## Citizen Science and Freshwater Plastics

# Citizen Science Exploration for Plastic Pollution in Freshwater Ecosystems: A Review

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## Abstract

The role of citizen science in environmental monitoring has received significant 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. The involvement of citizen science in aquatic research is growing. Recent studies highlight the successful application of citizen science to support plastic pollution research within marine systems. In contrast, our knowledge on how citizen science can support plastic pollution research in limnetic studies is limited, with no known published systematic reviews on this topic. The involvement of citizen science within hydrological monitoring has been widely discussed, however, the majority of reviewed literature focuses on commonly targeted water quality parameters (i.e. nutrients). This review, for the first time, explores the current status of freshwater citizen science focused on plastic pollution based on a synthesis of 12 peer-reviewed publications. In this paper we consider the environmental and geographic extent of the research, scope and methodological approaches taken, involvement of citizen science within the research and the quality of the data collected. Alongside this, emerging issues in freshwater are also discussed with a strong focus on how citizen science can contribute to this growing knowledge pool. The use of citizen science within the field of freshwater plastic pollution remains niche, with the majority of projects following the contributory model of citizen participation. The inclusion of methods and standardized approaches relating to citizen recruitment, engagement and training in the peer-reviewed literature are limited; with greater transparency key to opening up citizen science potential within this evolving research field.

## 1. Introduction

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). As such, water quality degradation and quantity translate directly into an environmental, social and economic problem. Recently, newly emerging contaminants, including pharmaceuticals, personal care products, pesticides, hormones, artificial sweeteners and plastic, are becoming recognised as a significant threat to aquatic ecosystems and are synonymous with anthropogenic activity (Lambert & Wagner, 2018). Of these contaminants, plastic has received considerable attention, rising up the global agenda and becoming recognised as a contemporary global challenge. 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 strongly lacking (Wagner et a., 2014); while plastic awareness is growing so too is the complexity of the issue.

Plastic pollution has been heavily included within the scope of marine research (Blettler et al., 2018), with freshwater systems only recently receiving attention (Eerkes-Medrano et al., 2015) leaving considerable knowledge gaps (Blettler & Wantzen, 2019). Despite this, recent ecotoxicological studies have stressed the importance of considering plastics within freshwater environments highlighting biological ingestion (Horton et al., 2018; Ma et al., 2020), the release of plasticizing chemicals (Lambert & Wagner, 2018; Ma et al., 2020) pollutant absorption (i.e. metals; Naqash et al., 2020) and biological sorption (Ma et al., 2020) as key toxicants posing severe impacts on freshwater ecosystems. This extends to comprehensive data on freshwater plastic abundance and fate, alongside the ecological effects of plastics on freshwater species (Winton et al., 2014), with some plastic litter potentially beneficial in supporting diverse assemblages of freshwater macroinvertebrates (Wilson et al., 2021).

In recent years, an increased focus on plastics in freshwater environments have started to emerge within the scientific literate (Schwarz et al., 2019; Bellasi et al., 2020; Wilson et al., 2021). However, the majority of these studies are dedicated to microplastics (Winton et al., 2020; van Emmerick et al., 2021), despite macroplastics being a key source of environmental plastic. Macroplastics are strongly associated with physical environmental damage posing as an entanglement and ingestion risk to aquatic species, with implications on human livelihoods (van Emmerik & Schwarz, 2020). Five of the most prevalent macroplastics in freshwater environments include: food wrappers, bottles and lids, bags, cigarette butts and sanitary products (Winton et al., 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 this area is particularly relevant to plastic freshwater research with riverbanks and foreshores representing key potential hotspot locations for plastic mobilization into rivers under the correct climatic conditions (i.e. storm events and high tides).

Future water resource management demands a system thinking approach, with an urgency to understand the dynamic interactions between societal, hydrological, ecological and geomorphological parameters, in the context of water quality and quantity (Smith, 2008; Collins et al., 2020). Long-term catchment-scale monitoring is needed to determine catchment-specific health and resilience across freshwater ecosystems (i.e. rivers, lakes, ponds and wetlands), with this data vital to develop best practice solutions. This is particularly relevant in the context of plastics with plastic emissions pathways diverse and strongly influenced by human contributions. For example, the direct disposure of plastic debris or indirect loss through storm water, wind, sewage or accidental lost. Citizens can play a key role in gathering scientific evidence and by engaging in the data collection, processing and developing toolkits needed for integrated catchment management.

