

- Water Sampling (surface and subsurface, 5–10 studies): Volunteers collect water samples with pre-cleaned bottles, Niskin bottles, or simple low-cost tools. Protocols, such as the Microplastics Sampling and Processing Guidebook [41,42], specify the collection depth, volume, and filtration methods. Projects such as ANDROMEDA have shown that standardized instructions can enhance comparability [43].
- Trawl-based Techniques (Surface Trawls, 5 to 10 studies): Low-cost nets such as the LADI and AVANI trawls are used from small vessels, whale-watching tours, or paddleboards, allowing for collection in various environments [44–47]. Their versatility makes these tools accessible to volunteers and effective for capturing meso- and microplastics.
- Sediment Sampling (Beaches, Riverbanks, Estuaries, less than 5 studies): Volunteers utilize quadrats and pre-cleaned tools to gather sand or riverbank sediment samples for analysis at central laboratories [48–50]. Initiatives like COLLECT and Microplastic Detectives have trained students and local communities to use standardized techniques, generating data valuable for freshwater and coastal environments [49,51]. Additionally, citizen-led monitoring of nurdles on beaches has resulted in datasets that inform policy decisions [52].
- Air Sampling (emerging, rare): Although still in early development, projects such as HOMEs [53] have tested passive samplers and low-cost microscopes to detect airborne microplastics both indoors and outdoors. This demonstrates the opportunity for citizen participation in a field usually limited to laboratory environments.

3.3. Scalability of Citizen Science Approaches

Citizen science strategies for monitoring plastic pollution are scalable, allowing data collection both locally and globally. Standardized protocols, such as beach clean-ups and shoreline surveys, are designed to be reproducible in different geographic contexts. For example, the OSPAR and EU Marine Strategy Framework Directive (MSFD) protocols have been adopted by many countries, enhancing coordinated monitoring and enabling data comparability across borders [29].

Large-scale initiatives demonstrate how scalability can enhance citizen science [54–57]. The "Plastic Pirates" initiative involved school groups across Germany and several European countries in collecting data on river litter, resulting in a consolidated dataset from multiple source regions [54,55]. Similarly, the "Científicos de la Basura" program in Chile has involved thousands of students and educators in coastal and river litter surveys, creating comprehensive datasets that support both national and international research [56].

National campaigns highlight scalability. In Denmark, the "Mass Experiment" involved over 57,000 students in a survey on plastic waste, resulting in the first nationwide dataset on environmental plastic pollution and increasing public awareness [24]. Additionally, a decade-long citizen science project studied 736 beaches in the UK, building one of Europe's largest datasets on coastal plastic pollution [58]. Citizen-collected beach cleanup data is becoming more significant for national reporting within international frameworks such as SDG indicators [59], in addition to official datasets. Such long-term and widespread efforts can even indicate a reduction in beach litter over time in specific regions [60].

Digital tools further enhance scalability, as mobile apps and online platforms improve data entry consistency, optimize geolocation, and enable the real-time sharing and aggregation of observations over large areas [33,34]. These technologies support the involvement of extensive and varied volunteer networks in effectively monitoring plastic pollution across diverse coastlines and river systems.

Additionally, citizen science initiatives often collaborate with schools, community groups, and local officials to broaden their impact and promote ongoing participation. This strategy increases both the quantity and diversity of data collected while fostering a sense of responsibility and care among participants. Therefore, the flexibility, replicability, and community-focused nature of citizen science make it a highly scalable method for monitoring plastic pollution, capable of producing valuable datasets from local to global levels.

3.4. Data Quality Assurance and Quality Control (QA/QC)

Maintaining high data quality is crucial for the credibility and scientific significance of citizen science projects that focus on monitoring plastic pollution. Quality assurance and quality control (QA/QC) protocols are incorporated into the project design and implementation; however, their application can differ between macroplastic and microplastic monitoring, depending on the characteristics of the materials and the complexity of the analyses involved.

3.4.1. Macroplastic Monitoring

For macroplastics, quality assurance and control (QA/QC) focus on standardization, volunteer training, and field data validation. Many large projects utilize globally recognized protocols, such as those established by OSPAR or the EU Marine Strategy Framework Directive (MSFD), to ensure consistency across various sites and periods [29]. Volunteers usually receive detailed instructions, training materials, and data sheets or mobile applications to assist in identifying and categorizing litter [33,34].

For instance, the "Plastic Pirates" initiative in Germany and other European nations provides school groups with field kits and protocols for consistent data collection along rivers and coastlines [55]. Similarly, a study in Chile demonstrated the reliability of citizen-collected data on small plastic debris by conducting detailed laboratory recounts to validate results produced by students [61]. In the UK, ongoing beach litter surveys include regular expert assessments and re-evaluations to improve volunteer accuracy [58]. Monitoring litter in urban and river settings, like the "Clean Rivers" project [62], frequently modifies protocols to ensure accessibility and safety while maintaining standardized data formats and routine cross-verifications. In urban areas, app-based reporting [33] uses geotagged images and validation processes to minimize data entry errors and enable expert assessment.

Photo documentation is increasingly used for verification, allowing specialists to assess and validate field identifications remotely [56]. Specific programs, like the UK's extensive beach litter surveys, integrate regular audits or expert re-surveys to enhance volunteer accuracy [58]. Furthermore, digital platforms provide integrated validation processes, such as required fields and error-checking, to reduce data entry errors.

3.4.2. Microplastic Monitoring

Monitoring microplastics presents significant QA/QC challenges due to the small size and diversity of particles, as well as complex processing and analysis requirements. While citizen scientists can collect water, sediment, or sand samples using standardized protocols, extracting and identifying microplastics typically requires laboratory methods and expertise [46,51].

To address this problem, many projects use a hybrid approach: volunteers collect and label field samples, which are then sent to accredited laboratories for processing and polymer identification using advanced techniques like FTIR or Raman spectroscopy [50,63]. Field blanks and control samples are regularly employed to detect contamination, and chain-of-custody documentation guarantees sample integrity [21,48]. The "Clean Rivers" project uses this model in freshwater, where volunteers collect river and stream samples, which are processed centrally to maintain quality standards [62]. Furthermore, urban microplastic monitoring often involves sampling sediment or stormwater at parks or near industrial areas. In these cases, QA/QC may involve duplicate sampling, negative controls, and strict contamination prevention protocols, due to higher contamination risks in densely populated areas.

Therefore, while macroplastic citizen science depends on standardized protocols, volunteer training, and digital validation to ensure data quality, monitoring microplastics necessitates additional laboratory QA/QC and expert supervision. Utilizing photo documentation, digital tools, and hybrid approaches enhances the accuracy and utility of data for both micro and macro plastics.

3.5. Technological Integration

Technological innovation drives citizen science efforts in tracking plastic pollution. Digital tools, mobile applications, remote sensing, and advanced laboratory techniques have significantly enhanced the amount and quality of data collected by volunteers, thereby broadening participation and involvement.

First, the widespread use of smartphones has led to the development of specialized apps that simplify data collection, standardize procedures, and enable real-time information sharing. Initiatives like Plastic Pirates utilize mobile apps to support volunteers with survey instructions, automate location tracking, and facilitate the uploading of geotagged images for expert review [33,55]. These applications typically feature integrated quality assurance and quality control features, such as required data fields, dropdown menus for litter classification, and error detection algorithms, which reduce reporting inconsistencies. In urban areas, these apps enable the rapid identification of litter hotspots, while volunteers in coastal regions can record and share observations from even the most remote beaches [34].

In addition to ground-based data collection, some projects utilize remote sensing and drones to monitor plastic pollution in large or inaccessible areas, such as estuaries and riverbanks. Drones capture high-resolution images of floating or stranded litter, supporting initial assessments and long-term monitoring efforts. Artificial intelligence (AI) and machine learning algorithms are increasingly used to analyze volunteer photographs, automate litter identification and classification, and improve data consistency and scalability [34].

It should be noted that technological integration is essential for microplastic monitoring. Volunteers collect water, sediment, or sand samples in the field, which are then analyzed using advanced laboratory equipment as previously mentioned. Samples are labeled with barcodes or QR codes and are examined using Fourier-transform infrared (FTIR) or Raman spectroscopy to identify polymer types [50,63]. Digital laboratory management systems facilitate secure connections between sample metadata and analytical results, making it easy to access data for further scientific research and reporting. This integrated approach enables the collection of samples from diverse environments, ensuring that data quality meets established scientific standards.

Digital platforms are vital for training and engaging volunteers. Many initiatives provide online tutorials, interactive guides, and virtual workshops, allowing participants to follow protocols and utilize technological tools effectively. Additionally, online dashboards and interactive maps deliver real-time feedback, highlight collective achievements, and promote a sense of community and shared objectives. These communication tools are key to maintaining long-term engagement and sharing project results with the public and policymakers.

The level and nature of technological integration often vary depending on the environment. Coastal and urban projects often rely on mobile applications and digital reporting, which facilitate broad participation and quick data collection. Conversely, riverine and remote marine areas may benefit more from drones, remote sensing technologies, or hybrid sampling methods that combine field data collection with centralized laboratory analysis. For microplastics, laboratory technologies are essential to ensure data accuracy across all environmental contexts, while monitoring macroplastics is most effectively performed through real-time digital reports and photographic documentation.

As a result, our review suggests that carefully integrating technology into citizen science projects has transformed plastic pollution monitoring by increasing participation, enhancing data quality, and enabling more efficient communication. Continuous innovation and efforts to improve accessibility will be essential for expanding these tools across different settings and project sizes.

Table 1. Key methodologies, their main features, and representative examples from the literature.

Methodology	Brief Description and Targets (Macro—Micro)	Key Reported Strengths	Key Reported Limitations—Weaknesses	Scalability	Common QA—QC Approaches	Technological Integrations and Effectiveness	Key References
Beach/Shoreline Litter Surveys and Cleanups (Standardized Protocols like ICC, OSPAR, MSFD TG10)	Systematic collection and counting of litter on beaches, coastlines, and riverbanks, focusing on macroplastics, mesoplastics, and general litter. SDG 14.1.1b monitoring.	Cost-effective for large areas, increases public participation and awareness, and can contribute to national SDG reporting.	Data can have biases (opportunistic sampling, volunteer effort/skill variation), data quality issues (non-standardized protocols), and data classification differences.	Replicable, extensive coverage.	Data validation (national statistical services, experts), standardized data cards (ICC), training for volunteers, and photo verification.	Global Earth Challenge Platform, TIDES database, Clean Swell, Marine Debris Tracker, Litterati, AMDI Database, Rydde.	[29,31,32,36,39,40,52–54,56–73]
Visual Estimation Method (Coastal Debris)	Citizen scientists assess pollution and categorize macro-debris along 100 m coast transects.	Rapid and cost-effective for extensive areas, it helps prioritize cleanups, monitors trends, and informs the public.	Depends on training; potential for subjectivity and errors, especially at low pollution levels; uncertainties in estimation.	Highly scalable with trained volunteers.	Training workshops, photo verification, double-checking data, standardized survey width, and reference photos.	Mobile apps, QGIS, drones and AI (proposed).	[32]
Stakeholder Analysis (SA)	Participatory approach to engage diverse stakeholders in developing marine litter monitoring plans and policies. Target policy/strategy for marine litter.	Enhances knowledge and resources for policymaking, facilitates contextualized decisions, promotes broad inclusion, and empowers stakeholders.	Variable participation; potential underrepresentation of some sectors (e.g., private).	Applicable at subnational/national levels.	Expert consultations, snowball sampling, questionnaires, and interest-power matrix.	In-person or virtual workshops, regional meetings.	[38]
Fishing for Litter (FFL)	Fishers collect marine litter (often plastic) during regular fishing activities (passive) or dedicated trips (active). Targets marine litter (macroplastics) in the sea.	Enhances ecosystem quality, potential income for fishers, and raises awareness.	Not the most effective for overall reduction, as it faces challenges with motivation, costs, time, and hazardous material risks.	Implemented in various seas; incorporated into national policies.	Relies on fisher participation and accurate reporting; requires legal, institutional technological support	Surveys or questionnaires for public perception.	[36]
Paddle Trawl/Surf Trawl	Low-cost, lightweight trawl towed from small craft for sampling floating micro, meso, and macroplastics in nearshore surface waters.	Cost-effective; samples inaccessible areas; enhances spatial-temporal resolution; public engagement; comparable data.	GPS app accuracy; volunteer skill dependency.	User-friendly, encourages participation with various recreational gear.	Volunteer training, sample handling protocols, visual classification, and chemical ID (FTIR) of subsets.	Smartphone app for geolocation and social media.	[45]
Mini-Manta Trawl	Custom-built, smaller manta trawl for surface water microplastic sampling from small boats.	Cost-effective; enhances spatial coverage; complements national monitoring.	Mesh size and towing speed affect collection, contamination risks, and are best suited for larger microplastics.	Feasible for broader coverage with motivated volunteers.	Enzymatic digestion; hot needle test; FTIR for polymer confirmation.	Custom-built trawl.	[47]
Sieve—based Collection (Arctic)	Water samples collected using metal sieves, then filtered for microplastic analysis.	Cost-effective for remote regions; involves diverse volunteers; data from under-sampled areas.	Distinguishing synthetic—natural polymers.	Feasible for targeted studies in remote regions.	Professional guidance; lab analysis (microscopy, FTIR).	Sieves, FTIR.	[42]
Riverine Net Sampling (e.g., Plastic Pirates)	Schoolchildren use custom nets (e.g., 1000 µm mesh) to collect floating meso/microplastics in rivers.	Large-scale data collection; identifies hotspots; educational value; comparable data with QC.	High data exclusion occurs if protocols are not followed, which may result in missing the smallest microplastics and introducing observer bias.	Nationwide/Europe-wide.	Standardized protocols, training; photo verification; data normalization; FTIR for polymer ID.	Interactive maps; smartphone apps (suggested).	[54,55,74]
Grab Samples (Riverine)	Volunteers collect 1 L grab samples from river sites, which are then filtered and analyzed for microplastics. Targets microfibers.	Watershed-scale assessment identifies spatial/temporal variations.	Microfibers ubiquity makes source attribution hard; airborne contamination risk.	Applicable for large-scale river studies.	Training: field/procedural blanks; microscopy; FTIR—Raman.	Standardized collection kits.	[51,75]

