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Review

Citizen Science as a Monitoring Tool in Aquatic Ecology: Trends, Gaps, and Future Perspectives

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Abstract: Aquatic ecosystems are essential for biodiversity and ecosystem services, but anthropogenic pressures threaten them. In this context, citizen science has emerged as an innovative strategy for biodiversity conservation and environmental monitoring. We conducted a scientometric analysis to identify patterns and gaps in the scientific literature on citizen science in aquatic ecology. We analyzed 185 articles published between 2003 and 2024 on the Web of Science and Scopus databases, with the highest number of publications on the topic (15.14%) in 2023. The United States, Australia, and the United Kingdom were the most productive and frequently studied countries. Studies focused on marine ecosystems (50.28%), while freshwater environments, such as rivers (12.99%), remain under-represented. Taxonomic groups such as fish (30.64%) and aquatic mammals (13.87%) were most commonly studied. The focus of monitoring was on ecology and species conservation. The projects adopted a contributory model of citizen engagement (92.97%), with a predominance of urban citizens (60.51%). Participants were trained through online platforms (25.75%) and in-person courses (21.56%), while communication methods involved sharing photos and videos (38.77%) and online uploads (23.79%). Therefore, expanding studies on freshwater ecosystems and rural and traditional communities, and integrating different levels of citizen participation, is essential.

Keywords: open science; aquatic ecosystems; citizen engagement; environmental education; scientific democratization

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1. Introduction

Aquatic ecosystems are key to global environmental balance, providing essential services such as climate regulation, potable water supply, and biodiversity support [1,2]. Despite their importance, they face growing anthropogenic pressures, including pollution, degradation, climate change, and overfishing, which compromise their integrity and resilience [3,4]. About 24% of assessed freshwater species are at risk of extinction [1,5], threatening biodiversity and essential ecosystem services for billions of people [6,7].

Biodiversity conservation and ecosystem service sustainability are now global environmental priorities [8]. International agreements, such as the Convention on Biological Diversity (CBD), the Paris Agreement, and the Kunming-Montreal Global Biodiversity Framework, have set ambitious targets to mitigate anthropogenic pressures [9,10]. These initiatives emphasize integrated strategies that combine environmental protection with societal engagement [11,12]. The Sustainable Development Goals (SDGs), particularly SDG 14 (Life Below Water), SDG 15 (Life on Land), and SDG 17 (Partnerships for the Goals), offer a roadmap for aligning local and global efforts in sustainability, aquatic ecosystem conservation, and public engagement [2,7].

Amid urgent global and socioeconomic challenges, sustainable solutions demand efficient, transparent, and broad scientific efforts from both research and society [13]. Open science promotes access to reliable scientific data and results, encouraging active participation from all stakeholders [14]. By aligning science with societal needs and fostering equal opportunities for scientists, policymakers, and citizens, it bridges gaps in science, technology, and innovation within and across countries, while upholding the right to science [15]. Although open access to data and research outputs is essential for addressing global change in nature conservation, it alone cannot fully transition conventional science to open science [16]. In this perspective, citizen science (CS) enables open, holistic, and participatory knowledge generation [17]. Furthermore, CS should be recognized as a pillar of open science, supporting universities and the co-production of research that benefits society [18].

Citizen science (CS) is a promising approach to bringing communities closer to the scientific process [19,20]. Some authors define CS as active public participation in scientific research [21,22]. CS gained prominence in the 1990s and rapidly expanded with technological advances like online databases, smartphones, and georeferencing tools [23]. This inclusive approach enhances knowledge production, strengthens science–society relationships, provides valuable data for decision-making, and inspires future scientists [24,25].

Citizen science projects are widely applied in environmental monitoring, species conservation, and water quality control [26]. In Brazil, participatory monitoring initiatives led by the Chico Mendes Institute for Biodiversity Conservation (ICMBio) in protected areas are notable [11,27]. However, the application of CS in aquatic ecology remains limited, with few studies analyzing its trends and gaps [28,29]. North America and Europe have demonstrated their effectiveness in hydrological monitoring and environmental modeling, expanding these efforts to other regions, particularly those ecosystems threatened by human activities [30–32].

From this perspective, scientometric analysis is valuable for assessing citizen science in aquatic ecology and identifying patterns, trends, knowledge gaps, and key advancements [33,34]. Despite increasing research interest, no global synthesis has evaluated the development of citizen science in this field. Given this scenario, this study aims to conduct a scientometric analysis to identify patterns and gaps in the scientific literature on citizen science in aquatic ecology. Specifically, we formulated eight guiding questions: (i) What is the temporal trend of publications? (ii) Which countries have the highest academic production and are the most studied? (iii) What are the most relevant research topics? (iv) What types of aquatic ecosystems are being studied? (v) Which taxonomic groups are most studied in citizen science research on aquatic ecology? (vi) What is the focus of participatory monitoring? (vii) What types of participants are involved, and what are their levels of engagement? (viii) What training programs and communication methods are most used for data transmission?

2. Materials and Methods

2.1. Search and Selection Process

To analyze trends and gaps in scientific publications over the past 21 years, we conducted a scientometric analysis, a widely used method for examining large volumes of research and understanding field dynamics [35]. The study focused on academic articles indexed in the Web of Science (WoS) and Scopus databases, recognized for their interdisciplinary coverage and citation analysis reliability [36]. The search strategy was based on keywords frequently used in the literature on citizen science and aquatic ecology, formulated in English and applied to both databases: (citizen science OR participatory monitoring OR citizen scientist) AND (aquatic OR freshwater OR water OR river OR stream OR lake OR sea OR ocean OR mangrove OR estuary OR glacier) AND (ecology OR aquatic ecology).

2.2. Inclusion and Exclusion Criteria

The search was restricted to peer-reviewed scientific articles published between 2003 and 2024, as the earliest record of citizen science linked to aquatic ecology in our search dates to 2003. Although some studies from 1997 onward were retrieved, they lacked a direct connection to aquatic ecology and were excluded. This finding guided the analysis of academic trends up to the latest search on 10 October 2024. Books, book chapters, conference proceedings, and technical documents were excluded, as peer-reviewed articles offer more excellent reliability for literature reviews [37,38]. However, we recognize that database selection and inclusion criteria may introduce biases, which are discussed in Section 5, "Limitations and Future Research".

We did not restrict the search to a specific field, as CS is a multidisciplinary topic with applications across various domains [39]. This broadened the research scope, ensuring a more representative sample of global studies. Language was also not an exclusion criterion, as disregarding non-English studies could have limited the validity of the results and introduced publication bias [37,40]. Consequently, four non-English publications were included (two in French, one in Russian, and one in Afrikaans), with translations conducted using online tools, supplemented by cross-checks and manual revisions to ensure accuracy. The search was performed on 28 November 2024, using the WoS and Scopus databases.

