CITIZEN SCIENCE:
THEORY AND PRACTICE

Research Infrastructures in Citizen Science: State of Knowledge and Taxonomic Framework As a Pathway to Sustainability

REVIEW AND SYNTHESIS PAPER

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KAREN SOACHA-GODOY
PRANESH PRAKASH
ANA ÁLVAREZ
ADRIANA GIRALDO TEJADA
ALEXANDRE LÓPEZ-BORRULL
XAVIER SALVADOR
CARLOS RODERO
DIEGO TORRES
IVAN RODERO
MABEL AYURE
JAUME PIERA

*Author affiliations can be found in the back matter of this article

ABSTRACT

Citizen science platforms (CSPs) and citizen observatories (COs) are rapidly expanding research infrastructures (RIs) that support the growth of citizen science. These systems have boosted data collection capabilities and broadened participant engagement across spatial and demographic dimensions. Despite their essential role in advancing citizen science, the current state of knowledge of these infrastructures remains largely unexplored, affecting both theoretical understanding and practical implementation. The study discussed herein addresses this knowledge gap through a systematic review of 474 articles, with in-depth analysis of 72 publications spanning a 15-year period across multiple disciplinary domains. The methodological framework integrates bibliometric analysis with qualitative investigation, utilizing Web of Science and Scopus databases, supplemented by grey literature from Zenodo and Google Scholar. Findings indicate that research in this field has developed across three main waves: technological development and engagement, monitoring systems and openness, and frontiers technologies. This evolution reflects a progression in the CSP body of knowledge from technical documentation to complex socio-technological systems. Analysis of 450 articles identified 98 unique terms referring to CSPs, highlighting conceptual fragmentation. To clarify the landscape of overlapping, we propose a CSP purpose-based taxonomic framework comprising nine platform categories, contributing to a clearer understanding of the CSPs' role in citizen science. Additionally, our systematic analysis reveals key research trajectories essential for strengthening CSPs and COs as sustainable infrastructures.

CORRESPONDING AUTHOR:
Karen Soacha-Godoy
EMBIMOS research group, Institut de Ciències del Mar (ICM-CSIC), Barcelona, Spain; Universitat Oberta de Catalunya (UOC), Barcelona, Spain
soacha@icm.csic.es

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INTRODUCTION

Participatory sciences, including citizen science, are seen as a growing practice in which people, in and out of the academic domains, collaborate to produce new knowledge for science and society (Vohland et al. 2021). Recently, citizen science has witnessed a global surge in participation, with volunteers generating a substantial influx of data spanning diverse domains. Particularly notable is the substantial contribution to biology, ecology, and biodiversity conservation efforts (McKinley et al. 2017). However, the impact of citizen science extends well beyond this domain, permeating a spectrum of scientific disciplines, including astronomy, geography, health, social sciences, and physics (Palumbo, Fakhar Manesh, and Sorrentino, 2021). Within the specialized context of environmental monitoring and biodiversity assessment, millions of volunteers undertake biodiversity censuses and collect environmental data, harnessing an array of technologies. These span conventional web interfaces and mobile applications, alongside cutting-edge tools such as do-it-yourself (DIY) instruments like KduPRO (Rodero et al. 2022), and sensor-driven applications, with an emerging integration of machine learning capabilities. Although citizen science implementation does not rely exclusively on digital technology, an increasing number of citizen science initiatives are using online platforms for data collection, management, monitoring, sharing, and publication, as well as for participant engagement and community building (Margherita 2021).

The integration of information and communication technologies (ICTs) into citizen science has enabled the creation of datasets with extensive global coverage, nearly in real time, and readily accessible to anyone interested (Newman et al. 2012). One example is the contribution of citizen science to the Global Biodiversity Information Facility (GBIF). Conceived as a global initiative in 2001, GBIF has facilitated the publication of over 2.5 billion open biodiversity records spanning all seven continents. By the year 2016, citizen science accounted for over 50% of the data available within GBIF, highlighting its key role in international biodiversity monitoring efforts (Chandler et al. 2016). Citizen science platforms (CSPs), especially citizen observatories (COs), are among the most prolific data contributors to the GBIF. The top three amongst them are eBird, Artportalen, and iNaturalist (Waller 2019). iNaturalist, founded in 2008, has a community exceeding five million contributors that have created 113 million nature records (iNaturalist n.d.). Similarly, eBird, originating in the year 2002, has more than 723,000 participants, resulting in a repository surpassing more than 1.1 billion bird observations (eBird, 2021).