Table 1. *Cont.*

Methodology	Brief Description and Targets (Macro—Micro)	Key Reported Strengths	Key Reported Limitations—Weaknesses	Scalability	Common QA—QC Approaches	Technological Integrations and Effectiveness	Key References
Sediment Sampling and Analysis (Microplastics)	Collects sediment from beaches, estuaries, and riverbeds; processes in the lab (drying, sieving, separation, digestion) to extract and analyze microplastics. Targets microplastics.	Quantifies microplastics in sediments; identifies hotspots; data on particle characteristics.	Labor-intensive; sample heterogeneity; contamination risk; difficulty with some particle types/sizes.	Global application is possible, but lab analysis is a bottleneck for CS.	Triplicate/blank samples; cleaning protocols; Nile Red staining; microscopy; FTIR/Raman.	Stereo microscope, sieves, density separation units, and analytical instruments.	[47–49,55,63,67]
App-Based Litter Reporting and Analysis	Citizens use smartphone apps (e.g., Marine Debris Tracker, Litterati, Jetsam, Pirika, PlastOPol, CrowdWater to photograph, geotag, and categorize litter, sometimes using AI. They target various litter types in multiple environments.	Rapid, large-scale data collection; increased public engagement and awareness; hotspot identification; global database potential; cost-effective.	Data quality (accuracy, bias, image quality), participant recruitment/retention, data concentration, unsupervised sampling issues, and app barriers.	Highly scalable via smartphone use; platforms aggregate data.	Photo verification; expert validation; automated QA/QC; user registration; training; data filtering; standardized categories; image quality guidance.	Mobile apps with GPS, AI (YOLOv5, EfficientDet-d0 d0), GIS mapping.	[13,33,34,43,69,76–81]
Nurdle Patrols/Pellet Monitoring	Volunteers conduct timed searches (e.g., 10 min) on shorelines, collecting and counting plastic pellets (nurdles). Targets microplastic pellets.	Specific data on nurdle pollution helps identify sources, establishes policy-relevant baselines, and raises awareness.	Nurdle identification challenges, volunteer motivation, and quantifying survey area.	Nationwide/regional coverage (Gulf of Mexico, Germany). Replicable.	Training materials and ID guides; standardized collection time; data submission forms/apps; online maps.	Nurdle Patrol website/database; smartphone app (implied/development).	[50,52]
Underwater Litter Surveys (Diver-based)	Recreational divers collect and record seafloor litter data (e.g., Dive Against Debris). Targets macrolitter on the seafloor in marine environments.	Accesses underwater areas; data on seafloor litter; high engagement from divers.	Diver safety; limited by conditions/accessibility; observer bias; data collection challenges underwater.	Large-scale via global programs.	Standardized data sheets/protocols; training; photo documentation.	Data platforms (e.g., Project AWARE map).	[37,82]
Social Media Data Mining ***Not considered in this review***	Analyzing public social media posts (images, text) for marine litter interactions with megafauna. Targets evidence of litter impacts on wildlife.	Cost-effective opportunistic data, especially for data-poor regions, early warnings, and public awareness.	Variable data quality (non-standardized, misidentification); incomplete information; ethical concerns; underestimation.	Scalable by monitoring multiple platforms; automated search terms.	Expert verification; specific keywords/hashtags.	Social media platforms.	[83]
Review & Synthesis Studies	Critical analysis of existing CS literature to identify trends, best practices, gaps, and make recommendations. Targets broader understanding and improvement of CS for plastic pollution.	Provides a comprehensive overview, identifying key learnings and future directions, and informs the strategic development of CS.	Relies on the quality and availability of published primary studies; potential for publication bias.	Can influence global research agendas and policy discussions.	Systematic review methodologies; stakeholder consultations.	Not applicable directly as a field method.	[24,41,53,58,62,77,84,85]
Stakeholder Engagement and Participatory Planning	Involves various stakeholders (public, academia, NGOs, government, private sector) in co-designing monitoring programs, interpreting data, and developing management strategies for plastic pollution. More than just data collection, it aims for collaborative governance and policy influence.	Increases knowledge base, resources, and buy-in for solutions. Leads to more contextualized, locally relevant, and innovative strategies. Empowers communities. Can improve data quality and policy uptake.	Requires significant coordination and facilitation. It can be time-consuming. Ensuring equitable representation of all stakeholder groups can be a challenging task.	Applicable from local to international levels. Essential for initiatives like the UN Plastic Treaty.	Workshops, interviews, surveys, focus groups. Use of tools like interest-power matrices. Delphi method. Participatory modeling.	Online platforms for collaboration and information sharing.	[29,36,39,84,86]

Table 1. *Cont.*

Methodology	Brief Description and Targets (Macro—Micro)	Key Reported Strengths	Key Reported Limitations—Weaknesses	Scalability	Common QA—QC Approaches	Technological Integrations and Effectiveness	Key References
Stakeholder Engagement and Participatory Planning	Involves diverse stakeholders (public, academia, NGOs, government, private sector) in co-designing monitoring programs, interpreting data, and developing management strategies for plastic pollution. Broader than data collection, it aims at collaborative governance and policy impact.	Increases knowledge base, resources, and buy-in for solutions. Leads to more contextualized, locally relevant, and innovative strategies. Empowers communities. Can improve data quality and policy uptake.	Requires significant coordination and facilitation. It can be time-consuming. Ensuring equitable representation of all stakeholder groups can be a challenging task.	Applicable from local to international levels. Essential for initiatives like the UN Plastic Treaty.	Workshops, interviews, surveys, focus groups. Use of tools like interest-power matrices. Delphi method. Participatory modeling.	Online platforms for collaboration and information sharing.	[38,39,58,86]
Educational Interventions and Perception Studies	Using citizen science activities like cleanups, story writing, and "Mass Experiment" to educate participants, often youth, about plastic pollution and evaluate changes in their knowledge, attitudes, and behaviors. Aims to increase awareness, understanding, and pro-environmental actions related to (mainly macro) plastic pollution.	Enhances ocean and environmental literacy. Empowers youth to become agents of change through intergenerational learning. Able to identify public perceptions and misconceptions to customize educational programs. Promotes stewardship.	Measuring long-term behavioral change is complex. Self-reported data can be biased. "Ceiling effects" in populations already highly aware. Ensuring engagement beyond data collection. Requires careful curriculum design.	Scalable through integration into school systems and large-scale campaigns.	Pre—and post-activity questionnaires/surveys. Qualitative analysis of outputs (e.g., stories). Control groups (less common). Standardized scales for psychological constructs.	Mobile apps for activity delivery and data collection. Online platforms for resources.	[24,87–91]
Integration of CS with Advanced Modeling/Sensing	Combining citizen science data (e.g., litter locations, reported tags) with other data sources (e.g., oceanographic models, remote sensing) to understand pollution dynamics, sources, and pathways. Targets a broader understanding of plastic distribution and fate.	Validates and improves models. Provides ground-truth for remote sensing. Enhances predictive capabilities for identifying accumulation zones or sources.	Requires expertise in citizen science and modeling/remote sensing. Citizen science data may need substantial processing to be model-ready. Uncertainties can propagate into models.	Potential for large-scale environmental modeling when CS data is robust and widespread.	Comparison of model outputs with CS observations. Statistical validation of combined datasets.	Lagrangian particle tracking models, GIS, remote sensing data (e.g., Sentinel—2), and machine learning for image analysis combined with CS input.	[92–94]

4. Best Practices in Citizen Science for Plastic Pollution Monitoring

Successful citizen science projects for monitoring plastic pollution depend on solid methodologies and effective management principles. Literature reviews highlight best practices throughout these initiatives, from design and planning to data dissemination and policy engagement (Table 2). Following these practices improves data accuracy and enhances the impact, including public awareness, education, community empowerment, and policy relevance. This section summarizes best practices in three key areas: (i) project design and planning, (ii) volunteer recruitment, training, and engagement, and (iii) data collection, management, and quality assurance.

4.1. Project Design and Planning

Effective project design and careful planning are essential for the success of any citizen science initiative, particularly in monitoring plastic pollution. This phase establishes a strategic direction, anticipates potential challenges, and ensures credible scientific results and a meaningful societal impact.

4.1.1. Set Clear Scientific and Societal Goals

A key best practice highlighted in the literature is to establish clear, specific, and measurable objectives at the beginning of any citizen science project [84,95]. These objectives should include clear scientific research questions and specified societal impacts. Scientific goals set the research focus, guiding methodological choices and data analysis approaches. For instance, they may involve assessing baseline pollution levels in unexamined areas [49,56], identifying pollution hotspots and tracing their sources [55,96], evaluating the success of specific mitigation strategies or policy initiatives [54,64,97], or improving the understanding of the distribution and types of specific pollutants, such as microplastics or nurdles [45,52].

Conversely, societal objectives often emphasize broader impacts, such as increasing public awareness and understanding of plastic pollution, as well as enhancing environmental literacy and scientific skills [89,90]. They also aim to promote community changes and eco-friendly behaviors [87], while providing actionable data to support policy decisions [53,67]. Aligning these goals with policy frameworks, including national environmental strategies and the UN Sustainable Development Goals (especially SDG 14.1.1b on marine debris), is crucial for ensuring policy relevance [29,59]. A participatory goal-setting approach is considered best practice, as it ensures that stakeholders, especially local communities, have their concerns addressed [38]. Clear scientific and societal objectives are essential; they act as a roadmap for all project stages, from selecting methodology and developing training materials to engaging volunteers, analyzing data, and evaluating project success. Well-defined objectives improve resource efficiency and effectively communicate the project's purpose to sponsors, partners, and participants.

Most studies (more than two-thirds) emphasize the significance of clear goal setting, indicating it as a nearly universal principle in citizen science projects. However, some researchers warn that setting overly ambitious societal goals without sufficient resources can undermine scientific rigor. Overall, projects that effectively balance scientific credibility with community relevance tend to have the most substantial long-term impacts.

4.1.2. Use Standard Frameworks Protocols

A best practice for enhancing the reliability and usefulness of citizen science data is to utilize established scientific frameworks and standardized protocols [62]. Initiatives should either adopt or modify well-known guidelines rather than creating methods in isolation. For example, many practical marine litter monitoring projects follow protocols from the International Coastal Cleanup (ICC), which provides a widely used data card and methodology [29,57,67], the OSPAR Commission for the North-East Atlantic [31,58], the EU Marine Strategy Framework Directive (MSFD) Technical Group on Marine Litter [65], or the comprehensive UNEP/GESAMP guidelines for marine litter monitoring [29].

The advantages of this methodology are considerable. Firstly, it utilizes existing scientific expertise and methodologies, thereby conserving time and resources while maintaining scientific rigor. Secondly, it enhances data comparability across various projects, regions, and periods [21], which is crucial for comprehensive datasets that reveal broader trends in plastic pollution. Such comparability is essential for global assessments and for tracking progress towards international objectives [59]. Thirdly, using established frameworks enhances the credibility and acceptance of citizen science data among scientists and policymakers. While the adoption of existing protocols is generally advisable, modifications may be required to accommodate local environmental conditions (e.g., different beach types), specific research questions (e.g., targeting particular litter categories), or the resources available to citizen scientists [95]. It is essential to consider and document these adaptations to preserve the fundamental aspects of the standardized protocol, thereby ensuring data comparability and consistency. For instance, although the goal was to standardize data collection, the "Plastic Pirates" project adapted methodologies to suit riverine environments appropriate for schoolchildren [55].

This recommendation was the most frequently mentioned best practice in the reviewed literature, highlighting its essential role in maintaining comparability and credibility. While there is some discussion about the need for flexibility to adapt protocols to local settings, the consensus is that any changes should be thoroughly documented to ensure interoperability. Our evaluation indicates that standardized frameworks are the most broadly supported and effective approach for creating datasets that guide policy.

4.1.3. Engage Stakeholders Early and Continuously (Co-Design Principle)

A key best practice for enhancing the relevance and sustainability of citizen science projects is early, meaningful, and ongoing engagement of diverse stakeholders [38,84]. Some authors [86] report that this engagement should evolve from simple consultation to co-design, involving stakeholders as active partners from the project's beginning to the dissemination of results.

Stakeholders may include end-users of the data, such as government agencies, international organizations, the scientific community, non-governmental organizations (NGOs), educational institutions, and representatives from local communities, including volunteer groups that are directly affected by the project. Initiating engagement early ensures that the project's scientific questions align with societal needs and policy priorities [29,38]. This process integrates local ecological knowledge, cultural considerations, and community concerns, thereby increasing the project's relevance. Involving stakeholders during the design phase helps identify logistical challenges, facilitates access to resources, builds trust, and establishes pathways for data use. For example, some authors [29] emphasize the importance of collaboration with National Statistical Offices. Continuous engagement through workshops, updates, and collaborative analysis of results maintains momentum, ensures alignment with changing needs, and promotes long-term support for monitoring initiatives [84].

While fewer studies directly focus on co-design compared to standardized protocols, those that do often highlight greater project relevance, improved trust, and higher chances of policy adoption. Nonetheless, some projects encounter difficulties because ongoing stakeholder engagement requires significant resources. We believe this approach is especially important for ensuring long-term sustainability and embedding into governance frameworks.

4.1.4. Plan Proactively for Data Quality, Management, and Ethical Considerations

From the initial design phase, projects should proactively address data quality assurance and control (QA/QC) to ensure the credibility of the collected information [95]. This process involves selecting methodologies relevant to the research questions, the type of plastic monitored (macro, meso, or micro), and the environment, while also considering the skills and limitations of volunteers [51]. It is crucial to establish clear definitions for litter categories and use consistent measurement units. Effective sampling strategies, such as transect design, site selection, or zonal sampling (as discussed by [68]), must be implemented to minimize bias, alongside practical training and validation procedures. For specialized monitoring, like microplastics, planning contamination prevention protocols is essential, as previously noted [42,48].

Planning for data management is equally important, as it includes storage, security, and sharing strategies. Following the FAIR (Findable, Accessible, Interoperable, Reusable) data principles is ideal for improving the long-term value and usability of the data [49,77]. Additionally, ethical considerations are crucial in project design, such as ensuring volunteer safety, obtaining informed consent, protecting data privacy (especially in app-based data collection), and promoting inclusivity and equitable participation [77,84,98]. Therefore, thoroughly addressing these elements during the planning phase establishes a strong foundation for a successful, impactful, and responsible citizen science project.

Although QA/QC is less emphasized than training or protocol use, about one-third of studies highlight its importance, especially for microplastic monitoring. Literature shows neglecting QA/QC undermines credibility, yet only a few projects fully apply FAIR principles. We believe investing more in these initial planning stages is among the most critical needs for future initiatives.

4.2. Volunteer Recruitment, Training and Engagement

The success of citizen science projects in monitoring plastic pollution is intrinsically linked to the effective recruitment, thorough training, and sustained engagement of volunteers. These individuals play a crucial role in data collection. Implementing practices to support them, ensure their well-being, and sustain motivation is essential for achieving high-quality scientific results and broader societal impacts.

4.2.1. Comprehensive Training

Different authors [84,95] suggest that a key part of effective citizen science is providing thorough, transparent, and accessible training specifically designed for the tasks volunteers must complete, while also taking into account their prior knowledge. This training should extend beyond simple procedural instructions by integrating the scientific context and objectives of the project to highlight the importance of volunteers' contributions and explain how the data will be used. Clear guidance should be provided on methods for litter identification, including distinguishing between human-made and natural items, accurate categorization typically based on standardized lists such as ICC or OSPAR, and consistent measurement or counting techniques [29,32].

For instance, the "Plastic Pirates" initiative provides schoolchildren with comprehensive educational materials and instructions [55], while the Científicos de la Basura project used virtual training for beach leaders to ensure standardized data collection across multiple teams [56]. In projects involving potential hazards or specialized sampling, such as microplastic collection, training must rigorously address safety protocols and measures to prevent contamination [41,42,49]. As suggested by [89], practical training provides essential skills, builds volunteer confidence, and improves scientific literacy, making it vital for ensuring data accuracy and reliability. The piloting of training materials and techniques, as recommended by [95], can verify their effectiveness before wider implementation.

Training was consistently identified as a significant predictor of data quality across nearly all volunteer-focused studies. However, a few studies mentioned that the effects of training decline over time unless refresher sessions are provided. Overall, the evidence suggests that comprehensive and repeated training should be regarded as one of the most effective and cost-efficient best practices.

4.2.2. Standardized and User-Friendly Protocols for Volunteers

While the comprehensive standardization of protocols improves overall data quality, as discussed in Section 4.3, it is considered best practice from an engagement perspective that these protocols to be simple, well-documented, and presented with clear visual aids to ensure that volunteers understand and consistently follow them [95]. Protocols should be designed to minimize ambiguity and be easy to follow for individuals with diverse scientific backgrounds or varying experience levels. Implementing clear data sheets or intuitive application interfaces that include predefined categories and image guides for litter types, as observed in various applications like Marine Debris Tracker [13], can significantly improve consistent data recording. The COLLECT project demonstrated the effective use of standardized methodologies by making them accessible and easy to understand [49]. As recommended by the authors [62], pilot testing protocols with targeted volunteer groups is essential to refine them for clarity and practicality, thereby enhancing adherence and data quality.

Many studies (about half) highlighted the importance of both scientific rigor and user accessibility. The main disagreements centered on balancing the simplification of protocol with the preservation of scientific detail. We believe that user-friendly designs that retain key standardization offer the optimal compromise.