2.3. Data Consolidation and Cleaning

The initial search yielded 345 articles—285 from WoS and 60 from Scopus. These were exported in CSV (comma-separated values) format for easier data integration and processing. Due to duplicate records across databases, we used RStudio (version 4.1.4) to consolidate data and remove redundancies, resulting in 306 unique articles. RStudio, an open-source tool widely used for data analysis, was chosen for its robust features in data visualization, debugging, and package management [41]. Integrating both databases minimized the risk of missing relevant documents.

A manual review was then conducted to eliminate persistent duplicates caused by slight variations in titles or author names, which RStudio may not detect, requiring manual intervention [37]. The final dataset of 306 articles was compiled into an Excel file containing metadata such as the title, abstract, keywords, and materials and methods. This structured dataset was used to analyze the following: (i) the temporal trend of publications;

(ii) countries with the highest academic output (the most productive countries based on the affiliation of the first author) and the most studied regions (areas where research was carried out); (iii) the most relevant research topics; (iv) the most studied types of aquatic ecosystems; (v) the most representative taxonomic groups in citizen science research on aquatic ecology; (vi) the focus of participatory monitoring; (vii) participant types and levels of citizen engagement; and (viii) training programs and methods of communication and data transmission. Articles unrelated to the research topic were excluded, resulting in 185 articles for detailed analysis (Figure 1).

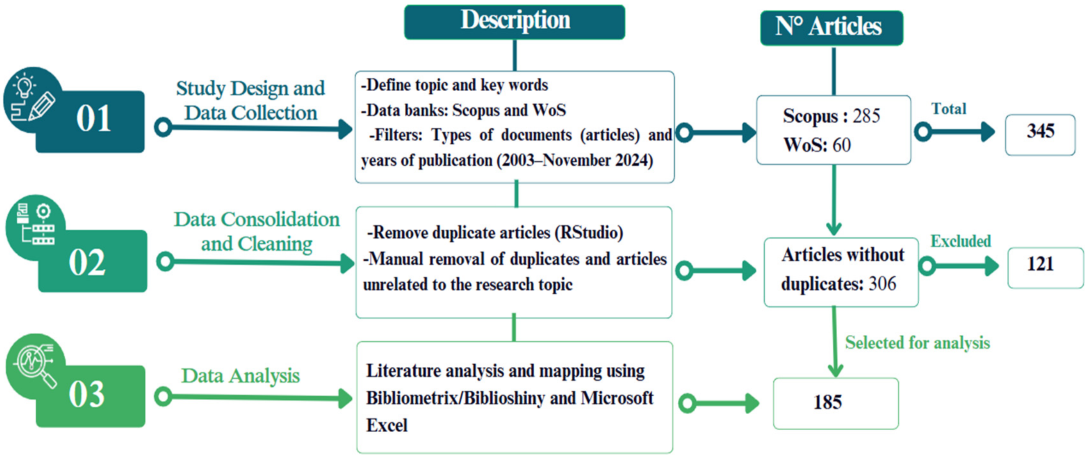

Figure 1. A general representation of the methodology used for searching, consolidating, cleaning, and analyzing data from articles on citizen science in the field of aquatic ecology in the Web of Science and Scopus databases from 2003 to 2024.

After this organization, we classified the information in the articles regarding the focus of participatory monitoring, levels of citizen engagement, training programs, and communication and data transmission methods used; each of these is described below.

(1) Focus of participatory monitoring: (a) Species ecology—articles addressing issues related to the spatiotemporal distribution and behavior of organisms in response to climate and anthropogenic changes affecting aquatic ecosystems; (b) Species conservation—studies focusing on the protection of aquatic biodiversity, particularly species threatened with extinction; (c) Bioindicators—publications that use organisms as indicators to assess the environmental quality of a region and the impacts of natural or anthropogenic factors; (d) Invasive species—articles investigating the origin, introduction sites, and potential dispersion mechanisms of invasive species; (e) Landscape ecology—studies analyzing how aquatic organisms interact in different types of landscapes, examining land use patterns, connectivity, and fragmentation effects; (f) Waste—documents providing information on the geographical distribution and volumes of solid waste items, such as plastics, glass, and metals, in aquatic environments; (g) Water quality—studies primarily focused on analyzing the physicochemical, biological, and/or environmental conditions of water; (h) Species identification—articles centered on the identification of aquatic fauna and flora species; (i) Water management—studies involving the protection, management, flow, and level of water to ensure water security and quality for local populations; (j) Environmental education—documents addressing nature preservation and restoration through sustainable actions aimed at fostering critical and responsible environmental awareness among citizens. For example, see the works of Bernardini et al. [42], Blake and Rhanor [43], Clements et al. [44], Ditria et al. [45], França et al. [46],

Hamer et al. [47], Lyon et al. [48], Pearson et al. [49], Rambahiniarison et al. [50], and Stefanelli-Silva et al. [51].

(2) Types of engagement: (a) Contributory—articles in this category address projects in which citizens play limited roles in data collection and submission of observations; (b) Collaborative—documents in this category discuss initiatives where citizens, in addition to collecting data and submitting observations, contribute to specific stages of the scientific process, such as data analysis and/or dissemination of research findings; (c) Co-created—articles in this category describe projects in which citizens are partially or fully responsible for project design and are actively involved in all or most stages of the scientific process; (d) Contractual—these are cases where researchers or communities hire citizens and request professional scientists to conduct specific scientific investigations and report the results back to the community [52–54].

(3) Training programs: (a) Lecture—articles that emphasize oral communication as the primary method for transmitting knowledge and information about citizen science in the field of aquatic ecology; (b) Course—documents focusing on the development of structured in-person educational activities, organized with a sequence of content aimed at providing participants with specific knowledge and skills; (c) Field practice—a strategy described in studies that focuses on theoretical and practical training; (d) Online platform—articles highlighting virtual environments as the main strategy for training citizen scientists and fostering interaction between scientists and participants [46,55,56].

(4) Methods of communication and data transmission used: (a) Photo and video sharing—studies in which participants share records of species and/or natural events with researchers for scientific studies; (b) Online upload—a process that involves sending Word or PDF files from a device to an internet server; (c) Manual data recording sheet—articles describing simple data collection systems, such as field notebooks, spreadsheets, or formats previously provided by researchers; (d) Sample submission—a method described in scientific studies that involves the systematic collection of various types of samples, which are adequately stored following standardized preservation and storage protocols, and later sent via mail or courier to specialized laboratories for detailed analyses according to the research objectives; (e) Smartphone applications—articles mentioning the use of software programs for mobile devices, developed for the collection of specific data, with the goal of facilitating tasks, providing real-time data, and promoting more significant interaction between users and scientists [57–59].

2.4. Data Analysis

We used a line graph to analyze the temporal trend of publications (i). We applied Pearson's correlation coefficient (r) to assess the association between the variables "Year" and "Number of articles". The r-value ranges from -1 (strong negative correlation) to 1 (strong positive correlation) [8,60]. Using histograms, we represented geographic patterns (ii) and the focus of participatory monitoring (vi). The most relevant research topics (iii) were displayed on a thematic map. The map positions the main research themes into four quadrants: (i) basic themes (high centrality and low density); (ii) motor themes (high centrality and high density); (iii) niche themes (low centrality and high density); (iv) emerging or declining themes (low centrality and low density). The size of the spheres represents the relative frequency of each theme in the literature. At the same time, their position on the X-axis (degree of centrality) and Y-axis (degree of development) indicates their relevance and maturity within the field of study. Other results were represented using frequency charts. We used RStudio software (version 4.4.1) and the Bibliometrix/Biblioshiny packages (version 4.1.4) for all analyses.