Emergence of citizen science methodologies in environmental monitoring has grown over the last two decades (Earp & Liconti, 2020). Some successful citizen science programs include CrowdWater, Litterati and Internaional Pellet Watch, all of which have been invaluable in helping us to better understand our environment.  While there is no universal definition of citizen science (Heigl et al., 2019), it has become recognised as the participation of the general public in collaboration with scientific institutions and regulatory bodies, with the potential to generate real world impact (Hadj-Hammou et al., 2017; Earp & Liconti, 2020). Citizen science is an evolving discipline, with recognised potential to contribute to long-term environmental monitoring (Silvertown, 2009; McKinley et al., 2017). However, both the uptake and acceptance of citizen science within academia and by catchment managers is more reserved (Parrish et al., 2018). This is largely rooted in scepticism over data reliability (Burgess et al., 2017; Wilson et al., 2018), alongside an appreciation of the nuances and challenges required to execute a successful citizen science programme (Thornhill et al., 2019).

In recent years, citizen science has become particularly prevalent within aquatic science with marine systems receiving a considerable amount of attention (Earp & Liconti, 2020). The growth of this field has correlated strongly with the involvement of citizen science within the field of plastic pollution (Syberd et al., 2017; Zettler et al., 2017). For example, the support of citizen science campaigns in ‘beach clean-up’ projects (Syberd et al., 2017) and marine litter studies (Hidalgo-Ruz & Thiel, 2015). Over the last decade the number of participants volunteering in clean-ups has doubled, with reports of over a million volunteers in 2019 (Ocean Conservancy, 2019). This positive and active participation of citizens in science has led to the development of guidelines in both monitoring and assessing plastic litter impact on marine systems (Group of Experts on the Scientific Aspects of Marine Environmental Protection, GESAMP, 2019).

The involvement of citizen science within the field of water quality assessment has also increased, with a review by Earp & Liconti (2020) reporting 63% of reviewed citizen science studies related to water quality monitoring. This is also reflected in the number of journals increasingly including citizen science research, including: Environmental Monitoring and Assessment, Science of the Total Environment and Frontiers, PLOS One, with a dedicated citizen science journal, Citizen Science: Theory and Practice, established in 2014. This 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). The majority of these studies, particularly within freshwater systems, are targeted at commonly sampled water quality parameters. For example, nutrients (Breuer et al., 2015; Storey et al., 2016; Abbott et al., 2018; Poisson et al., 2020), macroinvertebrates (Brooks et al., 2019; Blake & Rhanor, 2020), algae blooms (Cunha et al., 2017; Poisson et al., 2020) and pathogens (i.e., *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). Yet, the importance of freshwater ecosystems (i.e. rivers) within the field of plastic pollution is strongly recognised (Horton et al., 2017; Windsor et al., 2019). This is emphasised by Rech et al. (2015) stressing the limited current knowledge on both the sources and movement of anthropogenic litter within freshwater environments, due to limited study inclusion.

Citizen science offers an untapped resource for monitoring plastic debris within freshwater ecosystems, particularly in simple visual sampling methodologies (Emmerik & Schwarz, 2019). Yet, there exists no uniform citizen science led monitoring strategy to account for plastic debris within freshwater ecosystems. The ability for citizen science to contribute to plastic pollution research in freshwater ecosystems has great potential. This is particularly relevant in regions of the UK where a ‘Catchment Based Approach’ to water quality and resource management has been adopted (DEFRA, 2013). This framework enables robust community partnerships to collaboratively and flexibly manage local water resources, sensitive to the local environmental and socio-economic context in which it is operating in. Thus, offering an ideal space in which citizen science can be explored.

