Goals and approaches in the use of citizen science for exploring plastic pollution in freshwater ecosystems: A review

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Abstract: The role of citizen science in environmental monitoring has received interest in the research community over the last decade, with citizen scientists playing a key role in engaging with and gathering scientific evidence to support natural resource management. Likewise, the involvement of citizen science in aquatic research is growing. One area of aquatic research where there has been successful application of citizen science is in support of plastic-pollution research. Plastic-pollution research benefits from support by citizen scientists both because of the ubiquity of plastic within our environments, requiring data to be collected from a wide geographical area, and because of the need for systemic behavior change at both individual and societal levels. Recent studies highlight citizen science contributions to plastic-pollution research within marine systems, but our knowledge is limited about how citizen science can support limnetic plastic-pollution research, with no known published systematic reviews. The involvement of citizen science within freshwater monitoring has been widely discussed, but most peer-reviewed literature focuses on commonly targeted water-quality parameters (e.g., nutrients). This is not surprising given that freshwater plastic waste is a newly emerging field of interest; thus, the support of citizen science in this research area is only just beginning. This review is the 1st to explore the status of freshwater citizen science focused on plastic-pollution. Based on a synthesis of 12 peer-reviewed publications, we considered the environmental and geographic extent of the research, research scope, methods, involvement of citizen science, and data quality. We also discuss how citizen science can contribute to emerging issues in freshwater science. Through our review we found that the use of citizen science within the field of freshwater plastic-pollution research remains rare, with most projects following the contributory model of citizen participation. Additionally, methods and standardized approaches for citizen recruitment, engagement, and training were limited in the peer-reviewed literature. Greater transparency of methods and approaches used will be key to opening up the potential for citizen science within this evolving research field. This review can be used as a starting point for researchers to develop their own freshwater plastic-waste monitoring programs involving citizen scientists.

Key words: citizen science, plastic pollution, freshwater ecosystems, plastic-waste monitoring, natural resource management, citizen recruitment

Freshwater ecosystems are central to the global water cycle, yet they are one of the most altered ecosystems on earth (Carpenter et al. 2011). They are vital for maintaining a healthy and resilient environment, alongside supporting business, economic growth, and societal wellbeing (Heathwaite 2010, Matthews 2016). Rapid environmental change threatens the resilience of our natural environment. In freshwater systems, these changes are occurring directly through anthropogenic activities and the mistreatment of water resources, but also indirectly through climate change, with the resilience of aquatic ecosystems to environmental change a key research priority (Rockström et al. 2014). As such, water quantity and quality degradation translate directly into environmental, social, and economic problems. Recently, newly emerging contaminants, including pharmaceuticals, personal care products, pesticides, hormones, artificial sweeteners, and plastic, are becoming recognized as a significant threat to aquatic ecosystems that are associated with, and increase along with, anthropogenic activity (Lambert and Wagner 2018). Of these contaminants, plastic has received considerable attention, rising up the global agenda and becoming recognized as a contemporary global challenge (Dris et al. 2020). Measures to reduce plastic waste have been implemented at an international scale, yet the scientific evidence to underpin policy and close the policy–action gap is lacking (Wagner et al. 2014). Plastic awareness is growing, but so too is the complexity of the issue of plastic pollution in freshwaters.

Plastic pollution has long been researched in marine systems, with freshwater systems only recently receiving attention (Eerkes-Medrano et al. 2015). A review by Blettler et al. (2018) found 87% of plastic-pollution studies were conducted in marine environments vs only 13% in freshwater systems, leaving considerable knowledge gaps (Blettler and Wantzen 2019). Recent ecotoxicological studies have stressed the importance of considering plastics within freshwater environments, highlighting biological ingestion (Horton et al. 2018, Ma et al. 2019), the release of plasticizing chemicals (Lambert and Wagner 2018, Ma et al. 2019), pollutant absorption (e.g., metals; Naqash et al. 2020), and biological sorption (Ma et al. 2019) as key toxicants that impose severe impacts on freshwater ecosystems. The importance of continuing research in this field extends to gathering comprehensive data on freshwater-plastic abundance and fate, alongside research on the ecological effects of plastics on freshwater species (Winton et al. 2020). For instance, 1 study found that some plastic litter supports a more diverse assemblage of freshwater macroinvertebrates (Wilson et al. 2021).