Owing to their capacity for extensive data generation across diverse domains, CSPs and COs have increasingly attracted attention from academic and practical fields (Liu, Grossberndt, and Kobernus 2017). COs are recognized within political contexts, highlighted by the European Union's support through programs such as Horizon 2020 and Horizon Europe. These initiatives specifically target the development and operationalization of COs in critical areas like environmental monitoring, earth observation, sustainable development, and climate adaptation, aiming to utilize citizen-contributed data to inform environmental policies and integrate citizen science into policy frameworks (Montargil and Santos 2017a). The acknowledgment of COs and other forms of citizen-generated data as essential for tracking SDG progress is evident in their application to an increasing number of SDG indicators and recognition at high levels of global governance (Fritz et al. 2019; Fraisl et al. 2020).

The development of the concepts of CSPs and COs are at an early stage, and there are multiple approaches to defining them, especially when it comes to COs. One approach is to consider CSPs as an umbrella term that groups together web-based infrastructures with one single entrance point that contains one or several functionalities among them, like displaying data, cataloguing citizen science initiatives, and providing access to learning resources, among others (Liu et al. 2021). Within the spectrum of CSPs, those whose main objective is to facilitate the collection and management of citizen science data are known as COs. Some conceptualizations place COs as a part of a subset of citizen science (Gold 2018; Gold and Wehn 2020), others as an evolution of citizen science (Grainger 2017), and some platforms define themselves as technological means that facilitate citizen participation in citizen science (LandSense Citizen Observatory et al. 2019). There is no consensus on what a CO is, what it should do, and how it should be made (Hunt et al. 2015; Montargil and Santos 2017b; Grainger 2017). Deepening the understanding of what they represent could contribute to their long-term viability and strengthen their role in the development of citizen science.

Until now, no research has provided an overview of the state of knowledge of both CSPs and COs in citizen science across various domains, including a systematic review of literature on both concepts. The research that comes closest to this objective is available in three documents. The first one, by Palacin-Silva et al. (2016), analysed global and European trends in environmental applications, practices, engagement techniques, and technology use based on 108 observatories identified from the citizen science literature review. The second one, carried out by Grainger (2017), focused on the field of earth observation, where the concept of CO is discussed, as well as the essential features of COs, and a framework to integrate COs in the field of earth observation. The last one, by Rathnayake et al. (2020), like this review, sought to map the current landscape of research on COs. However, their review was specifically focused on COs in environmental monitoring, overlooking the broader scope of CSPs across various areas. While their study identified main topics within the literature, it did not provide an in-depth analysis of the state of research in CSPs or COs.

Given the existing knowledge gap, a bibliometric analysis and a systematic review were deemed necessary to provide a recent and integrated overview of the state of knowledge regarding CSPs and COs, as well as to offer insights for the conceptual development of the digital infrastructures supporting citizen science. The review was guided by the following research questions:

R.Q.1: What is the state of knowledge about CSPs and COs?
R.Q.2: How can the analysis of the existent knowledge of CSPs and COs advance our understanding of their roles in citizen science, and to what extent does this understanding contribute to their sustainable development and implementation?

The examination of these questions reveals an epistemological evolution of CSPs and COs, characterized by a complementary dynamic: European Union (E.U.) contributions to theoretical frameworks alongside United States (U.S.) emphasis on technological implementation. The analysis identifies three distinct developmental waves: technological development and engagement, monitoring systems, and openness and frontier technologies. Within this evolution, bibliometric analysis has uncovered 98 unique platform descriptors, reflecting the dynamic nomenclature, functions, and institutional identity of CSPs. This terminological diversity necessitated the development of a purpose-based taxonomic framework, advancing both the systematic categorization and theoretical conceptualization of CSPs.

The methodology section herein outlines the systematic review process undertaken to analyse peer-reviewed and grey literature on CSPs and Cos. The results section presents key thematic findings examining the current state of knowledge as well as the chronological and thematical evolution. The discussion section situates CSPs and Cos within broader Ris debates. Finally, the analysis suggests key research priorities necessary for the conceptual and operational evolution of CSPs.