At present, a quantitative assessment of citizen science within freshwater plastic studies is currently lacking, despite its promising application.  This review attempts to synthesize existing citizen science studies on plastic pollution within freshwater ecosystems, in order to highlight the diversity and full potential of this discipline within aquatic science. We also attempt to cover the diversity of methodological approaches taken by researchers to ensure the standardisation of methods and presence of quality control; demonstrating how citizen science data can be used in peer-reviewed research. To conclude our review, we attempt a horizon scan of the literature in order to consider the emerging environmental issues, within freshwater research, and how citizen science can assist. Based on this background we aim to address four research questions: 1) how is citizen science contributing to freshwater plastic research, 2) what are the current methods employed, 3) how can citizen science assist in future freshwater research, and 4) what are the emerging issues that need to be monitored?

## 2. Methodology

We focus on the application of citizen science in plastic pollution monitoring in freshwater ecosystems. Literature was extracted using a combination of Scopus, Web of Science, Google Scholar, and Google, with analysis only conducted on peer reviewed papers. While this represents a conservative method, this paper places emphasis on the use of citizen science within the academic community; collating informative data on the uptake of citizen science as a recognised stream of research within academic institutes.  The relevant literature was extracted using the Boolean string search method to target citizen science specifically on plastic waste which had been exclusively conducted in freshwater systems (Figure 1). Internet searchers were also used to cross reference the studies using the keywords ‘freshwater + plastic + citizen + science’. This produced a total of 42 returned searches. It should be noted that the papers excluded from this study (i.e. failed to meet the refinement protocol) were insufficiently matched with the Boolean string search. For example, 24 out of the 42 returned searchers were research focused on broader water quality parameters (i.e. organic matter) or were still heavily focused on marine plastic, including coastal and beach debris (six studies).

Papers were included based on the following scoping criteria, adapted from Njue et al. (2019): i) citizen science focused studies on plastic pollution monitoring within freshwater environments, ii) study where citizen scientists are actively engaged and the primary source of data collection, iii) study published within the last two decades (2000-2020, inclusive). Review papers were excluded from the research data pool. This interactive search process produced a total of 12 publications for review, based on our selection methodology. Data (Table 1) was then systematically extracted from each of the articles to address our research questions. It should be noted that while plastic pollution monitoring was the priority focus, studies which included plastic as a form of 'anthropogenic litter' were also included. Further details of all the reviewed studies are presented in Supplementary Material (Table A).

## 3. Results and Discussion

### *3.1 Geographic location and spatiotemporal extent*

Citizen science as a tool for assisting in freshwater plastic research is under explored but has received increased attention in recent years, with the majority of studies reported over the last two years (Figure 2). Similarly, to marine plastic studies (Njue et al., 2019; Earp & Liconti 2020), the majority of the research conducted, at present, is carried out in North America and Europe (67%; Figure 3). This may, however, reflect the methodological approach taken by this review with only projects published in peer-reviewed journals selected for assessment; communication strategies through alternative routes (i.e. local community groups/ word-of-mouth) may be more prevalent within developing countries.

The scope of the monitoring was heavily focused on macroplastics (83%), specifically the abundance and categorisation of macroplastics into defined categories based on structural characteristics. The prevalence of macroplastic research is likely a result of the more advanced equipment and resources required to sample microplastics; challenging within the crowd-based data collection framework (van Emmerick et al., 2020). However, some of the reviewed studies used the macroplastic data to make inferences about potential microplastic pollution (Mayoma et al., 2019). The longevity of the studies ranged from 1 day (Tasseron et al., 2020) to 4 years (Mayoma et al., 2019) with the spatial coverage ranging from country wide monitoring studies (Kiessling et al., 2019) to single observation points (van Emmerick et al., 2020). However, the majority of studies used a citizen science approach to assist in obtaining a large spatiotemporal coverage of the area of interest, with this advantageous quality noted heavily across studies (Rech et al., 2015; Cowger et al., 2019; Forrest et al., 2019; Berhardini et al., 2020).

### *3.2 Research scope and methodology*

While the number of citizen science studies in plastic research within freshwater ecosystems are small, the scope of research was diverse. Research scope ranged from temporal and spatial scale analysis (Barrows et al., 2018; Forrest et a., 2019), composition (Vincent et al., 2017; Mayoma et al., 2019) depositional regimes and accumulation hotspots (Rech et al., 2015; Bernardini et al., 2020; Schöneich-Argent et al., 2020), source identification (Cowger et al., 2019; Kiessling et al., 2019), and citizen science method development (Tasseron et al., 2020; von Emmerick et al. 2020). The range of environments was also broad including: rivers (i.e. Barrows et al., 2018), river banks (i.e Bernardini et al., 2020), riparian zones (i.e. Cowger et al., 2019), lakes (Mayoma et al., 2019) and urban waterways (Tasseron et al., 2020).