4.2.3. Strategies for Ongoing Engagement, Motivation, and Community Building

Maintaining volunteer motivation and ensuring long-term participation, especially concerning ongoing monitoring projects or tasks that require repetitive efforts, necessitates dynamic and continuous engagement strategies [33,84]. Some authors suggest that, establishing effective two-way communication channels, such as newsletters, dedicated social media groups, project websites, forums, or regular virtual and in-person meetings, is essential for keeping volunteers informed, addressing their questions, and fostering a responsive environment [86]. A fundamental best practice involves providing regular and meaningful feedback on their contributions. This includes sharing how their data is being used, presenting preliminary findings, for example, through visualized results on interactive maps as demonstrated in "Plastic Pirates" [55], and highlighting the project's achievements and impacts [56]. This feedback loop reinforces the importance of their participation and cultivates a sense of ownership and accomplishment.

Recognizing and appreciating volunteers' contributions through various means, such as certificates, public acknowledgments, inclusion in reports when appropriate, and celebrating milestones, is essential [84]. Moreover, encouraging a sense of community and shared purpose among volunteers through collaborative activities or interactive platforms can greatly enhance motivation and retention [87]. Understanding and addressing the diverse motivations of volunteers, which include environmental activism, a desire to contribute to scientific discovery, opportunities to acquire new skills, social interaction, or simply enjoying the outdoors, enables projects to adapt their engagement and recruitment strategies more effectively, as suggested by some authors [62].

Long-term engagement, although less often highlighted than training or protocols, is essential for project continuity. Some studies have reported a rapid decline in volunteer participation in repetitive monitoring tasks, while others have found that strong feedback loops can reduce attrition. We believe that sustained engagement strategies are essential for project longevity but require ongoing innovation.

4.2.4. Prioritization of Safety, Ethical Conduct, and Inclusivity

A fundamental best practice in any citizen science initiative is always to prioritize volunteers' safety and ethical behavior. This involves conducting thorough risk assessments for all fieldwork and providing clear, detailed safety guidelines and briefings for volunteers, especially in potentially hazardous environments like coastlines, riverbanks, or when on watercraft [55]. Ensuring access to essential safety equipment (e.g., gloves for cleanup activities, appropriate gear for specific sampling) and offering guidance on hazard avoidance is crucial.

Ethical considerations are complex and include obtaining informed consent from all participants regarding their involvement, the type of data collected (especially if personal information, such as location, is collected via applications), and how their data will be used, stored, and disseminated [77]. Ensuring data privacy and security is essential.

Additionally, projects should prioritize inclusivity and equity in their recruitment and engagement strategies. This involves intentionally reaching out to and supporting diverse communities and individuals, such as those from underrepresented groups, with different levels of digital literacy, and from various cultural backgrounds. It is important to make sure participation is accessible, welcoming, and respectful for everyone, as recommended by different authors [84,98]. This could involve providing resources in multiple languages, providing simple participation methods, and collaborating with community leaders to build trust and encourage participation.

Citizen science projects can cultivate a dedicated, skilled, and motivated volunteer base by strategically investing in various aspects of volunteer recruitment, comprehensive training, and continuous, thoughtful engagement. This approach significantly enhances the quality and quantity of scientific data collected for plastic pollution monitoring. It maximizes educational, societal, and stewardship outcomes, empowering individuals and communities in the global effort to address this urgent environmental challenge.

Ethical and inclusivity considerations appeared in roughly a quarter of the studies, indicating they are less consistently reported but are gaining recognition as vital. Although pursuing inclusivity can be resource-heavy, projects that deliberately expand participation can diversify datasets and boost social impact. We view this area as relatively underdeveloped, yet with great potential for enhancing the legitimacy and equity of citizen science.

4.3. Data Collection, Management and Quality Assurance

Rigorous data collection practices, systematic data management, and comprehensive quality assurance and control (QA/QC) measures fundamentally enhance the scientific value and policy relevance of citizen science data in the monitoring of plastic pollution. The integration of these best practices is essential for generating credible, reliable, and usable information.

A key element of high-quality citizen science is the consistent use of standardized data collection protocols [95]. This typically involves using or adapting internationally recognized guidelines, such as those from the International Coastal Cleanup (ICC), OSPAR, or the EU Marine Strategy Framework Directive (MSFD), to ensure consistent methods and improve data comparability across different projects and regions [29,58,65].

The OSPAR protocols on plastic pollution build on guidelines to reduce marine litter by preventing plastic waste from entering the ocean. They support the Convention for the Protection of the Marine Environment of the North-East Atlantic, focusing on reducing land- and sea-based sources, promoting cleanup, and raising public awareness. Similarly, the EU Marine Strategy Framework Directive (MSFD) sets binding measures to achieve Good Environmental Status (GES) in EU waters. Under Descriptor 10, it requires member states to monitor and reduce marine litter, including plastics, via regional cooperation. It emphasizes source reduction, better waste management, prevention policies, and measurable targets. Both frameworks promote prevention, monitoring, policy integration, and stakeholder engagement, supporting sustainable marine ecosystems and reducing plastic pollution.

Standardization involves using clearly defined litter categories (typically based on material, item type, and potential source) and uniform measurement units (e.g., items per meter, items per square meter, weight per unit area). This helps with accurate quantification, density calculations, and trend analysis [32,59]. Mobile applications, as illustrated previously, often significantly contribute to enforcing these standards by offering structured data entry forms with predefined lists and visual aids [13]. Providing comprehensive training for volunteers in these standardized procedures, as demonstrated in projects such as "Plastic Pirates" [55] and COLLECT [49], is crucial for the successful implementation of these procedures.

Collecting detailed and organized metadata is considered a best practice essential for interpreting, validating, and maintaining the long-term usability of citizen science data. Key metadata usually includes precise geolocation of the survey or sample (often automatically recorded via GPS-enabled devices or apps), the date and time of data collection, details of the survey effort (such as the number of volunteers, survey duration, and area covered), prevailing environmental conditions (like weather, tide state, and sea state), and any deviations from standard protocols [45,58]. Some authors [59] highlight that insufficient metadata can significantly limit the usefulness of collected litter data, potentially leading to its exclusion from analyses or official reports. Technological tools, especially mobile apps, greatly help in the systematic and often automated collection of this critical contextual information.

Furthermore, effective Quality Control (QC) is a continuous process integrated throughout the entire project lifecycle, not just a single step. It begins with comprehensive volunteer training (Section 4.2) and the adoption of clear, pilot-tested protocols, as reported by [95]. Some authors [32,56] suggest that photographic documentation of surveyed areas, litter items, or samples during data collection is a crucial quality control tool, enabling project coordinators and experts to verify findings remotely. In studies focusing on microplastics, careful use of control samples, including field and procedural blanks, is essential for detecting and preventing potential contamination [48,51]. Additionally, implementing data cleaning and filtering routines after collection assists in identifying and correcting outliers, inconsistencies, or incomplete records [59,60]. Moreover, involving experienced "super-users" or trained facilitators can enhance QC by providing on-site guidance or managing more complex verification tasks [99].

In addition, data validation procedures are essential for maintaining the scientific integrity of citizen science data. This might include expert assessments of data samples or submitted images [56], comparisons with information from professional surveys or official monitoring systems [21], and verification against established scientific protocols [29]. For data intended for official use, such as SDG reporting, collaborating with national statistical offices or relevant government agencies for formal validation is a key best practice as outlined by various authors [29,59]. Effective data management involves utilizing centralized databases or platforms (e.g., TIDES, EMODnet, AMDI Database, Global Earth

Challenge Platform, Rydde) that support standardized data entry, secure storage, and facilitate analysis and sharing [29,77]. Additionally, following the FAIR (Findable, Accessible, Interoperable, Reusable) data principles is increasingly viewed as essential for enhancing the long-term value and usefulness of collected data [49,77]. Finally, transparent communication of methodologies, quality assurance, and control processes, as well as any identified limitations in the data, is essential when sharing results. The effective use of data visualization tools, such as interactive maps or dashboards on online platforms, increases the clarity and accessibility of findings for both volunteers and broader audiences, thereby closing the feedback loop and demonstrating the project's impact, as noted by some authors [55,81].

Almost all reviewed studies highlighted the importance of standardized data collection, though fewer provided detailed descriptions of systematic quality control (QC) processes. Some projects questioned whether citizen science can entirely meet professional standards for quality assurance and quality control (QA/QC), while others demonstrated effective hybrid verification systems. We suggest that investing in metadata collection and transparent validation methods is essential for enhancing trust in citizen science outcomes.

4.4. Fostering Educational, Behavioral, and Societal Impacts

As previously mentioned, citizen science generates valuable data and serves as an effective educational tool, raising awareness and encouraging social mobilization. Well-designed projects go beyond data collection, providing experiences that inspire environmental responsibility, improve scientific literacy, and empower communities to address plastic pollution.

Indeed, engaging directly with plastic pollution in local areas provides participants, especially students, with experiential knowledge that often exceeds abstract classroom instruction [89]. This direct involvement enhances environmental awareness and understanding of the problem's sources, extent, and effects, serving as a crucial step toward changing behavior [87]. Furthermore, this engagement encourages positive shifts in attitudes and values, strengthening personal responsibility and connection to nature. Some authors [88] further propose that as participants improve their scientific skills and observe how their data contributes to a larger goal, they develop self-efficacy, defined as a belief in their ability to effect change, which serves as a significant predictor of sustained environmental action. Together, these elements (knowledge, attitude, and self-efficacy) catalyze noticeable shifts in behavior, such as reducing single-use plastics and increasing involvement in community advocacy and clean-up initiatives [90,91].

The social impacts of these initiatives can extend beyond individual participants to affect entire communities. The case study from Ghana provides a clear illustration of this [29]. The project promoted active stakeholder involvement by integrating citizen science into national monitoring systems, effectively bringing together local communities, civil organizations, universities, and government agencies. This teamwork not only built local capacity through training but also empowered communities by providing them with the necessary tools and information for effective environmental management.

Significantly, the successful validation and inclusion of this citizen-generated data into official Sustainable Development Goal (SDG) reporting increased its credibility, allowing it to directly inform national policies, including Ghana's Integrated Coastal and Marine Management Policy and the upcoming National Plastics Management Policy [29]. This demonstrates an essential best practice: citizen science serves as both a monitoring tool and a driver of social mobilization and evidence-based governance initiatives.

Moreover, citizen science projects are vital for promoting intergenerational learning (IGL), where children share knowledge and environmental values with adults, as discussed by [90]. Through participation in initiatives like "Plastic Pirates" [55] or the marine debris curricula outlined by [90], schoolchildren often act as information transmitters, sharing their newfound knowledge and environmental concerns with their families, which in turn influences their behaviors at home. Additionally, global collaborations, such as the COLLECT project, which involves students from Africa and Malaysia [49], provide platforms for wide knowledge transfer and capacity building. By sharing standardized methods and best practices, the educational impact of these projects is significantly enhanced, making it easier to replicate and adapt successful models in different regions and increase their global influence.

About half of the studies highlighted social and educational impacts, but their measurement methods varied significantly, and some showed limited long-term behavioral changes. Although self-reported results can be biased, evidence suggests that projects combining data collection with education generally produce greater societal benefits. We noted this dual function, which serves both scientific and educational aims, as a key strength of citizen science, even though it is still under-evaluated.

Table 2. Gaps and opportunities in citizen science for plastic pollution monitoring.

Category (Project Phase)	Best Practice Statement	Evidence of Enhancing Scientific Validity	Evidence of Enhancing Broader Impact	Key References
Project Design and Planning	Integrate CS data with national SDG reporting frameworks.	Standardization and official data integration address data gaps for SDG indicators (14.1.1b).	Policy relevance, national reporting, international comparability, model for other countries.	[29]
Project Design and Planning	Involve diverse stakeholders (government, academia, CSOs, private sector) in planning and validation.	Enhances the pool of knowledge, facilitates contextualized decisions, and validates findings through national statistical services.	Collaborative governance empowers stakeholders, innovative management strategies, and policy development.	[29,38]
Project Design and Planning	Utilize or adapt standardized monitoring protocols (e.g., ICC, UNEP/GESAMP guidelines).	Ensures data comparability, allows for global/national assessments, and facilitates data validation.	SDG reporting, understanding global/national trends, and informing policy.	[29,57]
Project Design and Planning	Define clear project goals and objectives, including specific scientific questions and their potential societal impact.	Ensures research focus, allows evaluation of project success, and aligns CS activities with larger scientific goals	Stakeholder engagement, policy impact, and SDG alignment.	[29,38,54,90,95]
Volunteer Training And Engagement Ensure that volunteers are well-trained, understand data protocols, and remain engaged to ensure project success and data accuracy.	Define clear scientific questions and goals for the project. Develop standardized protocols are in place, potentially based on established frameworks (e.g., ODP-MSP, GEO-TAG, MSFD TG10, ICC, EMODnet).	Ensures focused researchevaluates project success, aligns CS activities with scientific goals, provides comparable data, and ensures scientific relevance.	Facilitates policy relevance, SDG reporting, public engagement, and educational benefits.	[29,53–55,79,95]
Volunteer Training And Engagement	Provide thorough training, clear instructions, and ongoing support to volunteers to ensure accurate data collection and sustained engagement. Use engaging and accessible educational materials. Maintain continuous communication.	Improves data accuracy and reliability, increases volunteer retention, reduces observer bias, and ensures adherence to protocol.	Enhances scientific literacy, fosters environmental stewardship, empowers communities, increases participation, and knowledge co-production.	[29,32,40,45,52,54,55,59,63, 67,84,86,98,100]
Data Collection	Employ cost-effective methods suitable for large-scale volunteer participation (e.g., beach cleanups, visual estimation).	Broad spatial and temporal coverage, rapid assessment, and the ability to detect trends.	High public participation, awareness-raising, cost-efficiency.	[29,32,64]
Data Collection	Train citizen scientists adequately for the chosen methodology (e.g., visual estimation, species identification).	Improves data accuracy and reliability.	Enhances the scientific literacy of volunteers.	[32,44]
Data Collection	Use standardized data collection tools (e.g., data cards, mobile apps) and well-defined categorization schemes (e.g., ICC, MSFD TG10, OSPAR).	Ensures consistency and comparability across studies/regions, facilitates data aggregation.	Enables large-scale data analysis, global reporting, and informed policymaking.	[29,40,50,53–58,63,65]
Data Collection (Microplastics)	Utilize cost-effective and accessible sampling tools (e.g., paddle trawls for nearshore microplastics) specifically designed for citizen scientist use.	Sampling hard-to-reach areas, data comparable to traditional methods, enhances spatial/temporal resolution.	Fosters citizen engagement, public awareness, and user-friendly.	[45,101,102]