METHODS

This study presents a systematic review following the PRISMA (preferred reporting items for systematic reviews and meta-analyses) 2020 methodology (Page et al. 2021), combining quantitative and qualitative methods to examine CSPs and Cos research production. The research uses bibliometric analysis and thematic examination of literature from academic and grey sources through Scopus and Web of Science (WoS) databases, with additions from Zenodo and Google Scholar.

The method used a search strategy in September 2023, focusing on the terms "observatory" and "platform" within abstracts, titles, and keywords. These terms were selected for their scope in technological applications within citizen science. The review focused on citizen science and concepts including "participatory science," "crowd science," "community science," and related terms listed in Supplemental file 1: Appendix A. The exclusions included terms with "lab" and "participatory sensing", as these moved beyond the review's technological focus or did not align with the concept of citizen science adopted by this review. See Supplemental file 1: Appendix A for the final search string crafted for the exploration within the academic databases.

The search yielded 2,148 articles, refined through duplicate removal (789 articles), resulting in 1,359 publications. Screening based on criteria led to the exclusion of 909 papers, creating a dataset of 450 articles. The inclusion criteria required engagement with observatories or digital platforms within citizen science, while excluding publications that mentioned platforms without analysis or did not centre the platform in their work. Figure 1 outlines the systematic review process. The bibliometric dataset is available in the Supplemental file 2: Appendix B.

The 450 articles were classified according to their primary purpose, offering an overview of academic production in this field. Therefore, we grouped them into the following four categories: CSPs and COs documentation (COD; n = 198), focusing on platform components and implementation; CSPs and COs experiences (COE, n = 31), examining platform use contexts; CSPs and COs analysis (COA; n = 48), investigating platform function, implementation, or conceptualization; and CSPs and COs linked (COL; n = 173), which is not included in the previous categories yet contributes to the broader research panorama of CSPs. The method incorporated 24 supplementary documents, mainly grey literature, identified through searches in Zenodo, Google Scholar, and reference lists.

The set of publications served as the source for the quantitative analysis, including bibliometric analysis, which examined abstracts, keywords, titles, and category-specific content. The qualitative analysis focused on a refined dataset of 72 articles, comprising the 48 COA publications and the 24 additional documents. This subset served as the basis for an in-depth thematic examination, synthesis, and contextualization of the research landscape surrounding CSPs and Cos.