The recent increased focus on plastics in freshwater environments has not been balanced between the 2 types of plastics, microplastics (≤0.5 cm) and macroplastics (>0.5 cm), and the aquatic zones affected (Schwarz et al. 2019, Bellasi et al. 2020, Wilson et al. 2021). Most freshwater plastic studies are dedicated to microplastics (Winton et al. 2020, van Emmerik et al. 2021), despite macroplastics being a key source of environmental plastic from abrasion and degradation. Macroplastics in freshwater environments (the 5 most prevalent of which are food wrappers, bottles and lids, bags, cigarette butts, and sanitary products; Winton et al. 2020) are associated with physical environmental damage, posing entanglement and ingestion risks to aquatic species, and with implications for human livelihoods (van Emmerik and Schwarz 2020). In addition, plastic studies on freshwater systems largely focus on the water column, with contaminants along riverbanks and foreshores largely excluded (Bernardini et al. 2020). Inclusion of these areas is particularly relevant to freshwater plastic-pollution research because they represent potential hotspot locations for plastic mobilization into rivers under the correct hydrological conditions (e.g., storm events and high tides).

The episodic transport nature of plastics, along with their wide geographical distribution, means plastic-emissions pathways are diverse but are also strongly influenced by human contributions. For example, common plastic-emissions pathways include the direct disposal of plastic debris and indirect losses of plastic through storm water, wind, sewage, or accidental loss. Citizens can play a key role in gathering data on plastic pollution in freshwaters over large geographical areas. Additionally, by engaging in data collection and processing, citizen scientists can further their understanding of their own individual impacts on the surrounding environment.

Emergence of citizen-science methods in environmental monitoring has grown over the last 2 decades (Earp and Liconti 2020). Some successful citizen-science programs include CrowdWater, Litterati, and International Pellet Watch, all of which have been invaluable in helping us to better understand our environment. Although there is no universal definition of citizen science (Heigl et al. 2019), it has become recognized as the participation of the general public in collaboration with scientific institutions and regulatory bodies, with the potential to generate data that can be used in decision making (Hadj-Hammou et al. 2017, Earp and Liconti 2020). Citizen science is an evolving discipline, with recognized potential to contribute to long-term environmental monitoring (McKinley et al. 2017). However, both the uptake and acceptance of citizen science within academia and by catchment managers has been slow to catch on (Parrish et al. 2018). This delay is largely rooted in skepticism over data reliability (Burgess et al. 2017, Wilson et al. 2018), as well as an appreciation of the nuances and challenges required to execute a successful citizen-science program (Thornhill et al. 2019).

The growth of citizen science in aquatic-science contexts has paralleled the growing involvement of citizen science in the field of plastic pollution (Syberg et al. 2018, Zettler et al. 2017). For example, the support of citizen science campaigns in beach cleanup projects (Syberg et al. 2018) and marine-litter studies (Hidalgo-Ruz and Thiel 2015) have increased. Over the last decade, the number of participants volunteering in cleanups has doubled, with reports of over a million volunteers in 2019 (Ocean Conservancy 2019). This positive and active participation of citizen scientists has led to the development of guidelines for both monitoring and assessing the impacts of plastic litter on marine systems by the Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP 2019).

The involvement of citizen science in water-quality assessment has also increased. A review by Earp and Liconti (2020) reported that 63% of all reviewed marine citizen-science studies were related to water-quality monitoring. The increased involvement of citizen science in environmental monitoring is also reflected in the number of journals publishing citizen-science research, including Environmental Monitoring and Assessment, Science of the Total Environment and Frontiers, PLoS ONE, and Citizen Science: Theory and Practice, a dedicated citizen-science journal established in 2014. The increased involvement of citizen science in water-quality monitoring has been partly driven by the increased availability of low-cost water-quality testing kits (Buytaert et al. 2014), enabling observational and in-situ monitoring (Storey et al. 2016). Most of these studies, particularly within freshwater systems, are targeted at commonly sampled water-quality parameters, such as nutrients (Breuer et al. 2015, Storey et al. 2016, Abbott et al. 2018, Poisson et al. 2020), macroinvertebrates (Brooks et al. 2019, Blake and Rhanor 2020), algae blooms (Cunha et al. 2017, Poisson et al. 2020), and pathogens (e.g., *Escherichia coli*; Stepenuck et al. 2011, Wang et al. 2018). By comparison, emerging environmental contaminants, specifically plastic, are less commonly reported within freshwater citizen-science studies (Mayoma et al. 2019). This research gap is emphasized by Rech et al.

(2015), who highlighted the limited current knowledge on both the sources and movement of anthropogenic litter within freshwater environments because of limited study inclusion.