The methods employed differed depending on the research focus (see Table 2). The most popular method to quantify and characterise macroplastic debris was the use of transects, with some of the approaches adopted from marine collection protocols including 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 for volunteers to walk up and down along (Kiessling et al., 2019; Tasseron et al., 2020; Bernardini 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 an area to sample within for classification (Kiessling et al., 2019). In contrast, other studies approached plastic surveying using a less structured spatial method. 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), canoes were used by volunteers to scale segments of the river and collect all visible anthropogenic litter from the riparian areas.

In some studies, floating macroplastic was also included in the research scope. Rech et al. (2015) used neuston nets (mesh size 1 mm; open area 27 x 10.5 $cm^2$) hung across a bridge for a period of 1 hour. Plastic bottles were used to keep the net afloat and ensure that half of the open net area was submerged in 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). This is similar to the method employed by van Emmerick et al. (2020), with a visual counting method used to identify floating plastic, but also plastic on nearby riverbanks. This simple method yields a rapid assessment of the environment, and builds on the standard counting method outlined in González-Fernández and Hanke (2017), alongside van Emmerik et al. (2018) for marine systems.

Of the 12 studies, only one actively involved citizen science methodology in determining the source of the pollution (Kiessling et al., 2019) with others (i.e. the researchers) making inferences about plastic waste source domains from the analysed data (Rech et al., 2015; Vincent et al., 2017; Cowger et al., 2019). Here, Kiessling et al. (2019) asked participants to use a number of criteria (i.e. use of the encountered items, size of the item, and location) to infer where the likely source contributing to the presence of the pollutant may be coming from. This included visitors to the study area, local traffic, illegal dumpling or upstream sources. The participants were then asked to rank the sources on a five-point-scale. This methodological approach is similar to that of Outfall Safari's; a citizen science methodology developed by the Zoological Society London (ZSL, 2019) to visually assess local pollution, including plastic waste.

One of the largest spatial scale plastic studies reported in this review is conducted by Schöneich-Argent et al. (2020); using citizen science methods to gather data on both dispersal and accumulation of litter across three major tributaries in Germany. Here, wooden drifters were deployed, of varying sizes (10 x 12 x 2 cm; 10 x 12 x 14 cm), three times a year. While the study does not exclusively focus on plastic debris, further studies (in review) by Schöneich-Argent et al. (2020) suggest that the density of the wood is similar to that of plastic polymers, specifically low-density polyethylene and polypropylene. Each wooden drifter was fitted with a unique ID. This large-scale citizen science experiment relied on the general public registering the drifter identification number on the study's website, alongside the geographic location of the debris.

Of the 12 studies, only two were focused on microplastic pollution (Barrows et al., 2018; Forrest et al., 2019). Both studies used *in-situ* grab samples to identify microplastic pollution in river water. Barrows et al. (2018) used defined transects across field sites to collect data, whereas Forrest et al. (2019) gave the participants the freedom to decide where to collect samples from along the river. The methodological approach to grab sampling also differed between studies. Approximately 1 litre of surface water was filtered through stainless steel sample bottles (triple rinsed in table water and then with *in-situ* stream water) and filtered through 0.45 μm Whatman cellulose nitrate filters (Barrows et al., 2018). By contrast, Forrest et al., (2019) used 100 μm nitrex mesh filters to filter 100 litres of river water through.

A handful of the selected studies utilised digital applications within their methodology. For example, Barrows et al. (2018) asked participants to record field data using a smartphone application. Tasseron et al. (2020) and van Emmerick 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). Crowdwater can be used to collect a range of hydrological data through a user-friendly interface. In both cases Tasseron et al. (2020) and van Emmerick et al. (2020) used the app to categorise plastic items commonly found in urban and natural water systems to facilitate plastic hotspot mapping.