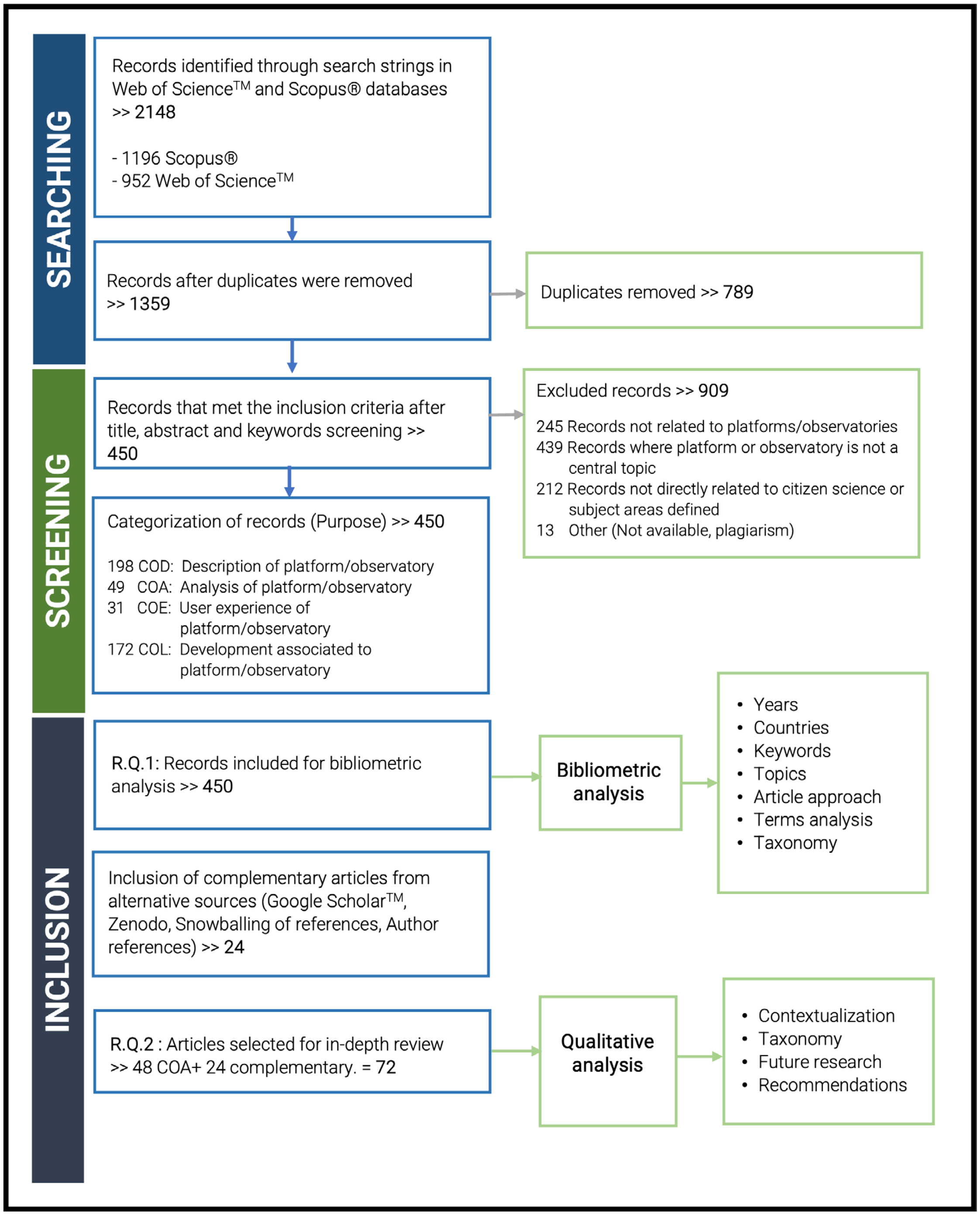


Figure 1 Overview of the method used for the systematic review. Based on the PRISMA (preferred reporting items for systematic reviews and meta-analyses) methodology to answer the research questions.

CITIZEN SCIENCE PLATFORMS AND CITIZEN OBSERVATORIES: CURRENT KNOWLEDGE LANDSCAPE

The systematic review identified 474 publications in the CSPs and COs literature corpus, with peer-reviewed articles (n = 450) constituting the primary scholarly output. Knowledge production emerged in 2009, with a notable inflection point occurring in 2021, as shown in Figure 2. This period marked a significant acceleration in scholarly output, characterized by a twofold increase from 40 publications in 2020 to approximately 90 publications annually in 2021–2022, suggesting a maturation of the field and growing academic recognition.

The knowledge distribution of research reveals a balanced bifurcation between technological documentation (COD) and investigations of engagement-technology methodologies and data dynamics (COL), each comprising