3. Results and Discussion

3.1. Temporal Trend of Publications

We found a consistent increase in the number of published articles over the years, with an annual percentage growth rate of 15.33%. This trend was evidenced by a strong positive correlation between the years and the number of publications (r = 0.879, $p < 0.001$), indicating a steady growth in scientific production in this field. The 95% confidence interval for the correlation coefficient was calculated as [0.690, 0.956], reinforcing the robustness of the observed relationship. The highest peak in publications occurred between the years 2022 (n = 27; 14.59%) and 2023 (n = 28; 15.14%) (Figure 2).

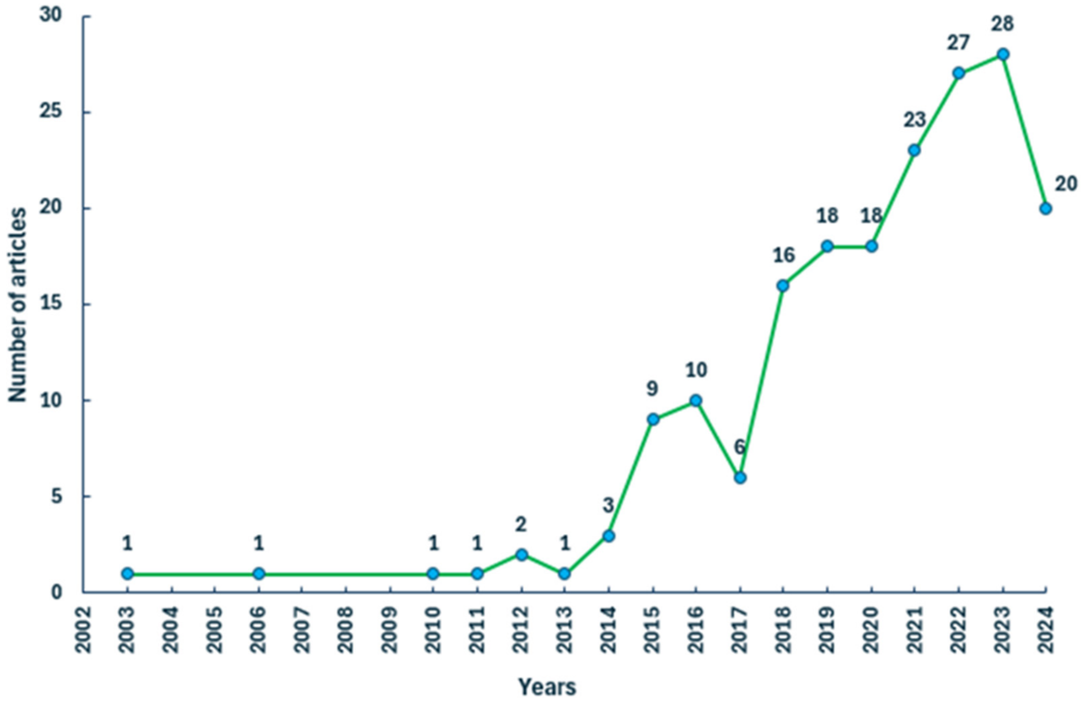

Figure 2. Annual scientific production on citizen science in aquatic ecology (2003–2024). Databases used: Web of Science and Scopus, from 2003 to 2024.

The sharp rise in publications on citizen science in aquatic ecology, mainly since 2015, stems from social, technological, and political factors that have made this field central to scientific research and environmental conservation [19,20]. The development of accessible technologies such as smartphones, georeferencing apps, and online platforms has been key to popularizing citizen science [19]. These tools enable large-scale data collection, sharing, and analysis, making projects more efficient and appealing for researchers and the public [61]. Additionally, machine learning and artificial intelligence have enhanced the analysis of large datasets, improving the accuracy and reliability of results [62].

Another crucial aspect was the launch of key international agreements, such as the Paris Agreement in 2015 [63] and the implementation of the Sustainable Development Goals (SDGs) by the United Nations in the same year [64]. These milestones placed environmental sustainability at the core of global agendas, encouraging innovative practices that combine conservation with social engagement [9,10]. SDG 14 (Life Below Water), SDG 15 (Life on Land), and SDG 17 (Partnerships for the Goals) specifically highlight the need for collaborative efforts to protect aquatic ecosystems and their biodiversity, which has also driven citizen science initiatives as an integrative strategy [2,65,66].

Expanding international collaboration networks has boosted scientific production [8]. Leading countries in this field, such as the United States, Australia, and the United Kingdom, have spearheaded interinstitutional and transnational partnerships, facilitating the exchange of data, methodologies, and expertise in citizen science and aquatic ecology [67]. Meanwhile, emerging contributors like Brazil, with its rich biodiversity and cultural traditions, show growing potential to enhance CS projects [11,27]. Integrating local and traditional knowledge from Indigenous and rural communities can enhance databases and provide solutions tailored to local realities [12].

Rising public awareness of environmental issues such as climate change, water pollution, and biodiversity loss has also fueled engagement in CS projects [19]. Increased scientific communication and social media dissemination have further stimulated public interest [61]. However, disparities in digital access between rural and urban populations remain challenging, requiring efforts to democratize CS participation [68]. Furthermore, the COVID-19 pandemic (2020–2022) significantly reshaped citizen science research [69]. Digital tools and remote engagement strategies became essential, allowing continued contributions, despite social distancing [70]. This shift likely contributed to the surge in publications in 2022 and 2023, as research from these years was consolidated [69].

3.2. Countries with Highest Academic Production and Most Studied Countries

We identified 43 countries conducting research in aquatic ecosystems using citizen science methodologies. Among these, the United States stands out (production: $n = 47$; 25.41%; studies: $n = 43$; 23.24%), followed by Australia (production: $n = 16$; 8.65%; studies: $n = 18$; 9.73%) and the United Kingdom (production: $n = 16$; 8.65%; studies: $n = 15$; 8.11%), leading both in scientific production and as the most studied countries (Figure 3).