Table 2. *Cont.*

Category (Project Phase)	Best Practice Statement	Evidence of Enhancing Scientific Validity	Evidence of Enhancing Broader Impact	Key References
Data Quality Assurance/Control (QA/QC)	Implement data validation processes, potentially involving expert review or comparison with official data sources.	Verification by national statistical offices, data filtering, and adjustments for survey effort.	Increased credibility for policy use, contributes to national statistics.	[29,59,75]
Data Quality Assurance/Control (QA/QC)	Utilize standardized data collection tools (e.g., data cards, mobile apps) and classification systems.	Consistency in data, enables aggregation and comparison (e.g., TIDES database).	Facilitates large-scale data analysis and global reporting.	[29,35,53,57,80,103]
Data Quality Assurance/Control (QA/QC)	Implement multi-stage validation processes, including expert review, photo verification, and comparison with official/professional data or guidelines. Data filtering.	Increases data reliability, credibility for policy use, and reduces bias. Verification, outlier detection.	Contributes to national statistics and supports evidence-based decision-making.	[29,32,50,54,55,59,75]
Data Management and Sharing	Use common databases (e.g., TIDES, EMODnet, AMDI, Rydde) and open data platforms for data collection, storage, and access. Promote FAIR data principles.	Facilitates data integration from multiple sources, allowing for broader analysis, transparency, and reusability.	Supports SDG reporting, global policy initiatives (e.g., the UN Plastic Treaty), cross-border collaborations, and scientific advancements.	[29,31,49,53,77]
Technological Integration	Leverage mobile apps for data collection, AI for image analysis, and GIS for mapping and spatial analysis. Develop user-friendly digital tools.	Enhances data collection efficiency, accuracy, and spatial/temporal coverage. Increases engagement and streamlines submission.	Scalability, wider reach, real-time data availability, improved user experience, and data visualization.	[13,33–35,43,45,77,79,104]
Engagement and Awareness	Design projects to actively engage the public and enhance environmental awareness.	(Indirectly by increasing data quantity and quality through motivated volunteers)	Increased public participation, behavioral change (implied), and support for conservation actions.	[36,45,53,64]
Policy Relevance and Application	Design CS projects with clear pathways to inform policy and management decisions.	Provides evidence for policy effectiveness (e.g., FFL, plastic reduction measures), supports SDG reporting, and informs strategic planning.	Enables evidence-based policymaking, collaborative governance, and public support for measures.	[29,36,38,52,64]
Policy and Management Relevance	Design projects to inform policy, management actions, and international agreements (e.g., UN Plastic Treaty, SDG reporting). Collaborate with policymakers.	Provides evidence for policy effectiveness, identifies pollution sources and hotspots for targeted action, and supports national/international reporting.	Facilitates evidence-based decisions-developseffective mitigation strategies, and supports advocacy.	[29,38,40,52–54,86,97]
Ethical Considerations and Inclusivity	Ensure ethical data handling, privacy, and promote diverse, inclusive participation, including marginalized groups.	Enhances fairness and equity in scientific participation. Builds trust.	Broader societal impact, more representative data, and empowerment of diverse communities	[77,85,98]
Methodology Adaptation and Innovation	Develop and test novel, cost-effective sampling methods suitable for citizen science (e.g., paddle trawl).	Allows sampling in new environments/contexts, with data comparable to traditional methods.	Increases accessibility of research, broadens participation.	[45,102]

Table 2. *Cont.*

Category (Project Phase)	Best Practice Statement	Evidence of Enhancing Scientific Validity	Evidence of Enhancing Broader Impact	Key References
Methodological Rigor and Adaptation	Employ rigorous sampling designs like zonal sampling, transects, or control sites, adapting methods to local contexts while maintaining standardization.	Increases robustness of findings, allows for detailed spatial/temporal analysis, and improves comparability if core elements are standardized.	More reliable scientific outputs, better understanding of pollution dynamics.	[47,50,51,55,56,68,105]
Community Engagement and Feedback	Foster ongoing communication, give feedback to volunteers, and build a sense of community and ownership. Involve participants in different stages of the project.	Increases motivation, retention, and data quality. Leads to the co-creation of knowledge.	Builds trust, empowers communities, fosters environmental stewardship, and enhances project sustainability.	[84,86,87,89–91,95,98,100]
Collaboration and Networking	Promote collaborations between research institutions, CSOs, government agencies, schools, and international bodies.	Leverages expertise and resources, enhances data harmonization, and increases project impact and reach.	Strengthens the CS community, supports larger-scale initiatives (e.g., global treaties), facilitates knowledge sharing	[21,29,49,84,86,98]

5. Persistent Challenges, Biases, and Research Gaps in Citizen Science for Plastic Pollution

While citizen science has become an important tool for monitoring plastic pollution, the existing literature highlights significant and persistent gaps, challenges, and potential biases that need to be recognized and addressed (Figure 2, Table 3). These barriers affect every stage of the project, including design methods, data collection, volunteer participation, and the use of the data. A thorough assessment of these challenges is crucial for enhancing the quality, reliability, and impact of future citizen science efforts, as well as for understanding the limitations of current methods and datasets.

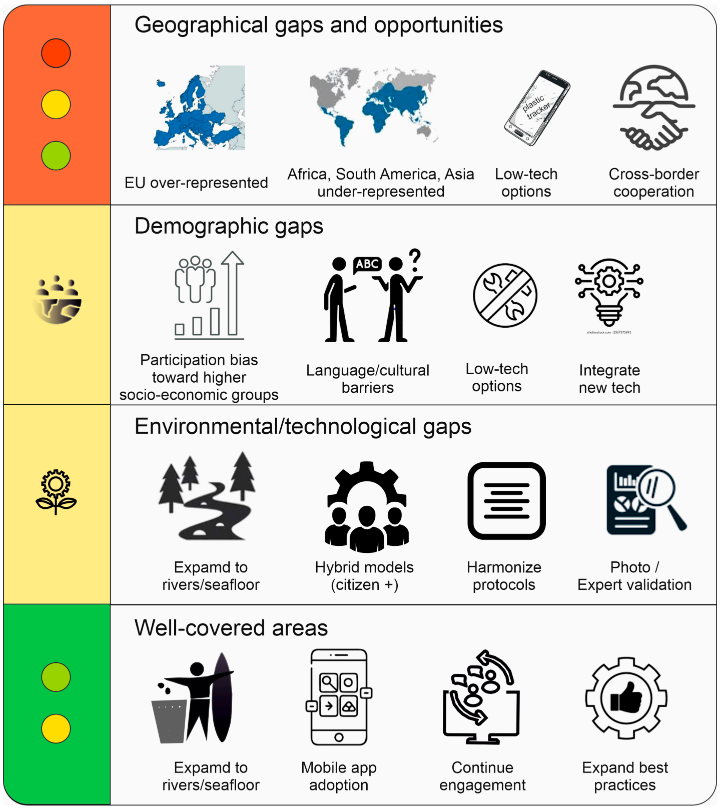

Figure 2. Identified Gaps and Opportunities in Citizen Science for Plastic Pollution.

The gaps identified across the 84 studies include:

- Methodological issues, like inconsistent protocols and interoperability problems.
- Data quality challenges due to volunteer differences and analytical limitations.
- Imbalances in geography and demographics in study participation.
- Technological barriers affecting accessibility and scalability.
- Limited integration of citizen science data into policy frameworks.

This review constitutes the evidence-based foundation for the subsequent sections, which examine methodological, social, and policy challenges associated with utilizing citizen science to monitor plastic pollution.

5.1. Challenges in Data Quality and Methodological Standardization

Maintaining consistent, high-quality data is one of the biggest ongoing challenges in citizen science efforts to monitor plastic pollution. Variations in observer skills, survey durations, and effort levels often complicate the comparison of data across different sites [58,60]. For example, volunteers might unintentionally focus more on large, colorful, or easily identifiable items, while missing smaller, transparent, or weathered debris, which can cause a systematic undercount [58]. Even experienced "super-users" find it hard to distinguish certain categories, like rope or soft plastics, which hampers source identification [60]. These issues add noise to the data, potentially hiding true environmental changes if not properly addressed through careful planning and validation [84,95].

Variability in volunteer training and protocol standardization had a significant impact on the quality of the data. Projects without standardized transect areas or harmonized item lists generated less comparable datasets. In contrast, initiatives that implemented updated ICC, OSPAR, or UNEP guidelines demonstrated notable enhancements in reliability and reproducibility [12,29].

In addition to individual performance challenges, the absence of standardization across projects remains a barrier to data interoperability [84]. Different sampling techniques, survey schedules, and classification systems limit the integration of data. Additionally, fragmented platforms and mobile applications create isolated silos [31,77]. These problems hinder regional and global comparisons, making it more difficult to align citizen science results with formal monitoring and policy frameworks, such as EPR regulations or SDG indicators [29,97].

Across the reviewed studies, this challenge was the most commonly reported, appearing in over half of the cases. Some authors believe that variability is unavoidable in volunteer-based monitoring, while others emphasize that using harmonized protocols can greatly reduce these issues. We believe that achieving comparability and interoperability is the most urgent methodological challenge. Projects that follow established international frameworks are best positioned to address this.

5.2. Biases

Citizen science methodologies inherently have limitations and potential biases. Studies involving institutional validation, such as Ghana's incorporation of citizen science beach litter data into SDG Indicator 14.1.1b, verified by the Ghana Statistical Service, demonstrate that external QA/QC procedures significantly enhance the validity and policy relevance of citizen science data [29]. Most land- and shore-based surveys concentrate solely on visible litter, which may not accurately represent the overall plastic contamination. This limited perspective can significantly underestimate the total plastic burden, as debris that is buried, submerged, or entangled is frequently overlooked, as mentioned by different authors [68,96].

Another concern is site selection bias, as surveys often occur in easily accessible locations, such as public beaches or parks, which may not represent broader environments or critical pollution hotspots [84]. This convenience sampling method distorts the data, often resulting in an overrepresentation of recreational litter while underrepresenting pollution from less frequented sites, including industrial coastlines, fishing zones, or areas affected by illegal dumping [33,84]. Although specific protocols, such as COASST, attempt to broaden search areas by incorporating wrack and wood lines [68], these methodologies are not consistently applied, leading to discrepancies and gaps within the data. In some projects, opportunistic or convenience sampling was frequently used, which limited the representativeness and increased site-specific biases. As a result, the findings of these studies should be viewed as exploratory baselines [61]. In contrast, conclusions drawn from standardized, quality-controlled monitoring efforts offer more robust evidence to guide best practices and policy decisions [29].

Biases were mentioned in at least one-third of the studies, though not always consistently. There is debate over whether biases critically undermine the usefulness of citizen science. Some believe that biases render data unsuitable for regulation, while others suggest that they can be mitigated through robust sampling and validation. We consider site-selection bias and the underestimation of hidden plastics as the most significant limitations, as they directly impact the ecological representativeness of the datasets.

5.3. Volunteer Engagement and Project Sustainability

Maintaining volunteer engagement in citizen science projects focused on plastic pollution remains a constant challenge. Despite widespread public concern about marine litter, this concern does not always lead to sustained participation. Tasks that are repetitive or require significant effort, like microplastic sorting, can cause fatigue [95]. Additionally, when volunteers perceive little action from authorities or industries, they may feel their efforts are ineffective, leading to discouragement [100]. Emotional factors such as frustration, pessimism, or eco-anxiety also diminish motivation and make retention more difficult [85]. Resource and funding limitations pose a significant threat to long-term sustainability. Many projects depend on short-term grants that do not guarantee continuity, making it challenging to develop ongoing, long-term monitoring programs essential for robust trend analysis and policy evaluation [84,97]. Limited human resources exacerbate the situation: small teams or individuals often handle coordination, data validation, and dissemination, even as datasets expand [33,77]. In microplastic research, the high laboratory processing costs remain a bottleneck, highlighting the importance of hybrid approaches where volunteers handle collection and expert labs perform analysis [47,50,95]. These expenses also restrict the number of samples that can be processed, lowering data density and limits the spatial and temporal resolution of citizen science monitoring.

Beyond resources and fatigue, continued participation relies on reciprocity and acknowledgment. When volunteers receive clear feedback on how their input is utilized, whether in scientific publications, management decisions, or policy development, they tend to stay engaged [84,98]. Conversely, if data are stored on inaccessible platforms or have little visible impact, enthusiasm tends to diminish. Co-designed strategies that consider volunteers as knowledge partners rather than mere data gatherers can enhance their sense of ownership. Additionally, recognition methods like authorship, certification, or inclusion in local decision-making can promote sustained commitment [86].

Approximately one-third of the reviewed papers focused on volunteer motivation and sustainability, particularly in projects involving repetitive tasks. While most agree that feedback and recognition are effective in retaining volunteers, their consistent implementation varies greatly. We believe that tackling funding insecurity and securing long-term institutional support are just as crucial as motivating volunteers, as both are essential for the long-term success of projects.

5.4. Methodological and Technological Constraints

Besides representational bias, citizen science projects face significant technical and technological challenges that limit accuracy and scalability. In microplastic research, the methods used are especially vulnerable to contamination from airborne fibers or sampling instruments, making it challenging to address this issue outside of controlled lab settings [42,47]. Additionally, water trawling surveys are influenced by the mesh size of nets, which determines the smallest particles that can be captured and may lead to the systematic exclusion of smaller microplastics, complicating comparisons between studies [45,47].

Riverine environments add even more complexity. In freshwater environments, dynamic factors such as changing flow rates, water levels, and turbidity make it challenging to obtain accurate snapshots of litter loads, as concentrations can vary rapidly and unpredictably [72,96]. Additionally, methodologies that depend on volunteers to identify the origin of litter visually introduce a subjective element, as it can be difficult to accurately determine if an object came from nearby or was carried from far away, or to definitively link it to specific activities like tourism or fishing, as observed by [70]. It is essential to report these methodological details so that limitations can be recognized and taken into account when analyzing the data.

Citizen science methods for microplastics face ongoing analytical challenges. Risks of contamination during sampling, mesh-size limits of trawls, and difficulties in polymer identification lead to trade-offs between scale and accuracy, even in well-designed projects [42,45,47]. Hybrid strategies, where volunteers collect samples and experts analyze them in laboratories, can reduce some problems but are still resource- and time-demanding [50,63]. Natural fibers are often mistaken for plastics, thereby inflating reported amounts [42], while small or degraded particles frequently go undetected without the use of advanced spectroscopy [63] (see Figure 3). These methodological challenges limit the comparability between studies and impede the potential for long-term citizen science monitoring.

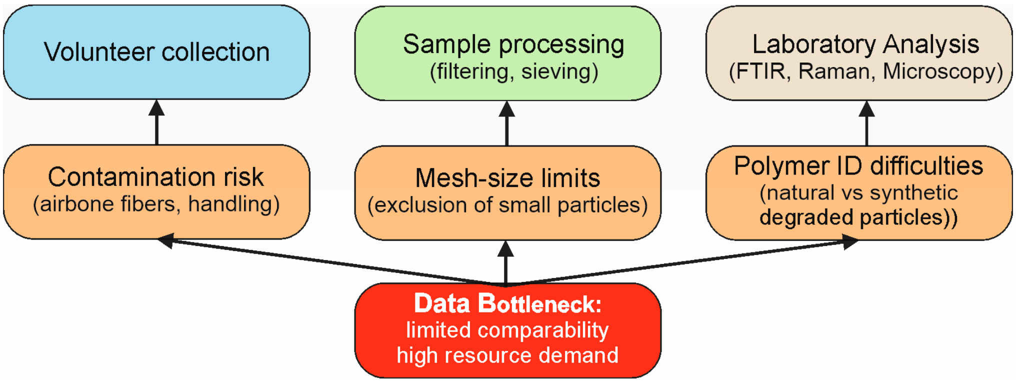

Figure 3. The Microplastic Analytical Bottleneck: Challenges in sampling, processing, and analysis, like contamination, size limits, misidentification, and reliance on advanced equipment, create a data bottleneck that limits comparability, scalability, and usability in citizen science.

Digital platforms have expanded participation but also created new forms of exclusion. Although mobile apps make reporting easier, issues such as technical glitches, limited offline options, and dependence on smartphones exclude those without reliable connectivity or access to smartphones [33,77]. This can reinforce demographic biases and reduce overall inclusivity. Moreover, relying solely on digital reporting may alienate participants less familiar with technology, emphasizing the importance of offering alternative, non-digital submission methods [33].

Beyond mere participation, ongoing governance issues continue to hinder technological adoption. Issues related to ownership, privacy, and consent are often inconsistent across different projects, especially concerning geolocation data [77]. Therefore, transparent communication and well-defined governance frameworks are essential to retain trust. Without these safeguards, technological advancements risk reducing engagement, particularly among communities that are already underrepresented in global monitoring initiatives.

Approximately one-quarter of the studies identified these technical challenges, primarily related to the monitoring of microplastics. While hybrid methods are widely recognized for enhancing accuracy, their high costs and resource needs remain obstacles. Digital tools increased participation but raised concerns about excluding some users. We believe that creating affordable, standardized hybrid techniques paired with inclusive digital platforms offers the best chance to address these issues effectively.