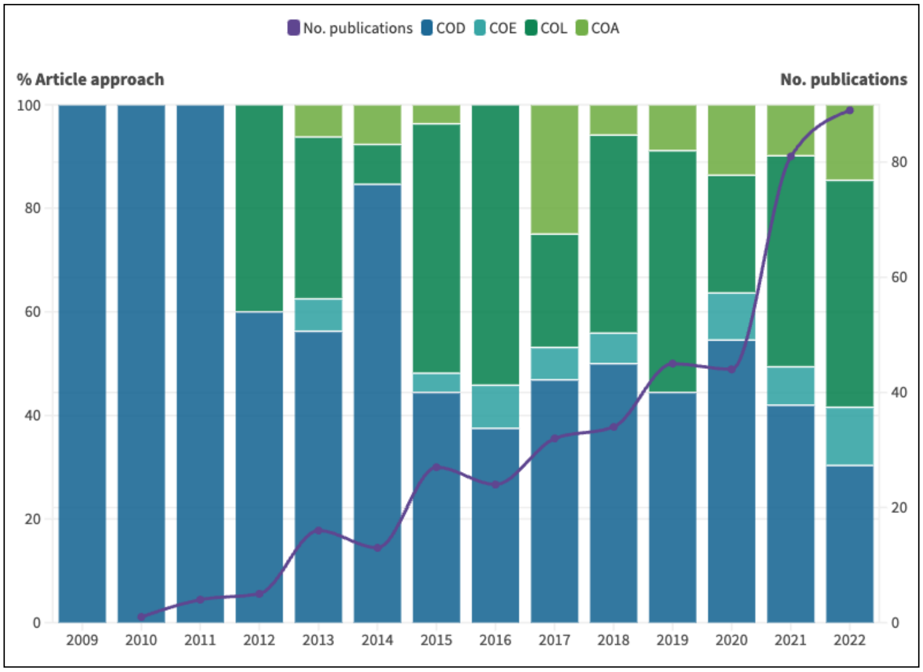


Figure 2 Citizen science platforms (CSPs) and citizen observatories (COs) publications between 2009 and 2022. Chronological distribution of published articles about CSPs and COs, alongside a categorization based on their approach. COD: CSPs and COs documentation, COE: CSPs and COs experiences, COL: CSPs and COs linked, COA: CSPs and COs analysis.

approximately half of the total corpus. However, this apparent equilibrium masks gaps in empirical validation, as evidenced by the limited representation of user experience studies (COE) and research examining CSPs and Cos as the primary unit of analysis (COA), which collectively constitute less than 20% of the scholarly output.

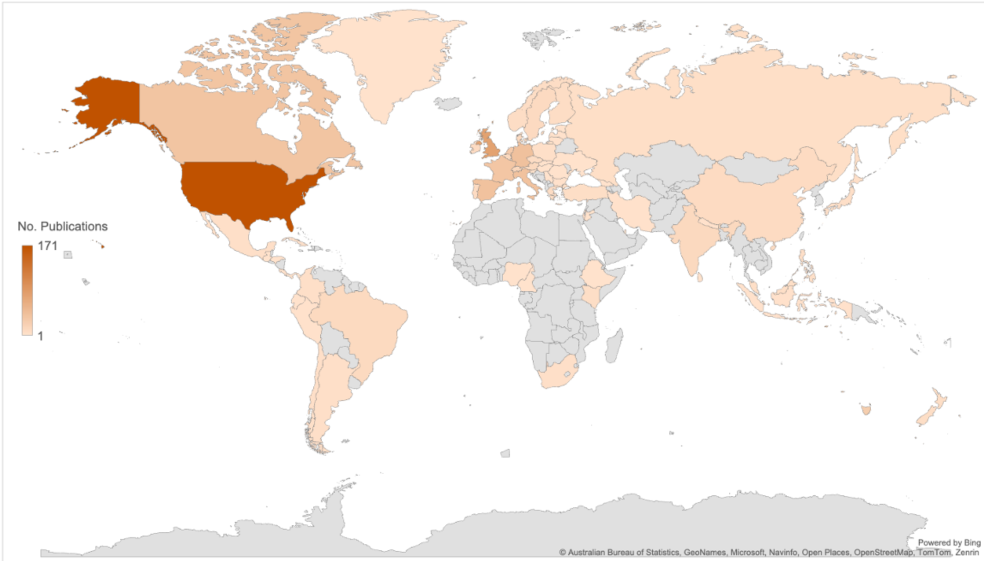
The knowledge production of CSPs as a subject remains notably underdeveloped within the extant literature, a gap only partially addressed by the work of Liu et al. (2021). This seminal publication, while providing a foundational ontology and categorization for understanding the role of CSPs in citizen science, is limited by its European context and fails to encompass the full spectrum of CSPs.

In contrast, COs have undergone more rigorous scholarly exploration, transcending technological frameworks to analysis of social dynamics and governance structures. Liu et al. (2014) and Liu, Grossberndt, and Kobernus (2017) established foundational frameworks for CO implementation within environmental governance, while Mazumdar et al. (2016) enhanced CO conceptualization through earth observation applications. Wehn et al. (2015) contributed through documentation of CO experiences in flood risk management and water governance, culminating in guidelines for COs implementation (Wehn and Pfeiffer 2020). Their work expanded understanding of ICT-enabled citizen observatories and societal innovation dimensions (Wehn and Evers 2014; Gharesifard, Wehn, and van der Zaag 2017). Applications emerged through cost-benefit analyses in flood risk reduction (Ferri et al. 2019) and exploration of COs as educational platforms (Momino, Piera, and Jurado 2017).