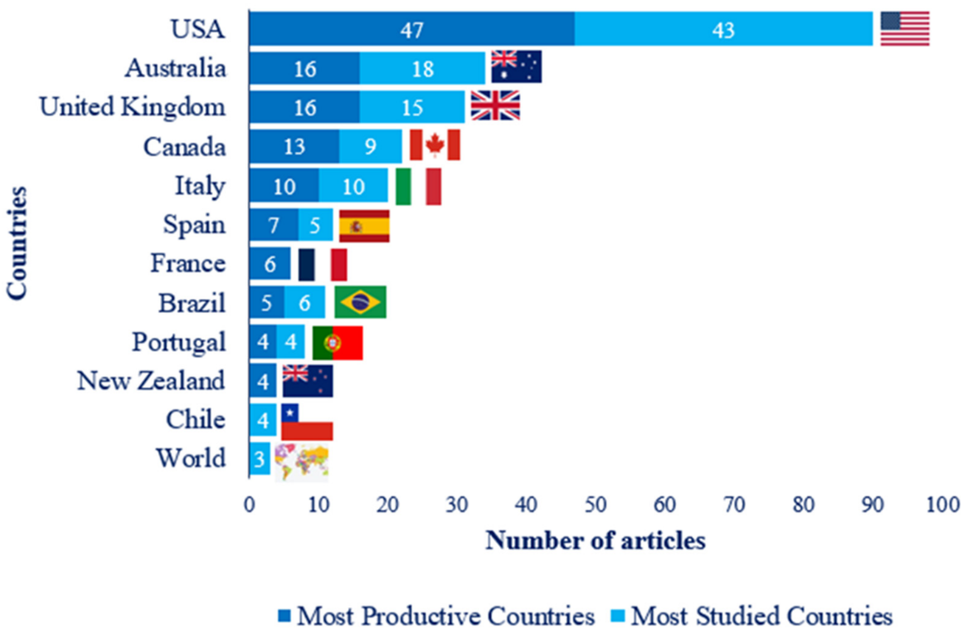

Figure 3. The geographic distribution of the 10 most productive and studied countries in citizen science in aquatic ecology. Databases used: Web of Science and Scopus (2003–2024).

The dominance of certain countries reflects a global trend whereby developed nations, with advanced scientific infrastructure, substantial funding, and well-structured environmental policies, lead citizen science research in aquatic ecology [11,37,40,71]. The United States holds a central role, supported by a robust network of universities, government agencies, and non-governmental organizations that actively promote public participation in environmental monitoring [8,27]. Additionally, the country's diverse aquatic ecosystems, including large rivers, lakes, and coastal zones, further drive research in this field [72].

Australia stands out due to its substantial investment in marine research, its coastal environments, and its great natural diversity [73]. The Great Barrier Reef, for example, is one of the main targets of participatory projects, mobilizing divers and citizens to monitor the rich local biodiversity and assess environmental impacts [74,75]. Well-defined ecological policies and community engagement incentive programs strengthen citizen science initiatives [76]. The United Kingdom, ranked third, has a strong tradition of marine research and aquatic conservation, with universities and civil society organizations working closely together [77]. A notable example is the Olive Ridley Project, which unites researchers, citizen scientists, environmentalists, and veterinarians in marine turtle conservation [78].

Despite the growth of citizen science, the concentration of research in a few developed nations raises concerns about geographical disparities in knowledge production [79]. Tropical regions, home to some of the planet's most diverse and vulnerable aquatic ecosystems, remain under-represented in the literature [80,81]. Factors such as limited funding, weak academic infrastructure, and restricted digital access contribute to this gap [82]. High journal publication fees further hinder research from emerging countries. Additionally, the lack of integration between citizen science and traditional knowledge from Indigenous and riverine communities limits research impact, despite these communities' deep empirical understanding of aquatic ecosystems [11,12,27].

Digital access inequality is another challenge [68]. Limited internet connectivity and smartphone availability in many developing countries restrict community participation in citizen science projects [83]. This prevents remote populations from contributing to and benefiting from scientific advancements, underscoring the need for investments in digital infrastructure and accessible tools [19]. In this sense, to reduce geographical disparities and expand citizen science, strengthening international collaboration networks is essential, fostering equitable partnerships between developed and under-represented regions for knowledge transfer and joint research funding [84]. Integrating traditional and local knowledge into academic projects can enhance aquatic biodiversity conservation, recognizing the vital role of communities living in these ecosystems [12]. Additionally, expanding digital infrastructure and decentralizing scientific funding, with targeted incentives for research in emerging countries and understudied ecosystems, are key strategies to address these challenges [85].

3.3. Most Relevant Research Topics

The thematic map results highlight the current research landscape on citizen science in aquatic ecology (Figure 4). Basic themes include climate change, water quality monitoring, and biodiversity conservation, which align with global environmental challenges and the Sustainable Development Goals (SDGs): SDG 13 (Climate Action), SDG 6 (Clean Water and Sanitation), SDG 14 (Life Below Water), and SDG 15 (Life on Land) [86]. Due to its global significance, climate change is a core theme [87]. Its effects on aquatic ecosystems, such as temperature shifts, altered hydrological patterns, and species distribution changes, are widely recognized [88]. However, its presence as a general category may reflect the lack of established citizen methodologies for monitoring climate change impacts on aquatic ecosystems, revealing a gap in public participation [89]. Biodiversity is the central theme, due to its role in the stability and resilience of aquatic ecosystems [1]. Its importance is driven by the need to document and protect endangered species, especially in biodiversity-rich regions [90]. Water quality monitoring is another primary focus of citizen science in aquatic ecology [91], reflecting growing concerns about pollution and resource degradation. It is directly linked to human health and well-being, as water quality impacts ecosystems and communities [11,92]. Citizen science is crucial in large-scale data collection, enabling continuous and accessible water quality monitoring. This is essential for understanding and addressing the effects of climate change and biodiversity loss in aquatic environments [93,94].

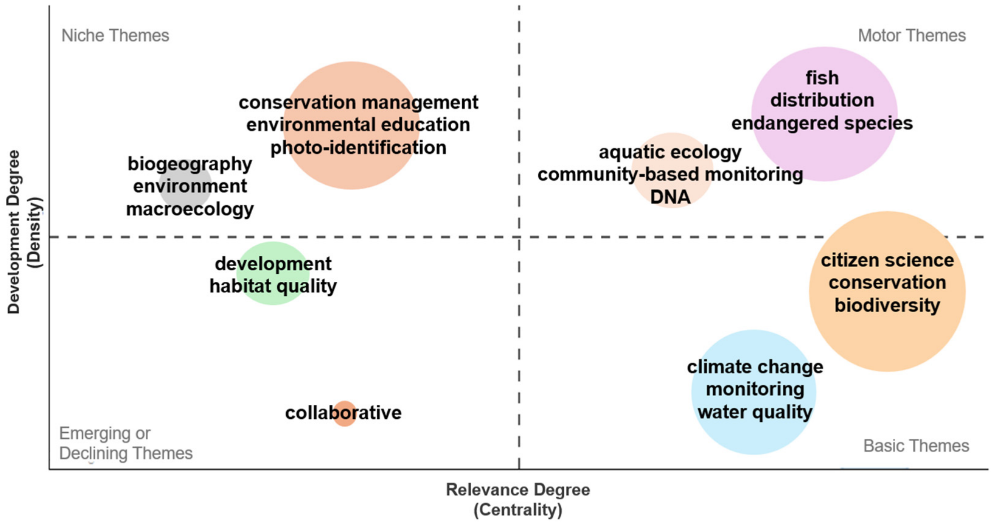

Figure 4. A thematic map of publications on citizen science in the field of aquatic ecology. Databases used: Web of Science and Scopus (2003–2024).