5.5. Geographical and Demographical Gaps

Citizen science has significantly expanded the geographic scope of monitoring plastic pollution; however, notable geographic and demographic disparities still exist, limiting the global representativeness and inclusivity of the results. Many citizen science studies on plastic pollution mainly focus on Europe and North America, resulting in a significant bias that neglects regions in the Global South, including Africa, South America, and Asia. These areas face serious challenges related to plastic pollution and waste management [31,33,49,58,105]. Initiatives such as COLLECT have aimed to bridge these gaps by involving citizen scientists from underrepresented African countries and Malaysia, using multilingual resources to improve accessibility and data collection [27,49,85]. Such initiatives are essential for building a more equitable global dataset, as the current dominance of wealthy countries skews our understanding of plastic pollution distribution and impedes effective worldwide mitigation strategies [106–108].

As mentioned, environmental coverage remains inconsistent, focusing on easily accessible coastal beaches, while other essential ecosystems receive significantly less attention. Freshwater systems, which serve as primary pathways for terrestrial plastics entering marine environments, are rarely monitored, despite initiatives like “Plastic Pirates” and “Clean Rivers” beginning to address this gap [55,62,96]. Similarly, the water column, seafloor, and urban hotspots are still underexplored because of logistical challenges and limited resources [33,37,45,82]. Demographic inclusivity remains a challenge. Participants often come from socioeconomically privileged and digitally literate backgrounds, leading to the underrepresentation of marginalized communities [85,95]. Reliance on smartphones and online platforms further exacerbates the digital divide, excluding those without proper access to devices or the internet [33,77,84]. Additional obstacles, such as language barriers, cultural communication styles, and distrust toward institutions, further exacerbate this gap [86]. As a result, datasets may miss traditional knowledge and diverse perspectives, weakening the fairness and social legitimacy of environmental policies.

The persistent underrepresentation of the Global South in citizen science projects addressing plastic pollution arises from various structural challenges. Limited funding and research infrastructure impede the development of ongoing monitoring efforts, while digital disparities and language biases in protocols and publications restrict participation. Moreover, global frameworks and journals are often dominated by institutions from the Global North, thereby marginalizing locally relevant approaches and reducing the visibility of contributions from the Global South. Case studies highlight both challenges and solutions. For instance, the COLLECT initiative [49] demonstrates that low-cost, co-created methods and community-led data systems are essential for sustaining engagement, as they align with local capacities and governance. Similarly, integrating citizen science data into Ghana’s SDG 14.1.1b reporting demonstrates how linking grassroots monitoring with national statistics can enhance data credibility and policy influence [29]. Moving forward, narrowing the participation gap requires more than outreach; it necessitates investing in capacity building and training, translating protocols and apps into local languages, fostering South–South collaborations to share suitable methods, and establishing mechanisms to ensure that citizen science results inform local and national management actions. These measures can enhance representation and ensure that the source-to-sea perspective accurately reflects the diversity of global pollution contexts. In addition, proactive outreach and collaborative project design with diverse communities are essential to tackling these issues, as demonstrated by partnerships with frontline sanitation workers to foster inclusive participation and improve equitable environmental management [98].

Geographical imbalances were among the most commonly recognized gaps, appearing in nearly half of the studies. There is a broad consensus on the need to expand coverage in the Global South and in less-studied areas, such as rivers and the seafloor. However, only a few initiatives, such as COLLECT, offer practical solutions. We believe that investing in capacity building, multilingual resources, and South–South collaborations is essential for tackling this inequality. Without these efforts, global citizen science could potentially reinforce existing knowledge gaps instead of bridging them.

5.6. Challenges in Policy Integration and Impact Assessment

Although citizen science produces large datasets, decision-makers often discuss the scientific credibility and policy relevance of citizen science data, requiring established quality assurance and control measures before trusting the information collected by volunteers [84]. Misalignments between citizen science categories and regulatory definitions further complicate their use in governance. For example, mismatched litter classifications hindered the evaluation of Canadian Extended Producer Responsibility schemes [97]. More broadly, adapting volunteer-collected data to meet legal frameworks or international reporting requirements, such as the Sustainable Development Goals (SDGs), usually requires significant top-down coordination and evidence of policy readiness [29,59].

Additionally, the processes for integrating citizen-generated data into governance frameworks are still underdeveloped. Without ongoing collaboration and co-design with policymakers, these valuable datasets may be excluded from official decision-making processes [86]. Significant examples from Ghana and Australia underscore the importance of establishing long-term partnerships with organizations, such as national statistical offices, to integrate citizen science into an integral part of environmental monitoring [29,59].

Beyond technical alignment, institutional pathways for adoption are insufficiently developed. Absent co-design and ongoing collaboration among researchers, NGOs, and policymakers, citizen science datasets face the risk of exclusion from decision-making processes [86]. Integrating projects into existing governance frameworks—such as national statistical offices or protected-area management plans—seems to be a vital condition for guaranteeing long-term policy relevance.

At the same time, assessing the social impacts of citizen science remains methodologically difficult. While many projects aim to increase awareness or promote behavioral change, most evaluations depend on short-term, self-reported surveys that can be biased [85,88]. Evidence of lasting changes in environmental behavior or empowerment is limited; for example, studies of Danish schoolchildren showed minimal long-term effects on risk perception despite active participation [86]. Without strong social impact evaluation frameworks, a key benefit of citizen science may be undervalued in policy discussions [87,90].

For example, in Ghana, citizen science beach litter data, verified by the Ghana Statistical Service, was incorporated into SDG 14.1.1b reporting, showing how aligning with national frameworks helps grassroots data inform global indicators [29]. In Australia, citizen science marine debris surveys are integrated into marine park management through partnerships with NGOs, universities, and government agencies, which have established common data standards to ensure regulatory compatibility [59]. These cases demonstrate that transforming citizen science data into policy necessitates not only data collection but also validation, standardization, and stakeholder collaboration to ensure credibility and adoption. To effectively implement policies and evaluate their impact, it is essential to ensure transparent data validation, conformity with legal standards, established governance frameworks, and thorough evaluation of societal outcomes. Implementing these measures maximizes the effectiveness of citizen science in fighting plastic pollution and enhancing environmental governance across various sectors.

This issue has been less frequently addressed in studies compared to methodological challenges, but it remains essential for unlocking the full potential of citizen science. While it is widely agreed that validation and alignment with official frameworks enhance credibility, there is ongoing debate about whether citizen science can fully meet all regulatory standards. We identify this as a crucial strategic gap: without effective policy integration, even top-tier data might have limited practical influence. The most effective strategies involve closer collaboration with policymakers in co-design and thorough assessment of societal impacts.

Table 3. Gaps and opportunities in citizen science for plastic pollution.

Gap/Challenge—Bias Area	Concise Description of the Issue	Impact on Global Potential and Policy Relevance	Potential Research Directions—Proposed Solutions	Key References
Data Quality and Reliability	Variability in volunteer effort, skill, and motivation; observer bias (e.g., in visual estimations, identifying small/transparent items, distinguishing sources); errors in identification, categorization, and counting; inconsistent data collection due to varying protocols or adherence.	Undermines data credibility and scientific rigor; hinders comparability across studies/regions; affects reliability for robust trend analysis, SDG reporting, and policy decisions; may lead to underestimation or overestimation of pollution levels and types.	Rigorous training, clear protocols, photo verification, expert validation (e.g., by national statistical services), data filtering algorithms, standardized data sheets/apps (e.g., Clean Swell, Litterati, Marine Debris Tracker), inter-calibration exercises, automated QA/QC in apps, use of "super-users", comparing with professional data, providing feedback to volunteers.	[31,33,52,55,58,60,63,66–69,84,95,99,100]
Standardization and Interoperability	Lack of standardized protocols for data collection (e.g., survey length, item categorization), units of measurement, and data reporting formats. Difficulty comparing or aggregating data from diverse CS projects and with official monitoring programs.	Limits large-scale analyses, trend assessments, SDG reporting efficacy, and policy integration. Prevents robust evaluation of mitigation strategy effectiveness across different contexts. Affects data harmonization and reusability.	Develop/promote of common core protocols (e.g., MSFD, OSPAR, ICC guidelines); create data dictionaries/ontologies; use interoperable platforms and open standards (FAIR principles); data harmonization efforts; condense categories for comparison; establish minimum data standards.	[21,29,31,34,54,65,66,77,84,95,97]
Volunteer Engagement, Motivation and Retention	Difficulty in recruiting participants, maintaining motivation, and ensuring long-term retention, especially for repetitive tasks or projects requiring significant commitment. Volunteer fatigue and high dropout rates.	Inconsistent data collection; limited coverage; incomplete datasets; projects failing to achieve long-term scientific or monitoring goals; potential for sampling bias if certain groups are less engaged.	Communicate project goals and societal impact; provide regular feedback and share results; foster a sense of community and ownership; offer diverse and flexible engagement strategies (digital/in-person); make tasks engaging (gamification, story writing); understand and cater to volunteer motivations (activism, learning, social interaction); co-design projects.	[24,33,52,84,95]
Methodological Limitations and Biases	Inherent limitations of specific methods (e.g., visual surveys missing buried/small items, nets not capturing all particle sizes, app data biased by user behavior). Site selection bias (convenience sampling, focus on accessible/popular areas). Effort variability. Challenges in accurate source attribution and quantifying rapidly changing litter loads.	Can result in an incomplete or skewed understanding of the extent, composition, sources, and fate of pollution. Limits the generalizability of findings and the accuracy of impact assessments. Underestimation of total litter or specific types.	Combine multiple methods (triangulation); develop/refine protocols for specific targets and environments; implement random or stratified sampling designs; rigorous volunteer training; cross-validation with other data sources (e.g., professional surveys, remote sensing); detailed source categorization protocols; normalization for effort.	[32,33,36,40,47,52,55,61,63,68,69,96,99]
Technological Challenges and Digital Divide	Issues with app usability, design flaws, registration barriers, accessibility across different devices/OS, and offline functionality. GPS inaccuracies. Reliance on participant-owned technology (smartphones) can exclude certain demographics. Data privacy concerns. Low-quality image submissions are affecting AI model performance.	Limits participation and data quantity/quality; introduces data errors; hinders scalability and broader adoption; raises ethical issues on data ownership and use; can create or exacerbate digital inequalities.	User-centered app design and testing; enable offline access; offer non-digital data submission options; ensure clear data privacy policies; provide image quality guidance for AI; collaborate with platform providers for UX improvements; consider open-source tools.	[33,34,43,77,79,81,104]

Table 3. *Cont.*

Gap/Challenge—Bias Area	Concise Description of the Issue	Impact on Global Potential and Policy Relevance	Potential Research Directions—Proposed Solutions	Key References
Policy Uptake and Impact Realization	Difficulty translating CS data into policy due to gaps between data generation and use, with CS data often seen as uncredible for official reporting or policy evaluation and not always meeting legal or regulatory needs.	Reduces the potential of CS to contribute to tangible environmental improvements and policy changes, as well as delays in addressing pollution. Additionally, data may not align with the specific information needs of decision-makers (e.g., EPR evaluations).	Co-design projects with policymakers and end-users from the outset; align data collection with policy needs (e.g., SDG indicators, specific directives); ensure robust QA/QC and transparent methodologies; clearly communicate results, limitations, and policy relevance; advocate for formal inclusion of CS data in monitoring frameworks; develop specific data frameworks for policy assessment.	[29,36,52,86,95,97,109,110]
Geographical and Ecosystem Coverage Gaps	Significant underrepresentation of specific geographical regions (e.g., Global South, remote areas), and various ecosystems (e.g., deep sea, freshwater systems like smaller streams, urban drains, specific habitats within urban areas). Focus often on easily accessible beaches.	Leads to an incomplete and potentially biased understanding of plastic pollution at the global and regional levels. Policy responses may not address critical but understudied sources, pathways, or accumulation zones.	Strategically target under-sampled regions/ecosystems; adapt or develop methodologies suitable for challenging environments (e.g., low-cost trawls, remote sensing integration); foster international collaborations and capacity building; engage local communities in remote areas.	[42,45,49,52,54,68,82,84,96,100,105]
Funding, Resources and Project Sustainability	CS projects often face challenges in securing sustainable, long-term funding, which impacts the continuity of monitoring, coordination, training, data management, analysis, and dissemination. Limited resources for advanced tools or personnel.	Prevents long-term monitoring and trend analysis, resulting in the loss of valuable longitudinal datasets. Projects may end prematurely, limiting scientific output and policy impact, and hindering the development and maintenance of infrastructure.	Diversify funding sources (government grants, private foundations, corporate sponsorship, crowdfunding); build strong institutional partnerships; advocate for integration of CS into statutory monitoring programs; develop low-cost, sustainable methodologies and open-source tools; and social enterprise models.	[38,84,95,98]
Participant Demographics and Inclusivity	CS projects may predominantly attract participants from specific demographics (e.g., higher education levels, particular age groups), potentially excluding marginalized communities, those with less digital literacy, or those from diverse cultural and socio-economic backgrounds.	This can lead to skewed perceptions of public concern and priorities, as solutions may not be representative or equitable. It also limits the diversity of knowledge and perspectives incorporated, and data may not accurately reflect the experiences of all affected populations.	Implement targeted outreach and recruitment strategies for underrepresented groups; co-design projects to be culturally relevant and accessible; offer various modes of participation (low-tech/no-tech options); provide multilingual resources and support; collaborate with community leaders and trusted organizations (e.g., frontline sanitation workers).	[62,84–86,98]
Evaluation of Broader Impacts (Social, Educational, Behavioral)	Difficulty in rigorously and systematically assessing the broader impacts of citizen science projects, such as changes in environmental awareness, attitudes, pro-environmental behaviors, scientific literacy, empowerment, social capital, and well-being.	Underestimation of the full value and societal benefits of Citizen Science makes it harder to justify funding/support. Missed opportunities to optimize projects for these outcomes and understand mechanisms of change.	Develop and apply robust, mixed-methods evaluation frameworks; conduct longitudinal studies with pre- and post-assessments and control groups where feasible; collaborate with social scientists; utilize standardized scales for psychological and behavioral constructs; and assess changes in scientific literacy and civic engagement.	[24,85,87–90,95]

Table 3. *Cont.*

Gap/Challenge—Bias Area	Concise Description of the Issue	Impact on Global Potential and Policy Relevance	Potential Research Directions—Proposed Solutions	Key References
Microplastic Analysis and Identification	Laboratory analysis of microplastics (<1 mm) is complex, costly, and time-consuming, requiring specialized equipment and expertise. It is highly prone to contamination, challenging for citizen science-led or large-scale citizen science data processing.	Limits the scale, frequency, and accessibility of reliable microplastic monitoring by citizen science. Data is often restricted to larger, visible microplastics or relies on visual identification, which can be inaccurate. High potential for variability and contamination affects data reliability and comparability.	Develop and validate low-cost, field-friendly screening/identification methods (e.g., Nile Red staining); establish tiered approaches (CS for sample collection, expert labs for detailed analysis); conduct inter-laboratory comparisons and proficiency testing; provide rigorous training on contamination prevention; simplify protocols; and utilize AI for image-based identification.	[42,45,47–50,55,63]
Long-Term Monitoring, Sustainability and Impact Assessment	Difficulty in establishing long-term monitoring programs to track plastic pollution, assess intervention effectiveness (e.g., policy, cleanup), and evaluate ecological or behavioral impacts.	Limits understanding of pollution dynamics over extended periods, the effectiveness of long-term interventions, and adaptive management needs. Hinders robust evaluation of progress towards long-term environmental goals and policy effectiveness.	Secure sustainable, long-term funding; integrate citizen science into monitoring frameworks; establish permanent monitoring sites/networks; ensure consistent methodologies over time; design projects with longitudinal evaluation; develop clear indicators for long-term impact.	[24,33,58,67,68,97,105]
Communication, Data Visualization and Dissemination	Challenges in communicating complex scientific findings from citizen science projects to diverse audiences in an accessible, understandable, and impactful manner. Difficulties in visualizing large, heterogeneous datasets.	Citizen science data may be underutilized or misunderstood, reducing its potential impact. Risk of misinterpretation by the media or the public. Important findings may not reach or resonate with key stakeholders or communities.	Develop tailored communication strategies and materials for different audiences; utilize effective data visualization tools (interactive maps, dashboards, infographics); create compelling narratives and story maps; involve communication experts; foster two-way dialog and co-interpretation of results.	[13,56,77,84,86,95]

6. Discussion

Citizen science has become an essential tool for monitoring plastic pollution, allowing the collection of extensive datasets across broad spatial and temporal scales. Although it cannot replace traditional scientific monitoring, it can serve as a significant complement to it. Based on approximately 80 papers, this review demonstrates that the actual scientific and policy significance of these initiatives relies on standardized methods and robust quality assurance. Projects that follow internationally recognized frameworks, such as OSPAR, MSFD, or ICC guidelines [29,65] are better positioned to generate comparable, policy-relevant data. Methodological inconsistency remains a significant challenge [84], especially in multinational projects, underscoring the need for unified data dictionaries and standardized protocols that combine local flexibility with essential comparability.