At present, a quantitative assessment of citizen science within freshwater plastic studies is lacking, despite its promising application. Citizen science offers an untapped resource for monitoring plastic debris within freshwater ecosystems, particularly in simple visual-sampling methodologies (van Emmerik and Schwarz 2020). However, there exists no uniform citizen-science-led monitoring strategy to account for plastic debris within freshwater ecosystems. This lack is particularly relevant in regions of the United Kingdom (UK) where a catchment-based approach to water quality and resource management has been adopted (DEFRA 2013). This catchment framework enables robust community partnerships to collaboratively and flexibly manage local water resources, thereby offering an ideal space in which citizen science can be explored. This review synthesizes existing citizen-science studies on plastic pollution within freshwater ecosystems to highlight the diversity and full potential of this discipline within aquatic science. We also report the range of methodological approaches taken by researchers, which will, perhaps, lead to opportunities to standardize methods and demonstrate how citizen-science data can be robustly used in peer-reviewed research. To conclude our review, we attempt a horizon scan of the literature to consider emerging environmental issues within freshwater research and how citizen science can contribute to research on these issues. Based on these objectives, we aimed to address 4 research questions: 1) how is citizen science contributing to freshwater plastic-pollution research, 2) what are the current methods employed, 3) how can citizen science contribute to future freshwater plastic-pollution research, and 4) what are the emerging issues in freshwater science that need to be monitored?

METHODS

To address our research objectives, we conducted a review of literature focused on the application of citizen science in plastic-pollution monitoring in freshwater ecosystems. We identified peer-reviewed literature through searches of Scopus, Web of Science, Google Scholar, and Google. Although limiting our review to peer-reviewed studies represents a conservative method, this paper places emphasis on the use of citizen science within the academic and research community by collating data on the uptake of citizen science as a recognized stream of research. We used the Boolean string search method (Livoreil et al. 2017) to extract the relevant literature and target citizen science, specifically pertaining to plastic waste, and exclusively conducted in freshwater systems (Fig. 1). We also used internet searches to cross reference the studies, for which we used the keywords ‘freshwater + plastic + citizen + science’. This search produced a total of 42 publications.

Papers were included based on the following scoping criteria, adapted from Njue et al. (2019): 1) citizen-science-focused studies on plastic-pollution monitoring within freshwater environments, 2) studies in which citizen scientists were actively engaged and were the primary source of data collection, and 3) studies published within the most recent 2 decades (2000–2020, inclusive). We excluded papers that were insufficiently matched with the Boolean string search (i.e., those that failed to meet the refinement protocol), as well as review papers, from the research data pool. For example, 24/42 (57%) returned studies were focused on broader water-quality parameters (e.g., organic matter) or were heavily focused on marine plastic, including coastal and beach debris (6 studies). Plastic-pollution monitoring was the priority focus, but we also retained studies that included plastic as a form of anthropogenic litter. This interactive search process produced a total of 12 publications. We then systematically extracted data (Table

1) from each of the articles to address our research questions. Further details of all reviewed studies are presented in the supplementary material (Table S1).

RESULTS AND DISCUSSION

Geographic location and spatiotemporal extent of studies

Citizen science as a tool for assisting in freshwater plastic research is underexplored but has received increased attention in recent years, with most studies published during 2019 and 2020 (Fig. 2). As with marine-plastic studies (Njue et al. 2019, Earp and Liconti 2020), most (67%) of the research was carried out in North America and Europe (Fig. 3). This geographic imbalance may, however, reflect our methodological approach of assessing only projects published in peer-reviewed journals. Alternative communication strategies (e.g., local community groups, word of mouth) may be more prevalent within developing countries.

Monitoring was mainly (83%) directed at the abundance and categorization of macroplastics based on structural characteristics. Despite microplastic research being more prevalent than macroplastic in freshwaters, the greater proportion of macroplastic citizen-science research in this review is likely a result of the more advanced equipment and resources required to sample microplastics, which presents challenges within the crowd-based data-collection framework (van Emmerik et al. 2020). However, some reviewed studies used macroplastic data to make inferences about potential microplastic pollution (Mayoma et al. 2019). Of the 12 reviewed studies, only 2 focused on microplastic pollution: Barrows et al. (2018) and Forrest et al. (2019). The longevity of the studies ranged from 1 d (Tasseron et al. 2020) to 4 y (Mayoma et al. 2019), with spatial coverage ranging from countrywide monitoring studies (Kiessling et al. 2019) to single observation points (van Emmerik et al. 2020). However, most studies used a citizen-science approach to assist in obtaining a large spatiotemporal coverage of the area of interest, with this advantageous quality noted across studies (Rech et al. 2015, Cowger et al. 2019, Forrest et al. 2019, Bernardini et al. 2020).