As niche themes, habitat management, environmental education, and macroecology emerge. Habitat management is a fundamental element in local conservation projects, where communities play an active role in ecosystem restoration and protection [95]. This involvement is essential, as active community participation in conservation initiatives strengthens natural resource management and expands knowledge about animal ecology and behavior [96]. This process helps to reduce unfounded fears and prejudices, promoting harmonious coexistence between humans and wildlife, especially in urban environments [16,97]. Similarly, environmental education is essential in fostering community engagement in biodiversity conservation [98]. Initiatives combining education and active participation enhance public awareness of the importance of aquatic ecosystems, encouraging sustainable practices and strengthening involvement in environmental monitoring programs [99].

Finally, emerging or declining themes include project collaboration and habitat quality. Collaboration in scientific projects, especially those based on citizen science, still faces challenges, limited by the predominance of contributory models [100]. While these models are easier to implement and allow for the collection of large volumes of data, they restrict participants' involvement to specific stages, such as sample analysis and result dissemination [101]. As a result, the entire engagement potential, which includes co-creation, analysis, and decision-making, remains underexplored, which may hinder a sense of ownership and the promotion of more active participation in the scientific process [102]. From this perspective, aquatic habitat quality emerges as a key factor for biodiversity and ecosystem functioning, often influenced by anthropogenic impacts, such as pollution, habitat fragmentation, and land use changes [103]. In the context of CS, habitat quality assessment has been widely incorporated into biomonitoring programs, where volunteers use standardized protocols to evaluate aquatic ecosystems' physical, chemical, and biological parameters [104].

3.4. Most Studied Types of Aquatic Ecosystems

The results show a clear dominance of studies focusing on marine ecosystems, which accounted for 63.27% of the publications analyzed (n = 112). Within this category, seas were the most commonly studied environments (n = 89; 50.28%), followed by oceans (n = 23; 12.99%) (Figure 5). Freshwater ecosystems represented 30.49% of the studies (n = 53), with the highest number of studies conducted in rivers (n = 18; 10.17%), watersheds (n = 11; 6.21%), and lakes (n = 11; 6.21%). Smaller lentic environments, such as lagoons (n = 5; 2.82%), streams (n = 5; 2.82%), and groundwater (n = 4; 2.26%), were less frequently represented (Figure 5). Estuarine ecosystems, which represent transitional zones between freshwater and marine environments, were under-represented in the literature, with only five studies identified (2.82%). Finally, six publications (3.42%) did not specify the type of ecosystem analyzed (Figure 5).

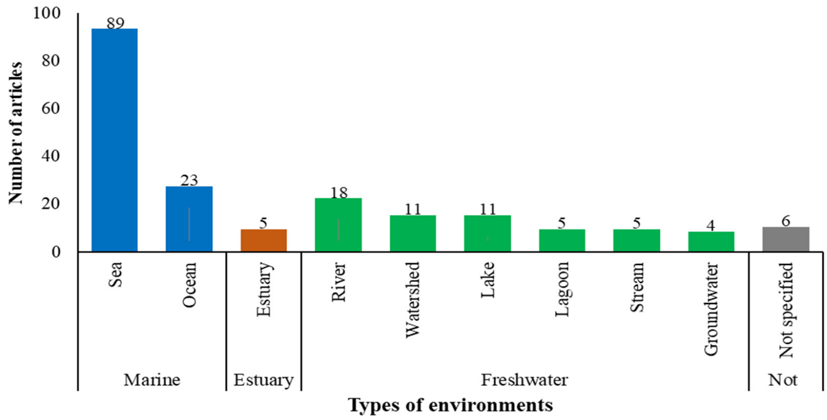

Figure 5. Types of environments where citizen science studies in aquatic ecology are conducted. Databases used: Web of Science and Scopus (2003–2024).

This distribution partly reflects the priorities established by the Sustainable Development Goals (SDGs), which guide global actions for the conservation of natural resources and influence research funding agendas [105]. SDG 14—Life Below Water explicitly focuses on oceans, seas, and marine resources, aiming to mitigate impacts such as pollution, overfishing, and global warming [106]. This prioritization largely explains the dominance of studies on marine and coastal ecosystems observed in the data. Environments such as seas and oceans receive wide attention due to their ecological, economic, and social importance and the high global visibility of issues affecting them, such as marine biodiversity loss and coral reef destruction [107,108]. Additionally, the charisma of marine species and the popularity of monitoring activities, such as beach cleanups and biodiversity observation (e.g., sea turtle nesting and nest monitoring), facilitate public engagement and the implementation of citizen science programs [109]. However, although marine ecosystems cover a significantly larger area, freshwater ecosystems host more than 10% of all known species, including approximately one-third of vertebrates and half of all fish species, despite occupying less than 1% of the Earth's surface [110].

On the other hand, SDG 15—Life on Land includes freshwater ecosystems, but as an extension of its approach to terrestrial environments [111]. This may justify the lower representation of studies on rivers, watersheds, lakes, streams, and groundwater aquifers. Despite playing essential roles, such as water supply and biodiversity support, these environments face challenges related to physical invisibility and lower public engagement [1]. This gap is particularly evident in the case of groundwater aquifers, which represent a tiny fraction of studies, despite being crucial for the water supply of millions of people [112].

The results suggest that the emphasis on marine ecosystems, driven by SDG 14, reflects global conservation priorities [105]. However, the under-representation of freshwater ecosystems indicates the need for greater integration between SDGs 14 and 15. For example, impacts on rivers and watersheds often ripple into seas and oceans, highlighting the interconnectivity of these systems [113]. Strategies that recognize this relationship could help to balance research and conservation efforts.

Transitional environments, such as estuaries and lagoons, have seldom been identified in scientific studies. Despite creating a highly biodiverse zone that combines characteristics of both freshwater and marine environments [114,115], they function as nurseries for many marine species and filter pollutants before they reach the oceans [116,117]. These aquatic ecosystems are often neglected, likely due to their difficult-to-access areas, the presence of mangrove forests, or unstable beds [118,119]. Furthermore, access may rely on river transportation or specialized equipment, which hinders citizen participation without proper infrastructure [120]. Most public policies and citizen science project funding prioritize areas with higher social or economic impact, such as coastal regions, touristic beaches, or urban water bodies [121,122]. To reduce the observed gaps, it is necessary to expand citizen science efforts in freshwater ecosystems, particularly those that are less accessible, such as streams and aquifers [1,112].

3.5. Most Studied Taxonomic Groups

Fish were the most studied taxonomic group in citizen science initiatives in aquatic ecology, representing 30.64% of the analyzed studies (Figure 6). This pattern reflects fish's ecological and economic importance, being widely recognized as sensitive indicators of environmental quality and critical resources for commercial and subsistence fishing [123–125]. The accessibility of fish data, through methods such as sport fishing or monitoring in aquariums, may also have contributed to their predominance in studies [126]. This is especially true considering that many people rely on the resources provided by the fishing market for their livelihoods.