The European project WeObserve (2017–2020) marks a foundational effort to map, characterize, and foster coordination among European COs. This initiative advanced CO research, producing analyses of CO contributions to SDG monitoring (Fritz et al. 2019; Fraisl et al. 2020), identification of implementation challenges (Gold et al. 2020), and the first CO lanscape web map (WeObserve Consortium 2020). The project generated the WeObserve cookbook (WeObserve Consortium 2021a) and the Roadmap for the uptake of the citizen observatories knowlege base (WeObserve Consortium 2021b), providing implementation guidelines and strategies for CO development in the European context. Hager et al. (2021) analysed experiences and challenges of EU-funded COs since 2012, documenting implementation impacts and calling for updated examination of CO concepts and operational models to reflect their diverse applications and evolutionary nature.

COUNTRY-WISE DISTRIBUTION OF PUBLICATIONS

CSPs and COs represent a global research domain, spanning 73 countries across most continents, although Africa remains underrepresented in the research landscape, as shown in Figure 3. The spatial analysis reveals a bipolar distribution, with the E.U. (44%) and U.S. (38%) constituting the primary nexus of scholarly production.



Country	No. Publications
United States	171
United Kingdom	77
Germany	40
Spain	39
Italy	39
Canada	35
France	34
Netherlands	29
Australia	26
Switzerland	15

Figure 3 Total number of citizen science platforms (CSPs) and citizen observatories (COs) publications by country. Out of the 450 total papers forming the body of knowledge, 444 included information regarding researchers' affiliations. Methodologically, the analysis focuses on the unique count of countries per article as a measure of country-level participation.

Both regions have predominantly produced technical documentation of CSPs and COs research-related data dynamics, technology innovation, and engagement. The theoretical foundations and implementation frameworks for CSPs and COs have emerged predominantly from European contexts, shaped by targeted policy initiatives and funding mechanisms that position COs as structured approaches to participatory environmental monitoring. This European concentration stems from structured support through European Commission funding programs initiated in 2012 under Seventh Framework Programme (FP7), which aimed to develop community-based environmental monitoring systems (Berre, Schade, and Roman 2013; Liu, Grossberndt, and Kobernus, 2017). The integration of COs into European policy frameworks, evidenced through green and white papers on citizen science (Socientize 2013; Serrano et al. 2014), has established COs as key components within earth observation systems. Subsequent Horizon programs expanded CO funding opportunities, solidifying Europe's role in CO conceptual and operational development (Hager et al. 2021).

CHRONOLOGICAL REVIEW OF RESEARCH TOPICS

The bibliometric analysis, visualized through VOSviewer in Figure 4, identifies three distinct waves in CSPs and COs research between 2016 and 2022: "technological and engagement", "monitoring systems," and "openness and frontiers technologies." The first wave (technological and engagement; 2016–2018) was characterized by research primarily focused on understanding the technological architecture and data dynamics of CSPs and COs, particularly in relation to engagement and conservation activities. Keyword nodes were concentrated around participatory sensing, conservation, and social media, terms that dominated early discourse in the field. Notably, 2017 marked a milestone in CSPs research, as studies explicitly addressed COs as research subjects, linking them to previous implementations of EU-funded projects, sustainable development, and environmental governance.

In the second wave (monitoring systems; 2019–2020), attention shifted towards applying these technologies to specific contexts, as indicated by the emergence of terms like biodiversity monitoring, air quality, water quality, participatory sensing, and earth observation. The keyword co-occurrence network demonstrates how biodiversity emerged as a central node strongly linked to data quality, big data, and open data, illustrating the convergence of biological monitoring with technical validation approaches.

The third wave (openness and frontiers technologies; 2021–2022) shows emerging nodes like open science, open innovation, and open source, connected to infrastructure development. Deep learning, artificial intelligence and iNaturalist create another cluster of nodes that suggest an evolution in the biodiversity monitoring field that involved cutting edge technologies. Emerging themes like SDGs, COVID-19, and digital health highlight the responsiveness of CSPs research to global health challenges. During this period, research production in CSPs and COs more than doubled, with 2022 witnessing more than 100 publications per year, a remarkable acceleration compared with previous periods.