Research scope and methodology

Although the number of applicable studies was small, the scope of research was diverse (Table 2). However, all studies generally focused on abundance and surveying of plastic debris, including identifying plastic item composition, plastic-accumulation hotspots, and pollutant sources, across a range of temporal and spatial scales. The range of environments studied was broad and included rivers (e.g., Barrows et al. 2018), riverbanks (e.g., Bernardini et al. 2020), riparian zones (e.g., Cowger et al. 2019), lakes (e.g., Mayoma et al. 2019), and urban waterways (e.g., Tasseron et al. 2020).

The methods employed also differed across studies (Table 2). Macroplastic studies used transects, neuston nets, visual observations, outfall criteria assessments, wooden drifters, and digital technologies. Both of the studies focused on microplastic pollution used grab-sample methods. Details of all methodological approaches are discussed below.

Transects Transects were the most popular method used to quantify and characterize macroplastic debris from bankside and riparian areas. Some papers adopted transect-protocol approaches from marine-collection protocols, e.g., the Marine Conservation Society (Bernardini et al. 2020) and the UK Environment Agency’s Aesthetic Assessment Protocol (Mayoma et al. 2019). Transects were often placed perpendicular to the river course to facilitate access and movement by volunteers (Kiessling et al. 2019, Bernardini et al. 2020, Tasseron et al. 2020).

Quadrats (Bernardini et al. 2020) or circles (Rech et al. 2015, Kiessling et al. 2019) were used to establish the abundance of plastic within a specific area or to define a sampling area for debris classification (Kiessling et al. 2019). In contrast, other studies used less-structured spatial approaches for plastic surveying. For example, both Vincent et al. (2017) and Cowger et al. (2019) allowed volunteers to collect as much anthropogenic litter from the sample area as possible within a set amount of time. In the case of Cowger et al. (2019), volunteers used canoes to access areas along the riverbank and collected all visible anthropogenic litter from the riparian areas.

Neuston nets and visual observations Some studies included floating macroplastic in their research scope. Rech et al. (2015) used neuston nets (mesh size 1 mm, open area 27 × 0.5 cm^2) hung across a bridge for a period of 1 h. Nets were kept afloat by plastic bottles, and ½ of the open net area was submerged under water during the entire sampling period. By comparison, Tasseron et al. (2020) used visual observations to identify any floating or partially submerged plastic (<10 cm in depth), and van Emmerik et al. (2020) used a visual counting method to identify floating plastic and plastic on nearby riverbanks. This latter simple method yielded a rapid assessment of the environment and added to the standard counting methods outlined in González-Fernández and Hanke (2017) and van Emmerik et al. (2018) for marine systems.

Outfall criteria assessment Of the 12 studies reviewed, only 1 actively involved citizen-science methods in determining the source of the pollution. Kiessling et al. (2019) asked participants to use criteria (e.g., item use, size, and location) to infer the likely source of the pollutant. Possible sources included visitors to the study area, local traffic, illegal dumping, and upstream sources. The participants were then asked to rank the sources on a 5-point scale. This methodological approach was similar to Outfall Safari, a citizen-science methodology developed by the Zoological Society London to visually assess local pollution, including plastic waste (ZSL 2019). In contrast, the researchers in the remaining 11 studies made inferences about plastic-waste sources after analyzing the volunteer-collected data (e.g., Rech et al. 2015, Vincent et al. 2017, Cowger et al. 2019).

Wooden drifters Schöneich-Argent and Freund (2020) conducted one of the largest spatial-scale plastic studies reported in this review. They used citizen-science methods to gather data on both dispersal and accumulation of litter across 3 major tributaries in Germany by deploying wooden drifters of varying sizes (10 × 12 × 2 cm, 10 × 12 × 14 cm), fitted with unique IDs, 3×/y. Although the study did not exclusively focus on plastic debris, further studies (in review) by the same authors suggest that the density of the wood was similar to that of plastic polymers, specifically low-density polyethylene and polypropylene. This large-scale citizen-science experiment relied on the general public to observe the wooden drifters and register the drifter ID numbers and geographic locations on the study's website.