### ***3.3 Participant role in data collection***

Each study (Table 2) was classified based on the involvement of the participants, as defined by Bonney et al. (2009), and outlined further by Thornhill et al. (2019), using the categories: contributory, collaborative and co-created. Here, we use the following definitions: i) *contributory* – in which the project scope and objectives are designed by the researchers but where participants contribute data resources, ii*) collaborative* – the primary project scope and objectives are set by researchers, but participants refine the project i.e. develop new areas to target, within the project scope, analyse the data and disseminate the findings and iii) *co-created* – researchers and participants work together to design the project aims and objectives, with participants actively involved in the majority of the project steps.

All studies, except one (Valois et al., 2020) were considered contributory. Here, in Valois et al. (2020) the community were first asked to define what attributes in their environment were meaningful to the characteristic of ‘recreational suitability’. One such factor was rubbish (i.e.

plastic waste degrading environmental aesthetics), which led to plastic being assessed within 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, the popular approach towards contributory citizen science is also noted by Njue et al. (2019) in their review of citizen science in hydrological research. Here, 73% of projects were defined as contributory (Njue et al., 2019) with similar findings reported by both Buytaert et al. (2014) and Earp & Liconti et al. (2020). However, the evolving nature and diversity of citizen science participation is pushing towards using more collaborative and co-created approaches to research involvement (Teleki et al., 2012; Hecker et al., 2018). This is particularly advocated within the sphere of catchment management, with the facilitation of partnerships between communities and stakeholders central to creating sustainable, transparent and decentralised policy changes (Colins et al., 2020).

In general, studies were open to a wide range of participant groups. The citizen scientists involved, ranged from school children (Kiessling et al., 2019) to university students (van Emmerick et al., 2020) and to any member of the general public (Schöneich-Argent et al., 2020). Cowger et al. (2019) had both civilians and scientists participate from the ages of 5 to 80 years old. Other projects were more restricted as to the group of volunteers; however, this was generally due to the design of the project methodology. Restrictions on citizen participants were included in both Rech et al. (2015) and Kiessling et al. (2019) who both targeted the citizen science study at school children. Few studies disclosed in detail the recruitment process and methodology undertaken to recruit participants. Of the studies reviewed only Barrows et al. (2018) included full guidance on their recruitment process, within the project's supplementary material. Here, a very thorough recruitment process was undertaken which required the volunteers to first complete an application form and then attend face-to-face interviews to assess competency. Several of the projects utilised existing volunteer networks to recruit participants namely, Barrows et al. (2018), Forrest et al. (2019) and Bernardini et al. (2020). This method is often popular in citizen science research to ensure the details of the project connect with like-minded individuals and facilitate the on-going dissemination of results and project progress through sustainable outreach mechanisms (Earp & Liconti, 2020).

All reviewed studies focused on the use to citizen science participation for data collection in the field, with methods for the field of investigation set at appropriate levels for the participants that were recruited. The tasks involved some form of sample collection, quantification, segregation and observation data extraction. Only one study mentioned the inclusion of volunteers in a laboratory-based setting (Barrows et al., 2018), which was restricted to vacuum filtration of water samples.

### ***3.4 Recruitment process and training protocol***

A key factor governing successful citizen science projects, and the acquisition of high-quality data, is the quality and attention to participant training (Burgess et al., 2017; San Llorente Capdevila et al., 2020). Detailed information regarding participant training was included across the majority of the citizen science projects. However, only one study (Barrows et al., 2018) explicitly stated that the prior capabilities of the volunteers were assessed before participation. Of those reviewed, three studies included all-day in person training (Vincent et al., 2017; Barrows et al., 2018; Valois et al., 2020). In some instances, the delivery of these training sessions was scripted to ensure consistency throughout the engagement process (Vincent et al., 2017). Both Vincent et al. (2017) and Barrows et al. (2018) included the facility 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) for additional training resources. Other studies chose a more in-direct approach to training through the use of basic presentations and field handouts containing a detailed sampling protocol (Forrest et al., 2019; Kiessling et al., 2019). To ensure consistency with data recording some studies gave participants predesigned data sheets (Mayoma et al., 2019), while others used smartphone applications to either compliment datasheets (Barrows et al., 2020) or as the dominant medium for data acquisition (von Emmerick et al., 2020; Tasseron et al., 2020).