Methodological inconsistency was the most common challenge across the studies, reported in over half of the cases. While some researchers consider variability as unavoidable in volunteer-based monitoring, others argue that standardized protocols can significantly mitigate such issues. We believe that the most significant methodological obstacle is ensuring comparability and interoperability, and projects adhering to international frameworks are best positioned to overcome this. Additionally, several studies stress that citizen science cannot entirely replace traditional long-term monitoring, especially in regulatory settings requiring legally defensible data. Instead, it should be seen as a complementary, scalable approach to extend coverage and increase public participation.

A primary theme is the ongoing effort to improve data accuracy and scientific rigor. A tiered, proactive Quality Assurance/Quality Control (QA/QC) system is vital for maintaining data credibility. This involves comprehensive training for volunteers, pilot testing, providing user-friendly digital tools [95], mandatory photo documentation for expert review [56], and systematic use of control samples, especially for microplastics [21,51]. Hybrid monitoring models, where citizen scientists focus on scalable sample collection while professional laboratories perform complex analyses [50], offer a practical solution for technically challenging monitoring, ensuring both scalability and scientific accuracy. Evidence from various studies suggests that training consistently improves data quality, although its impact tends to diminish over time unless refreshed. Therefore, repeated training emerges as a cost-effective best practice. Likewise, approximately 25% of studies reported using hybrid approaches, which are widely regarded as one of the most effective strategies for combining inclusivity with analytical precision. This aligns with the vision described in a review [111], which emphasizes the shift from basic data collection to the production of high-quality, scientifically suitable data suitable for complex modeling and management strategies. However, the high costs of laboratory analyses limit the number of samples, reduce data density, and constrain spatial and temporal resolution. Sustainable funding and cost-effective hybrid approaches are essential for maintaining robust and representative data.

Furthermore, the rapid progress of technology has transformed citizen science by enhancing scale, efficiency, and innovation. Smartphone applications, such as Marine Debris Tracker, Litterati, ML2, and Pirika [13,34,69,80], have simplified data collection and management. Meanwhile, advancements in AI and remote sensing integration are expected to generate even greater improvements [34,81,92,112]. A recent review [113] reinforces this perspective, positioning technological solutions as one of the three fundamental pillars in addressing microplastic pollution in Malaysia. However, dependence on digital tools introduces new challenges. The “digital divide” can systematically exclude less tech-savvy or lower-income individuals [77,84], potentially skewing data and reducing inclusivity. Usability issues, as seen with the Jetsam app [33], and concerns about data privacy and ownership [77] further complicate the situation. Digital technologies were acknowledged in approximately 25% of studies for enhancing participation. However, their potential to induce exclusion was also recognized. Developing affordable, standardized hybrid methods with inclusive digital platforms is the most effective way to expand outreach and mitigate increasing inequalities.

While citizen science efforts generate large datasets and public engagement, systematic pathways to formal policy adoption remain limited. Greater co-design of monitoring frameworks with policymakers, including consultations during early project phases and explicit alignment with regulatory data requirements, would enhance the policy relevance of citizen-generated data. Successful examples from Ghana and Australia suggest that integrating citizen science into statutory monitoring and maintaining dialog with national agencies builds credibility and facilitates the translation of observations into concrete management actions.

Only a small number of studies explicitly focus on policy integration; however, without these connections, even high-quality data may not have an impact. While it is widely agreed that validation and alignment with official frameworks increase credibility, there is debate about whether citizen science can fully meet all regulatory standards. We consider policy integration as one of the most critical gaps. Enhanced co-design with policymakers and thorough evaluation of societal outcomes seem to be the most effective solutions.

Therefore, to maximize benefits and reduce drawbacks, projects should focus on tools that are user-friendly, multilingual, and capable of offline operation, while also providing ways for non-digital participation. Transparent data governance and ethical practices are essential for maintaining volunteers' confidence and ensuring equitable participation [86].

Furthermore, as digital methods become increasingly common, it is crucial to acknowledge the growing ethical debates surrounding data privacy, security, and fair access, particularly in low-resource or marginalized communities. Current research indicates that dependence on technology can increase privacy risks, particularly in areas where legal protections and digital literacy are limited. Future citizen science projects should prioritize robust, context-aware consent processes, adopt privacy-by-design principles, and ensure participation is accessible to individuals without digital devices. At the same time, new solutions such as blockchain and distributed ledger technology can provide ways to verify data securely and track its origin transparently. Although these technologies are still in the early stages of adoption for addressing plastic pollution, they deserve more attention as tools to build trust and prepare citizen-generated data for policy use.

Despite the large amount of data produced, an ongoing gap remains between citizen science outputs and their integration into environmental policy and management. The reliability of the data and its "fitness-for-purpose" present significant challenges, as policymakers often require thorough quality assurance and quality control (QA/QC), as well as compliance with legal and regulatory standards [84,97]. The effective integration of policies, as demonstrated by Sustainable Development Goal (SDG) reporting in Ghana and Australia, necessitates intentional, long-term collaboration among citizen science organizations, national statistical offices, and environmental agencies [29,59].

The need for stakeholder analysis and the formal integration of citizen science into international agreements, such as the UN Plastic Treaty [86], underscores the importance of establishing institutional pathways from the beginning. Therefore, projects should be designed with clear policy goals and collaborative structures to ensure that data is both scientifically rigorous and directly relevant to decision-makers. Transitioning from occasional data sharing to collaborative creation and sustained engagement with policy stakeholders is crucial for realizing the full potential of citizen science.

Perhaps the most important aspect of citizen science is its human aspect. These initiatives go beyond just collecting data; they act as catalysts for education, behavioral change, and community empowerment [87,90] (Figure 4). Engaging volunteers in practical environmental monitoring enhances scientific literacy, raises awareness, and motivates pro-environmental behaviors [89]. However, measuring these broader effects is challenging, often relying on self-reported data that may be subject to bias [24,88]. Long-term and interdisciplinary studies are necessary to fully assess the educational and behavioral outcomes of participation [62]. Keeping volunteers engaged requires investment in feedback mechanisms, community development, and activities designed for varied motivations [62,84,87]. Usually, volunteers are already highly motivated and interested in the results, so it is important that they receive feedback on their work. An appropriate acknowledgment is also very appreciated.

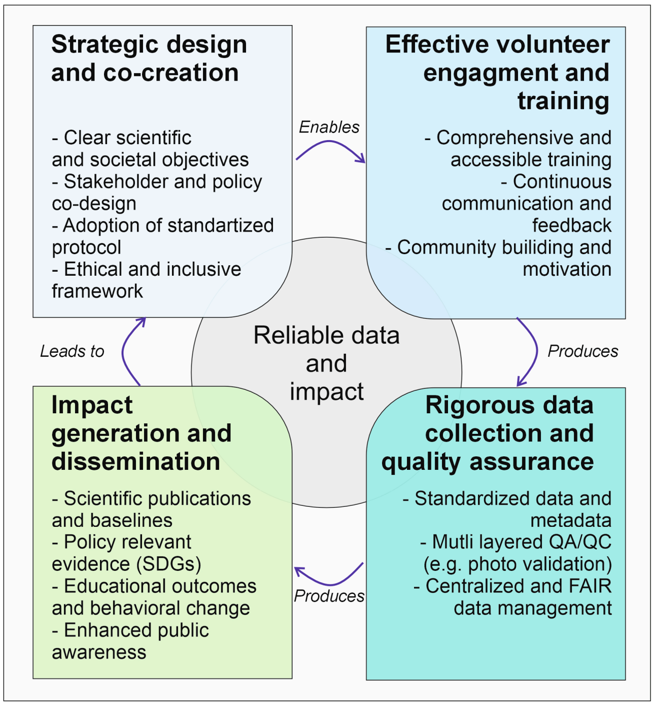

Figure 4. Best practices in citizen science.

Promoting inclusion and equity through the co-creation of projects with marginalized groups and addressing demographic gaps was mentioned in approximately one-quarter of the studies, suggesting that this area is still underdeveloped but holds great promise. Such measures not only diversify datasets but also strengthen the social legitimacy of citizen science. We consider this area to be one of the most important frontiers for enhancing both scientific robustness and ethical responsibility. Recognizing participants as valued partners rather than merely "sensors" is essential for unlocking the full transformative potential of citizen science.

Thus, recognizing participants as valued partners rather than merely "sensors" [111] is essential for unlocking the full transformative potential of citizen science.

Finally, to address the persistent gaps identified, we propose the following recommendations: (1) systematically focusing on underrepresented regions and ecosystems [49,55], (2) advancing research on methodologies and evaluations, including the development of low-cost, field-ready analytical tools [45], and (3) improving open data infrastructure and sustainable funding models [77,84,86]. Implementing these strategies can help citizen science become a strong, inclusive, and policy-relevant tool for addressing global plastic pollution.

7. Conclusions

This review systematically examines citizen science as a tool for monitoring plastic pollution, revealing a rapidly evolving and promising field. Citizen scientists use diverse and sophisticated methodologies, ranging from beach clean-ups to microplastic analyses. These initiatives expand data collection beyond traditional researcher efforts. By engaging the public, these projects generate essential data for science and policy, serving as catalysts for environmental education, behavioral change, and community management.

Our review confirms that the success and credibility of these projects depend on adhering to best practices, including meticulous project design with clear goals, standardized protocols, robust data quality assurance, and strong partnerships among citizens, scientists, and policymakers. The integration of technology, particularly mobile apps and data-sharing platforms, has significantly enhanced the efficiency and impact of these efforts.

While advancements have been made, notable challenges persist. The lack of universal standards hinders effective data comparison and synthesis. Variations in volunteer participation and methodological biases require continuous focus through training and validation. Additionally, gaps in geographical and demographic representation often disconnect data collection from successful policy integration. In specialized areas, such as microplastic monitoring, the high resource demands of laboratory analysis limit reliability, underscoring the need for a hybrid approach that combines citizen-led data collection with professional analysis.

The future of citizen science in combating plastic pollution requires direct action. Stakeholders must collaborate: project managers need rigorous QA/QC; researchers should address gaps and develop accessible technologies; funders and policymakers must ensure sustainable support and create data integration pathways. In transboundary contexts, harmonization and collaboration are essential for success.

Author Contributions: Conceptualization, all authors; formal analysis, C.C.; writing—original draft preparation, all authors; writing—review and editing, all authors; supervision, C.C.; project administration. M.C. and U.S.; funding acquisition, U.S. All authors have read and agreed to the published version of the manuscript.

Funding: This paper was supported by the IPA-ADRION Project 00140 AdriPLAST project, funded under the Interreg IPA ADRION 2021-2027 Programme, under Priority 2: "Supporting a greener and climate resilient Adriatic-Ionian region", Specific Objective SO 2.3: "Enhancing protection and preservation of nature, biodiversity and green infrastructure, including reducing pollution".

Acknowledgments: During the preparation of this manuscript, the authors utilized Grammarly (version 14.1247.0) for grammar checking, spelling correction, and enhancing the clarity of English language usage, as well as Zotero (version 7) for reference management and citation formatting. The authors have thoroughly reviewed and edited the output and assume full responsibility for the content of this publication.

Conflicts of Interest: Author Alexandre Lazarou was employed by the company Zanassi and Partners. The remaining 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.

References

1. Caruso, G.; Corsi, I.; Wu, C.; Bergami, E.; Corami, F.; Azevedo-Santos, V.M. Plastic pollution in marine and freshwater biota. *Water Biol. Secur.* **2024**, *3*, 100247. [CrossRef]
2. Azevedo-Santos, V.M.; Brito, M.F.G.; Manoel, P.S.; Perroca, J.F.; Rodrigues-Filho, J.L.; Paschoal, L.R.P.; Gonçalves, G.R.L.; Wolf, M.R.; Blettler, M.C.M.; Andrade, M.C.; et al. Plastic pollution: A focus on freshwater biodiversity. *Ambio* **2021**, *50*, 1313–1324. [CrossRef]
3. Gallo, F.; Fossi, C.; Weber, R.; Santillo, D.; Sousa, J.; Ingram, I.; Nadal, A.; Romano, D. Marine litter plastics and microplastics and their toxic chemicals components: The need for urgent preventive measures. *Environ. Sci. Eur.* **2018**, *30*, 13. [CrossRef]