Digital technologies The use of smartphone applications for data collection has become a popular choice within citizen-science methodology (Dickinson et al. 2012, Malthus et al. 2020). This is, in part, because of the ubiquity of smartphones around the globe, coupled with built-in global positioning systems (Dickinson et al. 2012, Njue et al. 2019). A handful of the selected studies used digital applications to ensure consistency with data recording. Digital methods were used to either compliment datasheets (Barrows et al. 2018) or as the dominant medium for data recording (Tasseron et al. 2020, van Emmerik et al. 2020). For example, Barrows et al. (2018) asked participants to use a smartphone application to record field data. Tasseron et al. (2020) and van Emmerik et al. (2020) both used a popular hydrological application called CrowdWater, which has been widely used in hydrological citizen-science studies (Strobl et al. 2019) and which can be used to collect a range of hydrological data through a user-friendly interface. In both cases the researchers used the app to categorize plastic items commonly found in urban and natural water systems to facilitate plastic hotspot mapping.

Grab samples Both of the studies focused on microplastic pollution (Barrows et al. 2018, Forrest et al. 2019) used in-situ grab samples to identify microplastic pollution in river water, but they differed in their spatial approaches to data collection. Barrows et al. (2018) used defined transects across field sites, whereas Forrest et al. (2019) gave participants the freedom to decide where to collect samples from along the river. Methodological approaches to grab sampling also differed between studies. Barrows et al. (2018) filtered ~1 L of surface water through stainless-steel sample bottles (triple rinsed in table water and then with in-situ stream water) and then through 0.45-µm cellulose nitrate filters (Whatman, Maidstone, United Kingdom). By contrast, Forrest et al. (2019) filtered 100 L of river water through larger 100-µm nylon-mesh filters and could have, therefore, failed to capture smaller particles of microplastic.

Participant role in data collection

All reviewed studies made use of citizen-science participation for data collection in the field, with methods set at appropriate levels for participants. Tasks involved some form of sample collection, quantification, segregation, and observation records. Only 1 study mentioned including volunteers in a laboratory-based setting (Barrows et al. 2018), which was restricted to vacuum filtration of water samples.

We classified each study by participant involvement, as defined by Bonney et al. (2009) and outlined further by Thornhill et al. (2019), into the following 3 categories: contributory, collaborative, and co-created (Table S1). Here, we use the following definitions: 1) contributory—the project scope and objectives are designed by the researchers but volunteers participate in data collection; 2) collaborative—the primary project scope and objectives are set by researchers but participants refine the project, for example by developing new areas to target, analyzing the data, or disseminating the findings; and 3) co-created—researchers and participants work together to design the project aims and objectives, with participants actively involved in most project steps.

All studies except Valois et al. (2020) were considered contributory. In Valois et al. (2020) community members were first asked to define which attributes in their environment were meaningful in terms of recreational suitability. One such factor was rubbish (i.e., plastic waste degrading environmental aesthetics), which led to plastic being assessed in the study (Valois et al. 2020). This active involvement of citizens in the decision of what data to collect reflects a more collaborative approach to citizen science. However, our finding that the contributory approach to citizen science was vastly more common in freshwater plastic-pollution studies was also noted by Njue et al. (2019) in their review of citizen science in hydrological research. In that review 73% of projects were defined as contributory (Njue et al. 2019), with similar findings by both Buytaert et al. (2014) and Earp and Liconti (2020). However, the evolving nature and diversity of citizen-science participation is moving towards more collaborative and co-created approaches to involving citizen scientists in research (Teleki 2012, Hecker et al. 2018). More active participation is particularly advocated within the sphere of catchment management, with the facilitation of partnerships between communities and stakeholders considered central to creating sustainable, transparent, and decentralized policy changes (Collins et al. 2020).

In general, studies were open to a wide range of participant groups. Depending on the study, citizen scientists ranged from school children (Rech et al. 2015, Kiessling et al. 2019), to university students (van Emmerik et al. 2020), to any member of the general public (Schöneich-Argent and Freund 2020). Cowger et al. (2019) included both civilians and scientists from the ages of 5 to 80 y old. Other projects were more restrictive in volunteer inclusion; however, this was generally linked to the project design and methods.