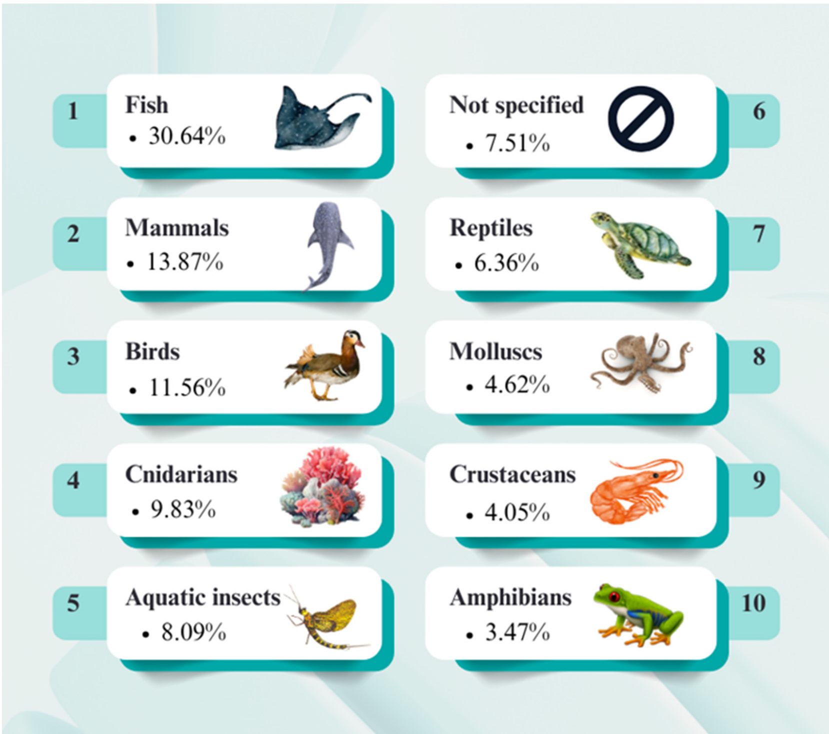

Figure 6. The most studied biological groups in articles on citizen science in aquatic ecology from the Web of Science and Scopus databases (2003–2024).

Aquatic mammals (13.87%) and birds (11.56%) were also well represented, possibly due to their charismatic appeal and visibility, traits that facilitate public participation in citizen science programs [127,128]. This pattern can be partially explained by the human tendency to show greater empathy and interest in phylogenetically closer organisms, which influences conservation preferences and engagement in environmental monitoring activities [129]. For example, dolphins, whales, and aquatic birds frequently attract public interest in community monitoring activities and ecotourism [130]. The observation of these groups is widely promoted in citizen science programs, especially in coastal regions, where human–wildlife interactions are frequent [131]. This taxonomic bias can impact conservation priorities, favoring charismatic species over others that are less visible or phylogenetically distant from humans [132].

On the other hand, groups such as amphibians (3.47%), molluscs (4.62%), and crustaceans (4.05%) were less represented. This low representation may be linked to the lack of charisma associated with these groups or the practical difficulties involved in their sampling, such as the need for specialized techniques for collection and identification [133,134]. Additionally, aquatic insects accounted for only 8.09% of studies, suggesting a potential underutilization of these organisms as water quality indicators in citizen science projects, despite their widespread use in traditional scientific research [135]. Smaller specimens are typically identified only at the family level, which may further limit their use in certain studies [136,137]. Finally, the unspecified category (7.51%) reflects the lack of a precise taxonomic classification in some studies. This could indicate that many projects focus on monitoring aquatic ecosystems without prioritizing specific groups, or that there are limitations in the metadata descriptions available in scientific databases [138].

The predominance of specific taxonomic groups may also be linked to geographical biases, as research tends to be concentrated in regions with higher financial resources [82]. Citizen science programs are more common in areas such as North America and Europe, where the distribution of aquatic mammals, birds, and fish may influence the selection of monitored groups [17,139]. Additionally, these regions' infrastructure and technological support facilitate data collection and analysis for these groups [8].

3.6. Focus of Participatory Monitoring

The results indicate that most participatory monitoring efforts in citizen science within aquatic ecology focus on species ecology (n = 69) and species conservation (n = 65) (Figure 7).

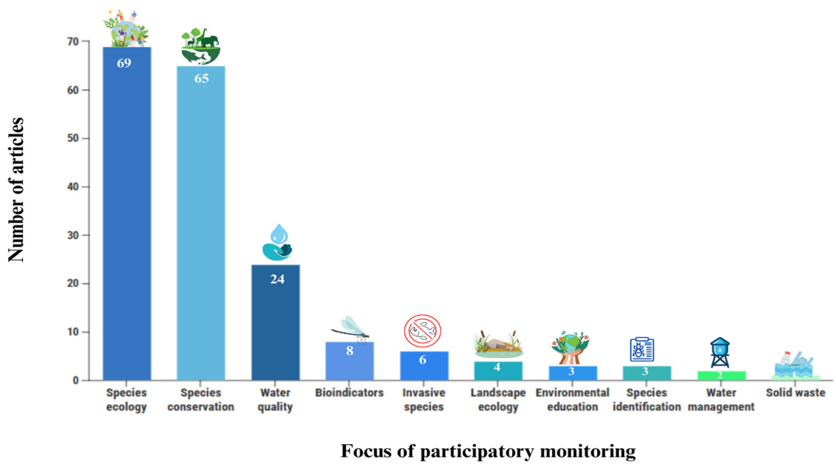

Figure 7. The focus of participatory monitoring in scientific articles on citizen science in aquatic ecology, available in the Web of Science and Scopus databases (2003–2024).

This predominance reflects a global trend of prioritizing topics that, in addition to being scientifically relevant, have strong public appeal, due to the ecological importance of the monitored species or the need to protect threatened species [140,141]. Studies indicate that this thematic choice is often linked to its greater capacity to engage participants, as it evokes emotional interest and fosters a deeper connection with biodiversity [142]. Additionally, the data generated by these programs are highly relevant for informing conservation policies and guiding management practices, reinforcing their central role in global participatory monitoring strategies [143,144].

Another notable aspect of the results is the emphasis on water quality (n = 24), a key topic in aquatic ecology [11]. The attention directed to this topic may be attributed to several factors, including its direct relationship with environmental health and ecosystem services that are fundamental to human well-being [145], such as the provision of drinking water and support for aquatic biodiversity [1]. Additionally, water quality monitoring plays a central role in identifying environmental impacts, especially within citizen science initiatives, contributing to detecting pollutants, eutrophication processes, and other environmental challenges [92,94]. Projects focused on water quality tend to be highly accessible to citizen scientists, as they often rely on practical tools and test kits that do not require advanced technical training [146]. This combination of operational ease and the urgent need for water pollution monitoring at different scales makes water quality a priority in various citizen science initiatives [92,94].