4. Eriksen, M.; Lebreton, L.C.M.; Carson, H.S.; Thiel, M.; Moore, C.J.; Borerro, J.C.; Galgani, F.; Ryan, P.G.; Reisser, J. Plastic pollution in the world's oceans: More than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. *PLoS ONE* **2014**, *9*, e111913. [CrossRef] [PubMed]
5. Geyer, R.; Jambeck, J.R.; Lavender Law, K. Production, use, and fate of all plastics ever made. *Sci. Adv.* **2017**, *3*, e1700782. [CrossRef]
6. Gallagher, A.; Rees, A.; Rowe, R.; Stevens, J.; Wright, P. Microplastics in the Solent Estuarine Complex, UK: An initial assessment. *Mar. Pollut. Bull.* **2016**, *102*, 243–249. [CrossRef]
7. Rhodes, C.J. Solving the plastic problem: From cradle to grave, to reincarnation. *Sci. Prog.* **2019**, *102*, 218–248. [CrossRef] [PubMed]
8. Bošković, N.; Jaćimović, Ž.; Bajt, O. Microplastic pollution in rivers of the Adriatic Sea Basin in Montenegro: Impact on pollution of the Montenegrin coastline. *Sci. Total Environ.* **2023**, *905*, 167206. [CrossRef] [PubMed]
9. Stöfen-O'Brien, A. The prospects of an international treaty on plastic pollution. *Int. J. Mar. Coast. Law* **2022**, *37*, 727–740. [CrossRef]
10. Walker, T.R. (Micro)plastics and the UN Sustainable Development Goals. *Curr. Opin. Green Sustain. Chem.* **2021**, *30*, 100497. [CrossRef]
11. Denta, S.M. Preventing plastic pollution with a global plastic treaty and public-private partnership for the climate. *Eur. Procure. Public Priv. Partnersh. Law Rev.* **2022**, *17*, 211–220. [CrossRef]
12. United Nations Environment Programme (UNEP). *Zero Draft Text of the International Legally Binding Instrument on Plastic Pollution, Including in the Marine Environment (UNEP/PP/INC.3/1)*; UNEP: Nairobi, Kenya, 2023. Available online: https://wedocs.unep.org/handle/20.500.11822/43239 (accessed on 4 September 2025).
13. Jambeck, J.R.; Johnsen, K. Citizen-based litter and marine debris data collection and mapping. *Comput. Sci. Eng.* **2015**, *17*, 20–26. [CrossRef]
14. Andrady, A.L. Microplastics in the marine environment. *Mar. Pollut. Bull.* **2011**, *62*, 1596–1605. [CrossRef] [PubMed]
15. Derraik, J.G.B. The pollution of the marine environment by plastic debris: A review. *Mar. Pollut. Bull.* **2002**, *44*, 842–852. [CrossRef]
16. Tursi, A.; Baratta, M.; Easton, T.; Chatzisymeon, E.; Chidichimo, F.; De Biase, M.; De Filpo, G. Microplastics in aquatic systems, a comprehensive review: Origination, accumulation, impact, and removal technologies. *RSC Adv.* **2022**, *12*, 28318–28340. [CrossRef]
17. Bakir, A.; van der Lingen, C.D.; Preston-Whyte, F.; Bali, A.; Geja, Y.; Barry, J.; Mdazuka, Y.; Mooi, G.; Doran, D.; Tooley, F.; et al. Microplastics in commercially important small pelagic fish species from South Africa. *Front. Mar. Sci.* **2020**, *7*, 574663. [CrossRef]
18. O'Donovan, S.; Mestre, N.C.; Abel, S.; Fonseca, T.G.; Carteny, C.C.; Cormier, B.; Keiter, S.H.; Bebianno, M.J. Ecotoxicological effects of chemical contaminants adsorbed to microplastics in the clam *Scrobicularia plana*. *Front. Mar. Sci.* **2018**, *5*, 143. [CrossRef]
19. Maximenko, N.; Corradi, P.; Law, K.L.; Van Sebille, E.; Garaba, S.P.; Lampitt, R.S.; Galgani, F.; Martinez-Vicente, V.; Goddijn-Murphy, L.; Veiga, J.M.; et al. Toward the integrated marine debris observing system. *Front. Mar. Sci.* **2019**, *6*, 437. [CrossRef]
20. Soto-Navarro, J.; Jordà, G. Observational requirements for marine litter concentration characterization in the Mediterranean Sea. *Mar. Pollut. Bull.* **2025**, *211*, 117434. [CrossRef]
21. Zorzo, P.; Buceta, J.L.; Corredor, L.; López-Samaniego, I.; López-Samaniego, E. An approach to the integration of beach litter data from official monitoring programmes and citizen science. *Mar. Pollut. Bull.* **2021**, *173*, 112902. [CrossRef]
22. Bonney, R.; Cooper, C.B.; Dickinson, J.; Kelling, S.; Phillips, T.; Rosenberg, K.V.; Shirk, J. Citizen science: A developing tool for expanding science knowledge and scientific literacy. *BioScience* **2009**, *59*, 977–984. [CrossRef]
23. Shirk, J.L.; Ballard, H.L.; Wilderman, C.C.; Phillips, T.; Wiggins, A.; Jordan, R.; McCallie, E.; Minarchek, M.; Lewenstein, B.V.; Krasny, M.E.; et al. Public participation in scientific research: A framework for deliberate design. *Ecol. Soc.* **2012**, *17*, 29. [CrossRef]
24. Oturai, N.G.; Pahl, S.; Syberg, K. How can we test plastic pollution perceptions and behavior? A feasibility study with Danish children participating in 'the Mass Experiment'. *Sci. Total Environ.* **2022**, *806*, 150914. [CrossRef]
25. Dalby, O.; Sinha, I.; Unsworth, R.K.F.; McKenzie, L.J.; Jones, B.L.; Cullen-Unsworth, L.C. Citizen science driven big data collection requires improved and inclusive societal engagement. *Front. Mar. Sci.* **2021**, *8*, 610397. [CrossRef]
26. Theobald, E.J.; Ettinger, A.K.; Burgess, H.K.; DeBey, L.B.; Schmidt, N.R.; Froehlich, H.E.; Wagner, C.; HilleRisLambers, J.; Tewksbury, J.; Harsch, M.; et al. Global change and local solutions: Tapping the unrealized potential of citizen science for biodiversity research. *Biol. Conserv.* **2015**, *181*, 236–244. [CrossRef]
27. Kawabe, L.A.; Ghilardi-Lopes, N.P.; Turra, A.; Wyles, K.J. Citizen science in marine litter research: A review. *Mar. Pollut. Bull.* **2022**, *182*, 114011. [CrossRef] [PubMed]
28. Popa, C.L.; Dontu, S.I.; Savastru, D.; Carstea, E.M. Role of citizen scientists in environmental plastic litter research—A systematic review. *Sustainability* **2022**, *14*, 13265. [CrossRef]
29. Fraisl, D.; See, L.; Bowers, R.; Seidu, O.; Fredua, K.B.; Bowser, A.; Meloche, M.; Weller, S.; Amaglo-Kobla, T.; Ghafari, D.; et al. The contributions of citizen science to SDG monitoring and reporting on marine plastics. *Sustain. Sci.* **2023**, *18*, 2629–2647. [CrossRef]
30. Wyles, K.J.; Pahl, S.; Holland, M.; Thompson, R.C. Can beach cleans do more than clean-up litter? Comparing beach cleans to other coastal activities. *Environ. Behav.* **2017**, *49*, 509–535. [CrossRef]

31. Falk-Andersson, J.; Berkhout, B.W.; Abate, T.G. Citizen science for better management: Lessons learned from three Norwegian beach litter data sets. *Mar. Pollut. Bull.* **2019**, *138*, 364–375. [CrossRef]
32. Yen, N.; Hu, C.-S.; Chiu, C.-C.; Walther, B.A. Quantity and type of coastal debris pollution in Taiwan: A rapid assessment with trained citizen scientists using a visual estimation method. *Sci. Total Environ.* **2022**, *822*, 153584. [CrossRef] [PubMed]
33. Winton, S.; Roberts, K.P.; Bowyer, C.; Fletcher, S. Harnessing citizen science to tackle urban-sourced ocean plastic pollution: Experiences and lessons learned from implementing city-wide surveys of plastic litter. *Mar. Pollut. Bull.* **2023**, *192*, 115116. [CrossRef]
34. Kako, S.; Muroya, R.; Matsuoka, D.; Isobe, A. Quantification of litter in cities using a smartphone application and citizen science in conjunction with deep learning-based image processing. *Waste Manag.* **2024**, *186*, 271–279. [CrossRef] [PubMed]
35. Saad, M.R.; Abdullah, N.F.; Abu-Samah, A.; Nordin, R. Empowering citizen scientists: A web app for plastic litter classification. *Expert Syst. Appl.* **2025**, *284*, 127776. [CrossRef]
36. Forleo, M.B.; Romagnoli, L. Fishing for litter for the reduction of marine plastic debris: What benefits and costs do Italians perceive? *Mar. Pollut. Bull.* **2023**, *192*, 115018. [CrossRef]
37. Consoli, P.; Scotti, G.; Romeo, T.; Fossi, M.C.; Esposito, V.; D'Alessandro, M.; Battaglia, P.; Galgani, F.; Figurella, F.; Pragnell-Raasch, H.; et al. Characterization of seafloor litter on Mediterranean shallow coastal waters: Evidence from Dive Against Debris®, a citizen science monitoring approach. *Mar. Pollut. Bull.* **2020**, *150*, 110763. [CrossRef]
38. Scrich, V.M.; Elliff, C.; De Andrade, M.M.; Grilli, N.M.; Turra, A. Stakeholder analysis as a strategic tool in framing collaborative governance arenas for marine litter monitoring. *Mar. Pollut. Bull.* **2024**, *198*, 115799. [CrossRef]
39. Philip, L.; Le Picard, M.; Lavergne, E.; Bourgain, P.; Sabard, B.; Troublé, R.; Meistertzheim, A.-L.; Ludwig, W.; ter Halle, A.; Lacroix, C.; et al. Comparison of macrolitter and meso- and microplastic pollution on French riverbanks and coastal beaches using citizen science with schoolchildren. *Environ. Sci. Pollut. Res.* **2024**, *32*, 10066–10080. [CrossRef]
40. Baxter, L.; Lucas, Z.; Walker, T.R. Evaluating Canada's single-use plastic mitigation policies via brand audit and beach cleanup data to reduce plastic pollution. *Mar. Pollut. Bull.* **2022**, *176*, 113460. [CrossRef]
41. Vasantha Raman, N.; Dubey, A.; Millar, E.; Nava, V.; Leoni, B.; Gallego, I. Monitoring contaminants of emerging concern in aquatic systems through the lens of citizen science. *Sci. Total Environ.* **2023**, *874*, 162527. [CrossRef] [PubMed]
42. Ershova, A.; Makeeva, I.; Malgina, E.; Sobolev, N.; Smolokurov, A. Combining citizen and conventional science for microplastics monitoring in the White Sea Basin (Russian Arctic). *Mar. Pollut. Bull.* **2021**, *173*, 112955. [CrossRef] [PubMed]
43. Zammit, A.; Deidun, A.L.A.N.; Gauci, A. Enhancing microplastic detection in coastal waters through AI-assisted citizen science. *Rapp. Comm. Int. Mer Médit.* **2024**.
44. Ovide, B.G.; Barbaccia, E.; Lorenz, C.; Basran, C.J.; Cirino, E.; Syberg, K.; Rasmussen, M.H. Validating citizen science for community-driven microplastic monitoring and marine protection in northeast Iceland's Hope Spot. *Mar. Pollut. Bull.* **2025**, *213*, 117638. [CrossRef] [PubMed]
45. Camins, E.; De Haan, W.P.; Salvo, V.-S.; Canals, M.; Raffard, A.; Sanchez-Vidal, A. Paddle surfing for science on microplastic pollution. *Sci. Total Environ.* **2020**, *709*, 136178. [CrossRef]
46. Clark, L.; Allen, R.; Botterell, Z.L.R.; Callejo, B.; Godley, B.J.; Henry, C.; Santillo, D.; Nelms, S.E. Using citizen science to understand floating plastic debris distribution and abundance: A case study from the North Cornish Coast (United Kingdom). *Mar. Pollut. Bull.* **2023**, *194*, 115314. [CrossRef]
47. Setälä, O.; Tirroniemi, J.; Lehtiniemi, M. Testing citizen science as a tool for monitoring surface water microplastics. *Environ. Monit. Assess.* **2022**, *194*, 797. [CrossRef]
48. Nel, H.A.; Sambrook Smith, G.H.; Harmer, R.; Sykes, R.; Schneidewind, U.; Lynch, I.; Krause, S. Citizen science reveals microplastic hotspots within tidal estuaries and the remote Scilly Islands, United Kingdom. *Mar. Pollut. Bull.* **2020**, *161*, 111776. [CrossRef]
49. Catarino, A.I.; Mahu, E.; Severin, M.I.; Akpetou, L.K.; Annasawmy, P.; Asuquo, F.E.; Beckman, F.; Benomar, M.; Jaya-Ram, A.; Malouli, M.; et al. Addressing data gaps in marine litter distribution: Citizen science observation of plastics in coastal ecosystems by high-school students. *Front. Mar. Sci.* **2023**, *10*, 1126895. [CrossRef]
50. Walther, B.A.; Pasolini, F.; Korez Lupše, Š.; Bergmann, M. Microplastic Detectives: A citizen-science project reveals large variation in meso- and microplastic pollution along German coastlines. *Front. Environ. Sci.* **2024**, *12*, 1458565. [CrossRef]
51. Barrows, A.P.W.; Christiansen, K.S.; Bode, E.T.; Hoellein, T.J. A watershed-scale, citizen science approach to quantifying microplastic concentration in a mixed land-use river. *Water Res.* **2018**, *147*, 382–392. [CrossRef]
52. Tunnell, J.W.; Dunning, K.H.; Scheef, L.P.; Swanson, K.M. Measuring plastic pellet (nurdle) abundance on shorelines throughout the Gulf of Mexico using citizen scientists: Establishing a platform for policy-relevant research. *Mar. Pollut. Bull.* **2020**, *151*, 110794. [CrossRef]
53. Sinha, R.K.; Kumar, R.; Phartyal, S.S.; Sharma, P. Interventions of citizen science for mitigation and management of plastic pollution: Understanding sustainable development goals, policies, and regulations. *Sci. Total Environ.* **2024**, *955*, 176621. [CrossRef]