Training protocol and recruitment process

A key factor governing successful citizen-science projects and the acquisition of high-quality data is the quality of, and attention to, participant training (Burgess et al. 2017, San Llorente Capdevila et al. 2020). Detailed information regarding participant training was included by most reviewed citizen-science projects; however, only 1 study, Barrows et al. (2018), explicitly stated that the prior capabilities of the volunteers were assessed before participation. Of those reviewed, 3 studies included all-day in-person training (Vincent et al. 2017, Barrows et al. 2018, Valois et al. 2020). In 1 instance, the delivery of these training sessions was scripted to ensure consistency throughout the engagement process (Vincent et al. 2017). Two studies included the option to refresh volunteers on the methodology, either through attending dedicated refresher courses (Barrows et al. 2018) or through online resources, including monthly webinars (Vincent et al. 2017). Other studies were less direct in their training, providing basic presentations and field handouts containing detailed sampling protocols (Forrest et al. 2019, Kiessling et al. 2019).

The level of training tended to reflect the complexity of the protocol (e.g., transect surveys, microplastic extraction). For most studies training appeared to be a route to promoting environmental education. However, Barrows et al. (2018) took a different stance, viewing training as a means to ensuring high-quality data. Detailed citizen-science recruitment and training protocols should be included as crucial elements of published study methodologies, both to illustrate the effort put into obtaining high-quality data as well as providing guidance for researchers who wish to integrate citizen science into their own research. The transparency of these processes within academic literature is essential for encouraging the integration of citizen science across academic fields and promoting it as a recognized stream of research.

Few studies disclosed details of their recruitment methods. Of the studies reviewed, only Barrows et al. (2018) included a full description of their recruitment protocol (within the project's supplementary material). The researchers undertook a very thorough recruitment process, which required volunteers to first complete an application form and then attend face-to-face interviews to assess competency. Several of the projects utilized existing volunteer networks to recruit participants (Barrows et al. 2018, Forrest et al. 2019, Bernardini et al. 2020). This method is popular in citizen-science research because it ensures that the objectives of the project resonate with like-minded individuals, thereby facilitating on-going dissemination of results and project progress through sustainable outreach mechanisms (Earp and Liconti 2020).

Volunteer engagement

Beyond describing the training protocols, very few of the reviewed projects included how project progress was communicated to their participants or the mechanisms used to ensure long-term engagement beyond the length of the project. This lack of continuous communication is emphasized by Earp and Liconti (2020), who noted the limited inclusion of outreach tools for volunteer retention and long-term involvement. Blaney et al. (2016) also commented on the infrequency of retention assessment in citizen-science projects. Only 1 reviewed study, Barrows et al. (2018), mentioned successful volunteer retention. They attributed their continued volunteer engagement to the competitive application and recruitment training processes, which fostered strong relationships between participants. Citizen retention was further discussed by San Llorente Capdevila et al. (2020). They linked high retention to appropriate data management, specifically through sharing and disseminating information, which ensures that a continuous line of communication is retained between researcher and citizen (San Llorente Capdevila et al. 2020). They also noted that feedback helps with volunteer retention by promoting trust between academics and citizen participants (San Llorente Capdevila et al. 2020). Tang et al. (2019) also reported that feedback can work to enhance the motivation of participants and influence future engagement.

Data quality

Data collected by volunteers can vary in quality, and this was the case for the studies we reviewed. Most of the data collection tasks performed by volunteers were undertaken unassisted. However, 2 studies did include the involvement of professionals to provide a comparative metric for volunteer-collected data validation (Rech et al. 2015, Valois et al. 2020). This form of sampling design is referred to as a split-sampling approach (Jollymore et al. 2017), and it has been used in many environmental citizen-science projects (Aceves-Bueno et al. 2015, Storey et al. 2016, Walker et al. 2016). Valois et al. (2020) found no difference in the data collected by volunteers vs professionals, with the volunteers and professionals collaborating with one another to support, train, and aid with quality assurance. Reports from citizen-science studies across environmental disciplines have similarly found the volunteer data to be of comparable quality to that of professionally collected datasets (Aceves-Bueno et al. 2015, Storey et al. 2016), with some studies from marine systems finding citizen-science data to even surpass professional-quality standards (Schläppy et al. 2017). However, Rech et al. (2015) reported substantial underestimates of litter quantities by volunteers. They concluded that a more precise sampling regime and a more structured training approach for supervisors should have been designed. Similar challenges relating to insufficient training were also discussed by Forrest et al. (2019), with procedural failures leading to inconsistencies in collected data. Missing information on sample sheets and variations in sample-collection procedures were noted, with only 6 participants, out of 17 groups of citizen scientists, following instructions exactly.