On the other hand, topics such as bioindicators (n = 8), invasive species (n = 6), and landscape ecology (n = 3) were less represented. The low attention to these topics may be attributed to technical and conceptual barriers. For instance, using certain bioindicators often requires specialized skills for identification and data interpretation, which can limit the participation of citizens without technical training [104]. However, some taxonomic groups, such as Odonata, can be identified at the suborder level (Zygoptera and Anisoptera), allowing for inferences to be made about aquatic ecosystem quality and facilitating their inclusion in citizen science programs [135]. Similarly, monitoring invasive species can pose logistical and methodological challenges, such as early detection and differentiation between native and invasive species, which hinder its broad implementation in participatory programs [17].

The low representation of environmental education, water management, and solid waste ($n \leq 2$) highlights a significant gap. Although these topics have high environmental and social relevance, their inclusion in citizen science programs appears to be limited, possibly due to factors such as lower emotional appeal, limited access to data collection tools, and difficulties in linking these topics to tangible conservation objectives [104,129].

3.7. Types of Participants and Levels of Citizen Engagement

We detected a predominance of participants from urban areas (60.51%) (Figure 8a) in citizen science projects in aquatic ecology, which sociocultural and structural factors can explain. Urban populations are more exposed to these initiatives due to their proximity to research centers, non-governmental organizations, and universities, which often lead such projects [147,148], in collaboration with schools and local communities. Additionally, urban citizens tend to have greater access to technologies, such as smartphones, apps, and the internet, which are essential tools for engaging in data collection and sharing platforms [149,150].

On the other hand, specific groups, such as divers and fishers, play crucial roles in citizen science initiatives focused on aquatic ecology. The significant participation of divers (15.90%) highlights their importance in projects related to underwater environments. Divers often have an intrinsic interest in aquatic ecosystem conservation, driven by their direct connection with these environments [151,152]. Organizations like the Reef Life Survey, which trains recreational divers to monitor marine biodiversity, demonstrate how this group can contribute to high-quality data [153]. These initiatives emphasize that divers' technical expertise is essential for the success of monitoring coral reefs, marine biodiversity, and environmental impacts [154].

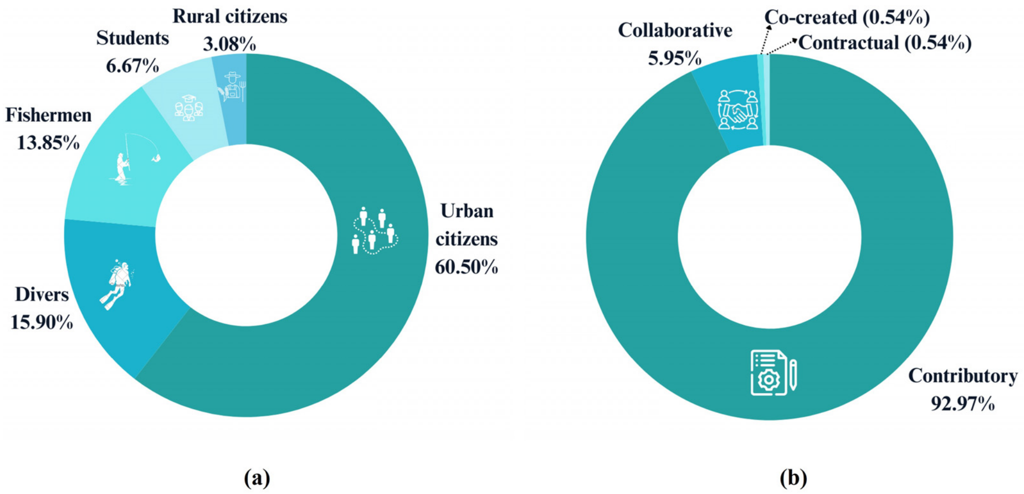

Figure 8. (**a**) Types of participants. (**b**) Levels of citizen engagement in citizen science studies in the field of aquatic ecology available in the Web of Science and Scopus databases (2003–2024).

Fishers, representing 13.85% of participants, also play a crucial role, due to their recognized traditional ecological knowledge. This group provides in-depth insights into ecological dynamics, accumulated through years of direct observation [155,156]. Initiatives such as the Fishers' Knowledge Project, which integrates traditional practices into fisheries' stock monitoring and environmental change assessments, highlight the importance of incorporating this knowledge into conservation efforts [157]. However, logistical barriers, such as limited access to technology and communication gaps between researchers and fishing communities, may hinder their full engagement [158].

Despite their engagement potential, students comprise only 6.67% of participants, a relatively low percentage, due to time constraints caused by educational demands, as well as the lack of projects integrated into school curricula [159]. Educational initiatives incorporating citizen science into formal education, such as water quality monitoring in science classes, have increased student interest and participation [160,161]. Integrating citizen science projects into educational settings could improve student representation and enhance scientific literacy [162].

The low participation of rural citizens (3.08%) highlights significant challenges related to access to technology and infrastructure. Many citizen science projects rely on digital platforms, which can exclude communities with limited access to these tools [163]. Additionally, the disconnect between research centers and rural communities leads to the under-representation of these populations, even in initiatives that could directly benefit their local ecosystems [164]. Successful examples, such as the Indigenous Guardians Program, which integrates traditional and scientific knowledge for ecosystem monitoring, demonstrate that including these populations can lead to more substantial environmental conservation outcomes [12,165]. Investing in digital training, local partnerships, and participatory methodologies is crucial to overcoming these barriers and valuing traditional ecological knowledge [27].

Furthermore, the analysis of engagement levels reveals the predominance of the contributory model (92.97%) (Figure 8b), which stands out for its simplicity, allowing large-scale data collection at a low cost and with minimal training requirements [101]. The Redmap project employs a contributory citizen science approach, inviting recreational fishers and divers to submit photographs of species observed or caught outside of their known or expected geographic distributions [166,167].

However, collaborative (5.95%) and co-created (0.54%) models are rarely explored, despite their more significant potential for social and scientific impact [54]. These models require more planning, continuous training investments, and public policies encouraging citizen inclusion in scientific design and analysis [168]. The Secchi app is an example of a collaborative project, where citizens measure seawater turbidity using a Secchi disk and report corresponding phytoplankton concentrations through a mobile app, while also analyzing and disseminating research results [169].

The contractual engagement level (0.54%) also showed low representation. In these projects, communities request professional researchers to conduct specific scientific investigations and report the results to the community. In rare cases, researchers pay citizens to collect data [170,171]. An example is the initiative by Fisheries and Oceans Canada, which has developed a network of paid citizen scientists to monitor their local beaches during the summer. These citizen scientists search for evidence of capelin (fish) spawning and categorize their observations [171].

3.8. Training Programs and Most Commonly Used Methods of Communication and Data Transmission

The most used training programs include online platforms (n = 43; 25.75%), courses (n = 36; 21.56%), field practice (n = 26; 15.57%), and lectures (n = 11; 6.59%) (Figure 9a). Notably, many studies did not specify the type of training strategy used (n = 51; 30.54%). Additionally, the most utilized methods of communication and data transmission include photo and video sharing (n = 88; 38.77%), online upload (n = 54; 23.79%), manual data recording sheets (n = 50; 22.03%), sample submission (n = 21; 9.25%), and smartphone applications (n = 14; 6.17%) (Figure 9b).