The level of training tended to reflect the complexity of the protocol (i.e. transect surveys and microplastic extraction). For the majority of studies training was seen as a route to promote environmental education. However, Barrows et al. (2019) took a different stance, viewing training as a goal to ensuring high quality data is produced not primarily as an educational aid. Citizen science recruitment and full training information should be seen as crucial elements of the study methodology, both for data assurance reasons as well as guidance for researchers wishing to integrate citizen science into their own line of research. The transparency of these processes within academic literature is essential for encouraging the uptake of citizen science in all academic fields and promoting it as a recognised stream of research.

### 3.5 Accessibility; public access to research data

Beyond the training side, very few of the reviewed projects included how the project progress was communicated to their participants and the mechanisms used to ensure long-term engagement beyond the length of the project. This is emphasised by Earp & Liconti (2020) who noted the limited inclusion of outreach tools for volunteer retention. Blaney et al. (2016) also comment on the lack of retention assessment frequency within the scope of citizen science projects. Within our review assessment, only one study by Barrows et al. (2018) commented on successful volunteer retention. Here, the continuing engagement of volunteers was attributed to the competitive application process and fostering of strong relationships between participants as a result of this recruitment training process. Citizen retention is further discussed by San Llorente Capdevila et al. (2020), with high retention also linked to appropriate data management, specifically in sharing and disseminating information; ensuring a continuous line of communication is retained between researcher and citizen (San Llorente Capdevila et al., 2020). Feedback is also noted to help with volunteer retention, by promoting trust between academics and citizens (San Llorente Capdevila et al., 2020). This can work to enhance the motivation of participants and influence future engagement (Tang et al., 2019).

### *3.6 Data Quality*

The majority of the data collection tasks performed by the volunteers were undertaken unassisted. However, two studies did include the involvement of professionals, as a comparative metric for volunteer 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 has been used in a number of 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 (volunteer versus professional), with the community and professionals working in collaboration 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 a comparable quality to that of professional datasets (Aceves-Bueno et al., 2015; Storey et al., 2016), with studies from marine systems finding citizen science data to even surpass professional quality standards (Schlappy et al., 2017). However, Rech et al. (2015) reported significant underestimates in litter quantities by volunteers. This led to the conclusion that a more precise sampling regime should have been designed, alongside a more structured training approach for supervisors. Similar challenges relating to insufficient training were also discussed by Forrest et al. (2019) with procedural failures leading to inconsistencies in collected data. Here, missing information on sample sheets and variations in sample collection procedures were noted, with only six of the participants following instructions exactly.

The majority of the studies reviewed collected data manually. However, automated approaches using smartphone applications were attempted by Tasseron et al. (2020) and von Emmerick et al. (2020), with a combination of both manual and automated collection performed by Barrow et al. (2018). 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, due to the ubiquity of smartphones around the globe, coupled with built in global-positioning-systems (Dickinson et al., 2012; Njue et al., 2019).

Alongside split sampling methods, a number of alternative approaches were used to validate the citizen science data. Self-awareness questions were used by Barrows et al. (2018) to ensure volunteers were remembering the correct procedural steps (i.e. to cap the sample bottles under the water). Volunteers were also asked to submit photographs of the clothing that they had worn during sampling to ensure that water samples had not been contaminated during particle analysis. A minimum of 10 randomly assigned duplicate samples were also taken in rapid succession to the citizen science collected samples to check for representative results. Photographs submitted by participants to identify collected plastic litter for validation was used by Kiessling et al. (2019), alongside a detailed stepwise verification flowchart to ensure consistency in the data pool. Vincent et al. (2017) used an existing quality assurance protocol by the local Environment Protection Agency to pull and review submitted data, comparing results to historical averages.

Key recommendations to help limit missing data and restrict result inconsistency stem from ensuring that structured and high-quality training is provided. The benefit of this approach is reflected in the results presented in Barrow et al. (2018) with 92% of the volunteer-collected samples passing high quality assurance measures, including duplicate sampling checks. This is further emphasised by Forrest et al. (2019) acknowledging 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) reports an uptake rate of 75% on these refresher courses, suggesting the need for continued education support throughout the lifespan of the project. This is further stressed by

Jollymore et al. (2017) who notes that the motivations of the participants, alongside the context of the research programme, are all factors that that can contribute to data quality outcomes.