Alongside split-sampling methods, a number of alternative approaches were used to validate the citizen-science data. Barrows et al. (2018) used self-awareness questions to ensure volunteers were remembering the correct procedural steps (e.g., to cap sample bottles under water). Volunteers were also asked to submit photographs of the clothing they wore during sampling to determine potential water-sample contamination from clothing fibers during particle analysis. Barrows et al. (2018) also randomly assigned a minimum of 10 duplicate samples, taken in rapid succession to the volunteer-collected samples, to check for representative results. Kiessling et al. (2019) used photographs submitted by participants to validate identification of collected plastic litter. They also used a detailed stepwise-verification flowchart to ensure consistency in the data pool. Vincent et al. (2017) used an existing quality-assurance protocol developed by the local Environment Protection Agency to review submitted data and compared results with historical averages.

Key recommendations to help limit missing data and minimize result inconsistencies centered around ensuring that structured and high-quality training is provided. The benefit of thorough training was reflected in the results presented by Barrows et al. (2018), with 92% of the volunteer-collected samples passing high-quality assurance measures. Forrest et al. (2019) further emphasized the importance of training by noting the need to educate volunteers on why certain procedural steps need to be followed. As previously discussed, both Vincent et al. (2017) and Barrows et al. (2018) offered their volunteers refresher courses. Barrows et al. (2018) reported an uptake rate of 75% on these refresher courses, suggesting the need for continued education support throughout the lifespan of a project. In addition, Jollymore et al. (2017) noted that the motivations of the participants, alongside the context of the research program, can contribute to data-quality outcomes.

Assistance of citizen science in future freshwater research and emerging priority areas

The development of low-cost sensing equipment is creating novel opportunities for citizen science to become involved in water-resource monitoring (Buytaert et al. 2014, Baalbaki et al. 2019). Water-quality sensors are becoming more user friendly and diverse. They are increasingly able to incorporate and obtain a wide range of water-quality parameters from field-based settings (Buytaert et al. 2014). One example is INTCATCH (https://www.intcatch.eu/index.php), which are autonomous boats fitted with sensors that provide real-time, continuous pollution-monitoring technology across a wide range of freshwater environments (e.g., lakes, rivers, reservoirs). A further example is outlined by Baalbaki et al. (2019), who reported on the use of field water-quality test kits to enable citizen scientists to test a wide range of physical, chemical, and biological parameters, including *E. coli*. These kits enabled the community to establish a local laboratory run by citizens to test their own water quality and independently report back to the local public authority.

Further advances in bioinformatics are opening up opportunities for citizen science in freshwater biomonitoring. Advances include the use of environmental DNA (commonly known as eDNA), which has the potential to be increasingly adopted into citizen science and freshwater studies (Biggs et al. 2015, Buxton et al. 2018). A review by Larson et al. (2020) on emerging citizen-science methods acknowledged the limitations associated with this technology, but its cost efficiency and user-friendly application makes eDNA a valuable new addition to the citizen-science toolkit. Biggs et al. (2015) reported on the success of eDNA for the detection of Great Crested Newts (*Triturus cristatus*) in the UK. eDNA has also been used to identify both eutrophication and harmful algal blooms in freshwater systems (further reviewed in Liu et al. 2020) illustrating its potential to be integrated into citizen-science programs to investigate environmental stressors related to water pollution (e.g., nutrient loading). Studies also suggest that eDNA can be used to detect pathogens in water, overcoming the conventional challenges associated with pathogen detection in freshwater systems (e.g., low concentration; Huver et al. 2015), with several studies reporting on its success (Bastos Gomes et al. 2017, Peters et al. 2018). The integration of eDNA into citizen-science methodologies provides opportunities for citizen science to contribute to the detection and quantification of infectious agents within water systems, with the potential for long-term data collection to allow for early detection and reduce waterborne disease risk for humans.