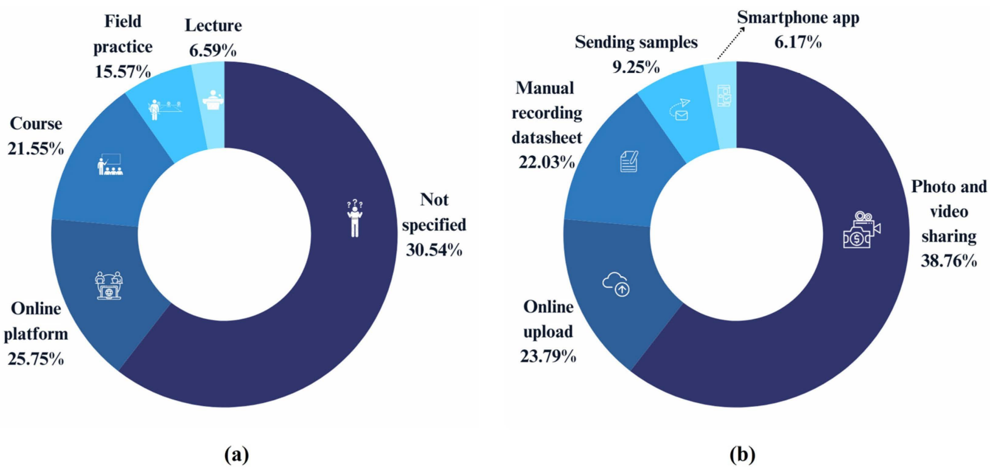

Figure 9. (**a**) Training programs. (**b**) The most commonly used methods of communication and data transmission in citizen science studies in the field of aquatic ecology available in the Web of Science and Scopus databases (2003–2024).

The most used training programs include online platforms, courses, and field practices. These methods reflect diverse approaches, combining digital accessibility with hands-on experiences [172]. However, the lack of specification regarding participant training in some studies is concerning, as unclear training methods may compromise data reproducibility and quality [173]. Additionally, adopting interactive techniques, such as mobile applications and educational games, could be expanded to engage new audiences and provide accessible training [174].

The data reflect the popularity of visual tools such as photos and videos, which facilitate species observation, identification, and event documentation [175]. The use of online uploads and manual data recording sheets suggests a combination of digital technologies and traditional methods, which are commonly applied in citizen science projects [29]. The submission of physical samples is primarily used for more detailed studies, requiring analysis in specialized research laboratories [26]. Despite the growth of mobile technology, the low adoption of mobile apps highlights an opportunity to expand the use of these interactive tools, which could enhance participant engagement [176].

4. Conclusions

The data reveal an increase in academic production on citizen science in the context of aquatic ecology in recent years, especially between 2022 and 2023, indicating a growing interest in this field. Scientific activity in the most productive and studied countries often involves specialists from various fields, allowing for a comprehensive view of challenges and innovative solutions for marine and freshwater aquatic ecosystems. The combination of these factors places these countries at the forefront of aquatic scientific research and the use of participatory approaches, such as citizen science, to address environmental problems. The analysis of scientific collaboration networks highlights the U.S. as a central hub, with strategic partnerships with countries such as Australia, the United Kingdom, and Canada. Nations with more excellent research investment lead global networks, benefiting from factors such as the use of English, economic proximity, and exchange programs.

Citizen science studies in aquatic ecology are predominantly concentrated in coastal and marine environments, while smaller freshwater ecosystems, such as underground systems and estuaries, remain relatively neglected. To expand the scope of studies, it is essential to encourage citizen science practices in under-represented aquatic environments, increasing awareness and public involvement in a greater diversity of aquatic ecosystems. The focus of citizen science monitoring in aquatic ecology is highly species-oriented, particularly on topics related to ecology and conservation. On the other hand, important issues such as waste, water levels, and environmental education are under-represented. Diversifying the issues involved is crucial for increasing public engagement in less-explored areas and promoting an integrative approach considering biodiversity and environmental impacts.

Efforts are needed to engage rural communities, traditional peoples, and students, who have the potential to provide valuable data and unique knowledge. Initiatives promoting collaborative and co-created engagement levels can strengthen the science–society relationship, leading to greater scientific democratization and environmental awareness. Projects should specify training methods and seek innovative strategies to improve data quality and participant engagement. The development of customized applications can make studies more accessible and accurate. Encouraging a broader diversity of biological groups, developing tools and educational materials to facilitate the identification of less charismatic organisms, and monitoring groups with critical ecological functions, together with fostering citizen participation in less-studied regions where these organisms are more diverse, are key strategies to enhance data quality and maximize the impact of studies on conservation and environmental management.

5. Limitations and Future Perspectives

5.1. Limitations

This study employed a rigorous scientometric approach to map and analyze the scientific literature on citizen science in aquatic ecology. However, we acknowledge that there are inherent limitations to this methodology. One of these limitations relates to the coverage of the databases used. Although Web of Science and Scopus are widely recognized and frequently used in scientometric analysis, it is possible that relevant articles published in journals indexed in other specialized or regional databases were not included in our search. This limitation may affect the representativeness of the analyzed scientific production, particularly in Global South countries, where citizen science initiatives may be documented in journals with limited international circulation or non-indexed institutional reports. Another important factor is the language restriction, as the journals indexed in the selected databases were predominantly published in English, reflecting a potential bias.

Additionally, excluding publications such as conference proceedings, book chapters, and technical documents may have omitted valuable contributions to the practical implementation of citizen science in aquatic ecology. Many citizen science initiatives are led by non-governmental organizations, environmental agencies, and local communities, whose outputs are not continuously published in peer-reviewed journals, despite containing valuable insights into participatory methodologies, operational challenges, and social impacts.

Another significant limitation concerns data interpretation. Although efforts to standardize article searches and classification were rigorous, the possibility of bias in the study categorization and analysis cannot be completely ruled out. Despite these limitations, this study contributes to understanding trends, patterns, and gaps in citizen science applied to aquatic ecology, and can serve as a foundation for future research.

5.2. Future Perspectives

A fundamental perspective within the scope of this research is the strengthening of methodologies that ensure data quality and standardization. The use of new technologies, such as remote sensors, digital platforms, mobile applications, and environmental DNA (eDNA) analysis, can significantly contribute to increasing the reliability of data generated by volunteers. At the same time, it is essential to develop accessible protocols and educational tools to facilitate the participation of diverse citizen profiles, ensuring that projects are inclusive and representative of the social and cultural diversity of the communities involved.

Finally, expanding citizen science efforts to under-represented regions, such as the Amazon, Southeast Asia, and parts of Africa, can contribute to a broader and more equitable perspective on aquatic ecology on a global scale. Most citizen science studies and initiatives are concentrated in European and North American countries, leaving gaps in megadiverse regions that are highly impacted by environmental changes.

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