54. Kiessling, T.; Hinzmann, M.; Mederake, L.; Dittmann, S.; Brennecke, D.; Böhm-Beck, M.; Knickmeier, K.; Thiel, M. What potential does the EU Single-Use Plastics Directive have for reducing plastic pollution at coastlines and riversides? An evaluation based on citizen science data. *Waste Manag.* **2023**, *164*, 106–118. [CrossRef]
55. Kiessling, T.; Knickmeier, K.; Kruse, K.; Gatta-Rosemary, M.; Nauendorf, A.; Brennecke, D.; Thiel, L.; Wichels, A.; Parchmann, I.; Körtzinger, A.; et al. Schoolchildren discover hotspots of floating plastic litter in rivers using a large-scale collaborative approach. *Sci. Total Environ.* **2021**, *789*, 147849. [CrossRef]
56. De Veer, D.; Baeza-Álvarez, J.; Bolaños, S.; Cavour Araya, S.; Darquea, J.J.; Díaz Poblete, M.A.; Domínguez, G.; Holtmann-Ahumada, G.; Honorato-Zimmer, D.; Gaibor, N.; et al. Citizen scientists study beach litter along 12,000 km of the East Pacific Coast: A baseline for the International Plastic Treaty. *Mar. Pollut. Bull.* **2023**, *196*, 115481. [CrossRef]
57. Mishra, P.; Kaviarasan, T.; Sambandam, M.; Dhineka, K.; Murthy, M.V.R.; Iyengar, G.; Singh, J.; Ravichandran, M. Assessment of national beach litter composition, sources, and management along the Indian coast—A citizen science approach. *Mar. Pollut. Bull.* **2023**, *186*, 114405. [CrossRef] [PubMed]
58. Nelms, S.E.; Coombes, C.; Foster, L.C.; Galloway, T.S.; Godley, B.J.; Lindeque, P.K.; Witt, M.J. Marine anthropogenic litter on British beaches: A 10-year nationwide assessment using citizen science data. *Sci. Total Environ.* **2017**, *579*, 1399–1409. [CrossRef]
59. Gacutan, J.; Tait, H.; Jones, J.; Charlesworth, B.; Hood, L. Citizen science supports national reporting of a sustainable development goal indicator: A case study of plastic debris density on beaches. *Environ. Sci. Policy* **2024**, *161*, 103870. [CrossRef]
60. Haarr, M.L.; Pantalos, M.; Kleffelgård Hartviksen, M.; Gressetvold, M. Citizen science data indicate a reduction in beach litter in the Lofoten Archipelago in the Norwegian Sea. *Mar. Pollut. Bull.* **2020**, *153*, 111000. [CrossRef] [PubMed]
61. Hidalgo-Ruz, V.; Thiel, M. Distribution and abundance of small plastic debris on beaches in the SE Pacific (Chile): A study supported by a citizen science project. *Mar. Environ. Res.* **2013**, *87*, 12–18. [CrossRef] [PubMed]
62. Rambonnet, L.; Reinders, H.; Land-Zandstra, A.M. Citizen science against the plastic soup: Background, motivation and expectations of volunteers studying plastic pollution on Dutch riverbanks. *Res. All* **2023**, *7*, 14. [CrossRef]
63. Jones, J.S.; Guézou, A.; Medor, S.; Nickson, C.; Savage, G.; Alarcón-Ruales, D.; Galloway, T.S.; Muñoz-Pérez, J.P.; Nelms, S.E.; Porter, A.; et al. Microplastic distribution and composition on two Galápagos island beaches, Ecuador: Verifying the use of citizen science derived data in long-term monitoring. *Environ. Pollut.* **2022**, *311*, 120011. [CrossRef]
64. Davies, L.; Kemp, A.; O'Loughlin, C.; Korczynskyj, D. Is conscientious beachcombing the key to 'unlock' marine plastic pollution trends through citizen science? A case study from Cockburn Sound, Western Australia. *Mar. Pollut. Bull.* **2022**, *177*, 113519. [CrossRef]
65. Vlachogianni, T.; Skocir, M.; Constantin, P.; Labbe, C.; Orthodoxou, D.; Pesmatzoglou, I.; Scannella, D.; Spika, M.; Zissimopoulos, V.; Scoullos, M. Plastic pollution on the Mediterranean coastline: Generating fit-for-purpose data to support decision-making via a participatory-science initiative. *Sci. Total Environ.* **2020**, *711*, 135058. [CrossRef] [PubMed]
66. Stanton, T.; Chico, G.; Carr, E.; Cook, S.; Gomes, R.L.; Heard, E.; Law, A.; Wilson, H.L.; Johnson, M. Planet Patrolling: A citizen science brand audit of anthropogenic litter in the context of national legislation and international policy. *J. Hazard. Mater.* **2022**, *436*, 129118. [CrossRef]
67. Walther, B.A.; Kunz, A.; Hu, C.-S. Type and quantity of coastal debris pollution in Taiwan: A 12-year nationwide assessment using citizen science data. *Mar. Pollut. Bull.* **2018**, *135*, 862–872. [CrossRef]
68. Willis, K.A.; Jones, T.; Cohen, R.; Burgess, H.; Lindsey, J.; Parrish, J. Using long-term citizen science data to distinguish zones of debris accumulation. *Mar. Pollut. Bull.* **2022**, *182*, 114028. [CrossRef]
69. Watkins, L.; Bonter, D.N.; Sullivan, P.J.; Walter, M.T. Methods for monitoring urban street litter: A comparison of municipal audits and an app-based citizen science approach. *Environ. Sci. Adv.* **2024**, *3*, 885–896. [CrossRef]
70. Lawen, A.; Lawen, J.; Turner, A. Beached plastic and other anthropogenic debris in the inner Seychelles Islands: Results of a citizen science approach. *Mar. Pollut. Bull.* **2024**, *201*, 116176. [CrossRef] [PubMed]
71. Chen, H.; Wang, S.; Guo, H.; Lin, H.; Zhang, Y. A nationwide assessment of litter on China's beaches using citizen science data. *Environ. Pollut.* **2020**, *258*, 113756. [CrossRef] [PubMed]
72. Van Emmerik, T.; Seibert, J.; Strobl, B.; Etter, S.; Den Oudendammer, T.; Rutten, M.; Bin Ab Razak, M.S.; Van Meerveld, I. Crowd-based observations of riverine macroplastic pollution. *Front. Earth Sci.* **2020**, *8*, 298. [CrossRef]
73. Vincent, A.; Drag, N.; Lyandres, O.; Neville, S.; Hoellein, T. Citizen science datasets reveal drivers of spatial and temporal variation for anthropogenic litter on Great Lakes beaches. *Sci. Total Environ.* **2017**, *577*, 105–112. [CrossRef]
74. Rech, S.; Macaya-Caquilpán, V.; Pantoja, J.F.; Rivadeneira, M.M.; Kroeger Campodónico, C.; Thiel, M. Sampling of riverine litter with citizen scientists—Findings and recommendations. *Environ. Monit. Assess.* **2015**, *187*, 4473. [CrossRef]
75. Forrest, S.A.; Holman, L.; Murphy, M.; Vermaire, J.C. Citizen science sampling programs as a technique for monitoring microplastic pollution: Results, lessons learned and recommendations for working with volunteers for monitoring plastic pollution in freshwater ecosystems. *Environ. Monit. Assess.* **2019**, *191*, 7297. [CrossRef]

76. Yeh, C.; Khan, F.H. Citizen science mobile apps with machine learning for recyclable objects. In Proceedings of the 2022 International Conference on Computational Science and Computational Intelligence (CSCI), Las Vegas, NV, USA, 14–16 December 2022; IEEE: Piscataway, NJ, USA, 2022; pp. 1539–1542. [CrossRef]
77. Millar, E.; Melles, S.; Rinner, C. Screens, streams, and flows: Implications of digital platforms for aquatic citizen science. *Geoforum* **2023**, *146*, 103864. [CrossRef]
78. Napper, I.E.; Davies, B.F.R.; Erskine, A.; Thompson, R.C.; Yates, R.; Koldewey, H. Citizen science reveals litter trends in the UK: Population density effects on coastal and inland regions. *Mar. Pollut. Bull.* **2025**, *214*, 117634. [CrossRef] [PubMed]
79. Scardino, G.; Martella, R.; Mastronuzzi, G.; Rizzo, A.; Borracesi, Q.; Musolino, F.; Romanelli, N.; Zarcone, S.; Cipriano, G.; Retucci, A. The nauticAttiva project: A mobile phone-based tool for the citizen science plastic monitoring in the marine and coastal environment. *Mar. Pollut. Bull.* **2022**, *185*, 114282. [CrossRef]
80. Saad, D.; Chauke, P.; Cukrowska, E.; Richards, H.; Nikiema, J.; Chimuka, L.; Tutu, H. First biomonitoring of microplastic pollution in the Vaal River using carp fish (*Cyprinus carpio*) as a bio-indicator. *Sci. Total Environ.* **2022**, *836*, 155623. [CrossRef]
81. Wu, D.; Liu, J.; Cordova, M.; Hellevik, C.C.; Cyvin, J.B.; Pinto, A.; Hameed, I.A.; Pedrini, H.; Da Silva Torres, R.; Fet, A.M. The PlastOPol system for marine litter monitoring by citizen scientists. *Environ. Model. Softw.* **2023**, *169*, 105784. [CrossRef]
82. Sciutteri, V.; Costa, V.; Malara, D.; Figurella, F.; Campbell, I.; Deery, E.; Romeo, T.; Andaloro, F.; Consoli, P. Citizen science through a recreational underwater diving project supports the collection of large-scale marine litter data: The Oceania case study. *Mar. Pollut. Bull.* **2024**, *200*, 116133. [CrossRef] [PubMed]
83. Abreo, N.A.S.; Thompson, K.F.; Arabejo, G.F.P.; Superio, M.D.A. Social media as a novel source of data on the impact of marine litter on megafauna: The Philippines as a case study. *Mar. Pollut. Bull.* **2019**, *140*, 51–59. [CrossRef]
84. Nelms, S.E.; Easman, E.; Anderson, N.; Berg, M.; Coates, S.; Crosby, A.; Eisfeld-Pierantonio, S.; Eyles, L.; Flux, T.; Gilford, E.; et al. The role of citizen science in addressing plastic pollution: Challenges and opportunities. *Environ. Sci. Policy* **2022**, *128*, 14–23. [CrossRef]
85. Severin, M.I.; Akpetou, L.K.; Annasawmy, P.; Asuquo, F.E.; Beckman, F.; Benomar, M.; Jaya-Ram, A.; Malouli, M.; Mees, J.; Monteiro, I.; et al. Impact of the citizen science project COLLECT on ocean literacy and well-being within a North/West African and South-East Asian context. *Front. Psychol.* **2023**, *14*, 1130596. [CrossRef]
86. Oturai, N.G.; Syberg, K.; Fraisl, D.; Hooge, A.; Ramos, T.M.; Schade, S.; Hansen, S.F. UN plastic treaty must mind the people: Citizen science can assist citizen involvement in plastic policymaking. *One Earth* **2023**, *6*, 715–724. [CrossRef]
87. Church, E.K.; Wilson, K.A.; Loder, J.; Dean, A.J. From citizen science experiences to stewardship action: The importance of both nature and social experiences. *Mar. Policy* **2025**, *173*, 106537. [CrossRef]
88. Peter, M.; Diekötter, T.; Kremer, K. Participant outcomes of biodiversity citizen science projects: A systematic literature review. *Sustainability* **2019**, *11*, 2780. [CrossRef]
89. Locritani, M.; Merlino, S.; Abbate, M. Assessing the citizen science approach as tool to increase awareness on the marine litter problem. *Mar. Pollut. Bull.* **2019**, *140*, 320–329. [CrossRef] [PubMed]
90. Hartley, J.M.; Stevenson, K.T.; Peterson, M.N.; Busch, K.C.; Carrier, S.J.; DeMattia, E.A.; Jambeck, J.R.; Lawson, D.F.; Strnad, R.L. Intergenerational learning: A recommendation for engaging youth to address marine debris challenges. *Mar. Pollut. Bull.* **2021**, *170*, 112648. [CrossRef] [PubMed]
91. Praet, E.; Baeza-Álvarez, J.; De Veer, D.; Holtmann-Ahumada, G.; Jones, J.S.; Langford, S.; Michel Dearte, J.; Schofield, J.; Thiel, M.; Wyles, K.J. Bottle with a message: The role of story writing as an engagement tool to explore children's perceptions of marine plastic litter. *Mar. Pollut. Bull.* **2023**, *186*, 114457. [CrossRef]
92. Molnár, A.D.; Málnás, K.; Bőhm, S.; Gyalai-Korpos, M.; Cserép, M.; Kiss, T. Comparative analysis of riverine plastic pollution combining citizen science, remote sensing and water quality monitoring techniques. *Sustainability* **2024**, *16*, 5040. [CrossRef]
93. Cividanes, M.; Aguiar-González, B.; Gómez, M.; Herrera, A.; Martínez, I.; Pham, C.K.; Pérez, L.; Machín, F. Lagrangian tracking of long-lasting plastic tags: From lobster fisheries in the USA and Canada to Macaronesia. *Mar. Pollut. Bull.* **2024**, *198*, 115908. [CrossRef]
94. Mayorga Adame, C.G.; Gacutan, J.; Charlesworth, B.; Roughan, M. Unravelling coastal plastic pollution dynamics along Southeastern Australia: Insights from oceanographic modelling informed by empirical data. *Mar. Pollut. Bull.* **2025**, *213*, 117525. [CrossRef] [PubMed]
95. Rambonnet, L.; Vink, S.C.; Land-Zandstra, A.M.; Bosker, T. Making citizen science count: Best practices and challenges of citizen science projects on plastics in aquatic environments. *Mar. Pollut. Bull.* **2019**, *145*, 271–277. [CrossRef]
96. Cowger, W.; Gray, A.B.; Schultz, R.C. Anthropogenic litter cleanups in Iowa riparian areas reveal the importance of near-stream and watershed scale land use. *Environ. Pollut.* **2019**, *250*, 981–989. [CrossRef]
97. Harris, L.; Liboiron, M.; Charron, L.; Mather, C. Using Citizen Science to evaluate Extended Producer Responsibility policy to reduce marine plastic debris shows no reduction in pollution levels. *Mar. Policy* **2021**, *123*, 104319. [CrossRef]
98. Shruti, V.C.; Pérez-Guevara, F.; Roy, P.D.; Kutralam-Muniasamy, G. Strengthening citizen science partnerships with frontline sanitation personnel to study and tackle plastic pollution. *Environ. Sci. Policy* **2022**, *137*, 70–74. [CrossRef]

99. Haarr, M.L.; Narvestad, A.; Falk-Andersson, J.; Staley, S.; Staley, H.; Cox, J.; Dahl, M.; Svendsen, H.; Sinisalo, A.; Stübner, E. Arctic marine litter: Composition and sources investigated by citizen scientist 'super-users'. *Mar. Pollut. Bull.* **2024**, *209*, 117061. [CrossRef]
100. Moreno, C.; Barreau, C. Citizen engagement: A driver for ocean protection. In Proceedings of the One Ocean Science Congress, Nice, France, 3–6 June 2025; p. 459. [CrossRef]
101. Paradinas, L.M.; James, N.A.; Quinn, B.; Dale, A.; Narayanaswamy, B.E. A new collection tool-kit to sample microplastics from the marine environment (sediment, seawater, and biota) using citizen science. *Front. Mar. Sci.* **2021**, *8*, 657709. [CrossRef]
102. De Haan, W.P.; Uviedo, O.; Ballesteros, M.; Canales, Í.; Curto, X.; Guart, M.; Higueras, S.; Molina, A.; Sanchez-Vidal, A. Floating microplastic loads in the nearshore revealed through citizen science. *Environ. Res. Lett.* **2022**, *17*, 045018. [CrossRef]
103. Merlino, S.; Locritani, M.; Guarnieri, A.; Delrosso, D.; Bianucci, M.; Paterni, M. Marine litter tracking system: A case study with open-source technology and a citizen science-based approach. *Sensors* **2023**, *23*, 935. [CrossRef] [PubMed]
104. Deidun, A.; Gauci, A.; Galdies, J.; Marrone, A.; Zammit, A.; Dewitte, B.; Kopke, K.; Sempéré, R. The development of the Andromeda microplastics smartphone app: A combination of citizen science and AI to mobilize public engagement along European coastlines. In Proceedings of the JPI Oceans Conference, Galway, Ireland, 14–15 September 2023.
105. Uhrin, A.V.; Lippiatt, S.; Herring, C.E.; Dettloff, K.; Bimrose, K.; Butler-Minor, C. Temporal trends and potential drivers of stranded marine debris on beaches within two US national marine sanctuaries using citizen science data. *Front. Environ. Sci.* **2020**, *8*, 604927. [CrossRef]
106. Mihai, F.-C. Role of geography in plastic pollution research and social implications. *Doc. Geogr.* **2025**, *3*, 28. [CrossRef]
107. Krawczyk, A.; Olivos Salas, B.; Grodzińska-Jurczak, M. Plastic Detectives are watching us: Citizen science towards alternative single-use plastic related behavior. *Recycling* **2025**, *10*, 4. [CrossRef]
108. Bergmann, M.; Lutz, B.; Tekman, M.B.; Gutow, L. Citizen scientists reveal: Marine litter pollutes Arctic beaches and affects wild life. *Mar. Pollut. Bull.* **2017**, *125*, 535–540. [CrossRef]
109. Li, J.-M.; Yu, M.-F.; Kao, C.-M.; Surampalli, R.Y.; Zhang, T.C. Global strategies/policies and citizen science for microplastic management. In *Microplastics in the Environment*, 1st ed.; Wiley: Hoboken, NJ, USA, 2025; pp. 577–597. [CrossRef]
110. Emam, W.W.M.; Soliman, K.M. Integrating geospatial approach with citizen science to combat marine plastic pollution. In *Developments in Environmental Science: Water Resources Monitoring, Management and Sustainability—Application of Geostatistics and Geospatial Modeling*; Pal, S.C., Roy, S.S., Saha, S., Abioui, M., Eds.; Elsevier: Amsterdam, The Netherlands, 2024; Volume 16, pp. 309–332. [CrossRef]
111. Peacock, M.; Ghilardi-Lopes, N.P.; Turra, A.; Rech, T.F.; Kawabe, L.A.; Gatersleben, B.; Wyles, K.J. The future of citizen science for marine litter research: What are the benefits to be realised and the challenges to be overcome? *Mar. Pollut. Bull.* **2025**, *217*, 117914. [CrossRef] [PubMed]
112. Zulkifli, A.N.; Shafri, H.Z.M.; Hirose, K.; Noor, N.M.; Maulud, K.N.A.; Asmawi, M.Z.; Mokraoui, L.; Ang, Y. Plastic waste mapping and monitoring using geospatial approaches. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1064*, 012008. [CrossRef]
113. Goh, K.C.; Kurniawan, T.A.; Sarpin, N.; Masrom, M.A.N.; Othman, M.H.D.; Anouzla, A.; Aziz, F.; Ali, I.; Casila, J.C.; Khan, M.I.; et al. Combating microplastic pollution in Malaysia's marine ecosystems using technological solutions, policy instruments, and public participation: A review. *J. Hazard. Mater. Adv.* **2025**, *17*, 100542. [CrossRef]