Persistent organic pollutants (POPs) is an emerging pollutant category within freshwater research (Choo et al. 2020) that offers opportunities for citizen-science participation. Interest in POPs within aquatic science has increased in recent years (Choo et al. 2020), yet many questions remain unanswered concerning their distribution, contamination patterns, and bioaccumulation impacts (Choo et al. 2020). Part of this interest is linked with the relationship between POPs and plastics, with the hydrophobic nature of POPs causing them to bind to plastic waste in the environment. The integration of citizen science within POP–plastic research has predominately focused on marine systems through the International Pellet Watch (IPW) project (Ogata et al. 2009, Hirai et al. 2011, Heskett et al. 2012, Zettler et al. 2017. This project has used citizens around the globe to collect pellets on beaches and send them to the IPW laboratory for analysis of POPs. IPW's efforts are providing valuable contributions to the POP field, including data on spatial patterns and differences in POP usage around the globe (Ogata et al. 2009) as well as methods that are being adopted by large international monitoring programs (Takada and Yamashita 2016). Plastic pellets are also present within freshwater systems (Karlsson et al. 2018, Tramoy et al. 2019), and we best understand how pellets are distributed across lake shores (Corcoran et al. 2020). However, there is limited knowledge about plastic pellets in other freshwater systems. This knowledge gap represents an opportunity for knowledge transfer across disciplines as emphasized by Dris et al. (2018), who reinforced the need to synthesize plastic analysis methodology across marine and limnetic systems. Evidence of the success of adaption of marine citizen-science methods for freshwater research are evidenced by the use of neuston nets, commonly used for marine surveys (Morét-Ferguson et al. 2010), for river plastic quantification (Rech et al. 2015) and adaption of sampling methodology from the Marine Conservation Society for surveys in the river Thames (Bernardini et al. 2020).

An identified research priority for the security of long-term water resources is the recognition of wider stakeholder participation in both policy and management (Horne et al. 2017), supporting both societal and environmental resilience. Data on the diverse uses of environmental resources, and their individual impacts on societal and environmental resilience, are needed to make sense of our consumptive choices and to inform both citizens and regulators. This data will be key to designing and implementing policies that drive forward sustainable actions that are sympathetic to societal needs but reflective of environmental constraints. Citizen science is a valuable platform to explore these issues, as well as a tool to facilitate dialogue between consumer and practitioner.

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FIGURE CAPTIONS

Fig. 1. Methodological approach taken for this review. Literature was extracted using several search databases and with a Boolean string method to target citizen-science research on plastic waste in freshwater systems. Internet searches were then used to cross reference the literature with the keywords ‘freshwater + plastic + citizen + science’, which returned a total of 42 initial studies. These studies were further refined using a set of 4 criteria, returning a final data pool of 12 studies.

Fig. 2. Number of citizen-science studies focused on microplastic and macroplastic pollution in freshwater environments.

Fig. 3. Geographic distribution of citizen-science studies focused on plastic pollution in freshwater environments and were published from 2015–2020.

Table 1. Data extracted from each of the 12 freshwater plastic-pollution papers reviewed.

Data category
Study aims and objectives
Geographic location
Spatiotemporal extent (no. of sampling sites and study duration)
Scope of research (including plastic category)
Methodology
Participant role in data collection
Training protocol
Recruitment process
Volunteer engagement
Data quality

Table 2. Summary of methodological approaches taken by citizen scientists focused on macroplastic (Macro) and microplastic (Micro) pollution in freshwater environments. We include the main types of data extracted from each approach and the corresponding broad scientific goal(s) that each approach addressed.

Plastic type	Research focus	Method	Scientific goal(s) addressed	References
Macro	Abundance and surveying	Transect and quadrat	Anthropogenic litter characteristics, composition, abundance, hotspot mapping, transport, and spatiotemporal coverage	Mayoma et al. 2019, Bernardini et al. 2020, Tasseron et al. 2020, van Emmerik et al. 2020
		Transect and circle	Spatiotemporal coverage of litter, quantity of litter, composition, sources, and potential hazards	Rech et al. 2015, Kiessling et al. 2019
		Maximum amount in a set time	Seasonal variability, dominant sources, spatiotemporal coverage of litter, sources, and hotspots	Vincent et al. 2017, Cowger et al. 2019, Valois et al. 2020
		Neuston net (floating plastic)	Quantity and composition of anthropogenic litter	Rech et al. 2015

		Visual observations (floating plastic)	Hotspot mapping of plastic waste in urban water systems	Tasseron et al. 2020
	Pollutant source	Outfall criteria assessment	Composition, sources, and potential hazards	Kiessling et al. 2019
	Dispersion and accumulation	Wooden drifters	Litter dispersal, point sources, and potential accumulation hotspots	Schöneich-Argent and Freund 2020
Micro	Abundance and surveying	Grab samples (1 L) filtered through 0.45-µm Whatman cellulose nitrate filters	Temporal and spatial extent of microplastics in an individual watershed	Barrows et al. 2018
		Grab samples (4 L) filtered through 100-µm nylon-mesh filters	Spatial extent and abundance	Forrest et al. 2019