### *3.5 Assistance of citizen science in future freshwater research; emerging priority areas*

Rapid environmental change threatens the resilience of our natural environment. In freshwater systems, this is 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 (Rockstrom et al., 2014).

The development of low-cost sensing equipment is creating novel opportunities for citizen science to become involved in water resource monitoring (Buyaert et al., 2014; Baalbaki et al., 2020). New technology is key to opening up new perspectives in this field of aquatic science. Water quality sensors are becoming more 'user-friendly' and diverse; able to incorporate and obtain a wide range of water quality parameters from a field-based setting (Buyaert et al., 2014). Examples include INTCATCH; autonomous boats fitted with sensors to providing real-time continuous pollution monitoring technology across a wide range of flow domains, providing immediate data feedback. This data transparency is vital for genuine local engagement and in supporting environmental advocacy. A further example is outlined by Baalbaki et al. (2019) who reports 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*. This 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 scope for citizen science in freshwater biomonitoring. This includes the use of environmental DNA (e-DNA) which has the potential to be more heavily adopted into citizen science and freshwater studies (Biggs et al., 2015; Buxton et al., 2018). Biggs et al. (2015) reports on the success of eDNA for the detection of great crested newts in the UK. A review by Larson et al. (2020) on emerging citizen science methods acknowledges the limitations associated with this technology but the cost efficiency of this tool and user-friendly application makes eDNA a valuable new addition to the citizen science toolkit. The eDNA technique has also been used to identify both eutrophication and harmful algae blooms in freshwater systems (further reviewed in Liu et al, 2020). Thus, this tool has the potential to be integrated into citizen science programmes to investigate environmental stressors relating to water pollution (i.e. 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 (i.e. low concentration; Huver et al., 2015), with several studies reporting on its success (Gomes et al., 2017; Peters et al., 2018). This opens up 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.

An emerging pollutant within freshwater research are persistent organic pollutants (POPs; Choo et al., 2020). Their interest within aquatic science has increased in recent years (Park et al., 2018; 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 POPs plastic research has predominately focused on marine systems through the International Pellet Watch (IPW) project (Ogata et al., 2009; Hiari et al., 2011; Heskett et al., 2012; Zettler et al., 2020). This project has used citizens around the globe to collect pellets on beaches and send them to the IPW laboratory for analysis of POPs. The success of the scheme is providing a valuable contribution to the POPs research field, including spatial patterns and differences in POPs usage around the globe (Ogata et al., 2009), with the methods utilised by large international monitoring programmes (Takada &

Yamashita, 2016). Plastic pellets are also present within freshwater systems (Karlsson et al., 2018; Tramby et al., 2019) with an understanding of how pellets are distributed across lake shores (Corcoran et al., 2020) but limited knowledge within other freshwater systems. This knowledge gap represents an opportunity for knowledge transfer across disciplines, as emphasised by Dris et al. (2018) reinforcing the need to synthesis plastic analysis methodology across marine and limnetic systems. Evidence of the success of the adaption of marine citizen science methods for freshwater research are evidenced within this review. For example, this includes the use of neuston nets, commonly used for marine surveys (Moret-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).

## 4. Conclusions

At present there still exists no unified robust methodology for validating citizen science led environmental data (Jollymore et al., 2017). Progression towards acceptance as a legitimate form of scientific enquiry is hindered by data quality. Equally, as demonstrated within this review, the prevalence of only contributory participation structures represents a significant barrier to citizen science potential, with the need for greater collaborative and co-created projects.  This is vital for evolving the discipline of citizen science beyond monitoring and data collection, integrating local perspectives and interpretation into research for translation into practical action.  Greater visibility in citizen science methodology is also needed, educating and sharing with the academic community ways to recruit, maintain and train high quality citizen science volunteers.

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 individual impacts and the diverse usage of environmental resources are needed to make sense of our consumptive choices, to inform both citizens and regulators. This is key to designing and implementing policies that drive forward sustainable actions; sympathetic to both societal needs but reflective of environmental constraints. Citizen science is a valuable platform to explore these issues, as well as an enabling tool to facilitate dialogue between consumer and practitioner.

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