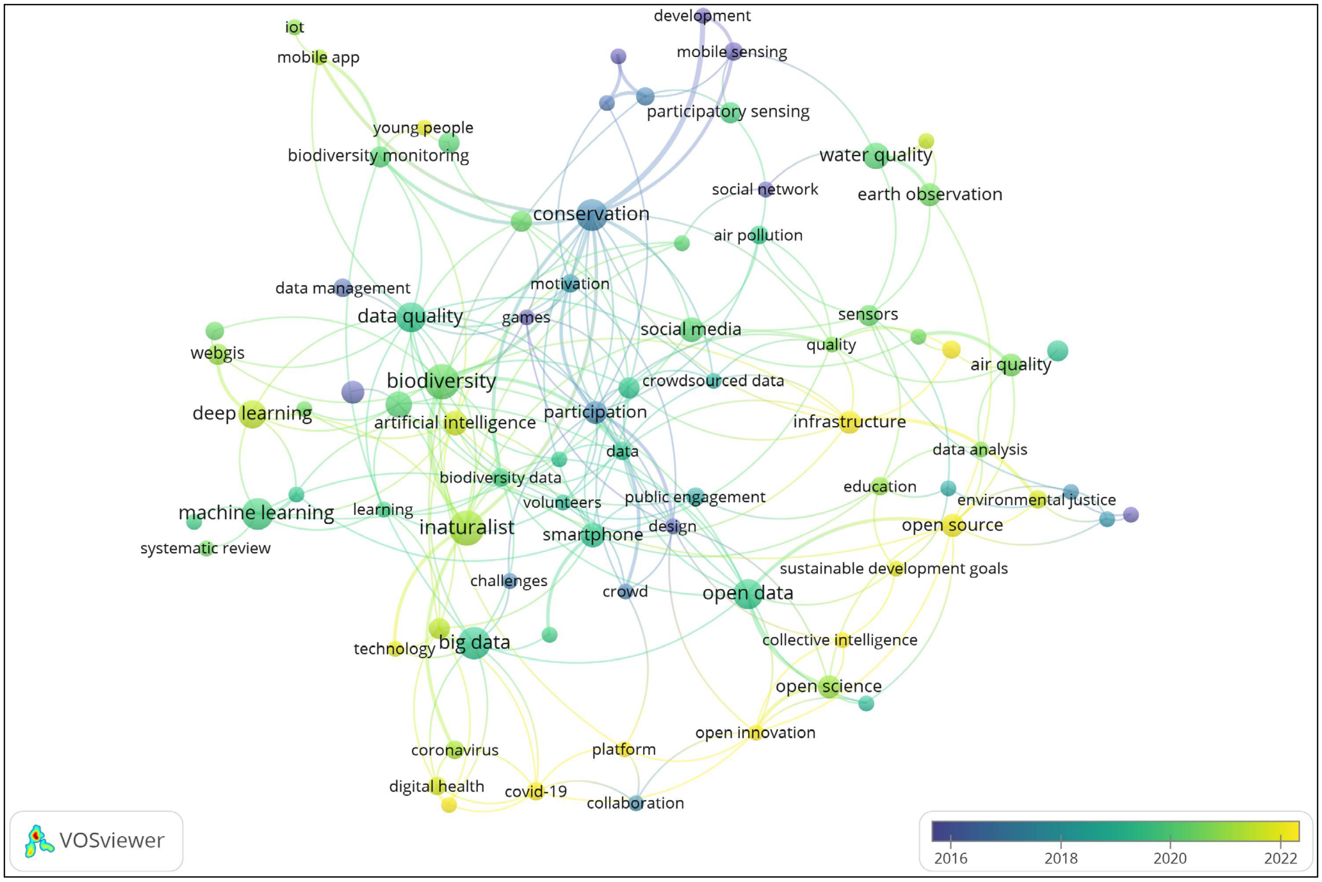


Figure 4 Chronological analysis of topic-related research of citizen science platforms (CSPs) and citizen observatories (COs). Co-occurrence analysis of author keywords extracted from the 450 articles selected made with the software VOSviewer. Out of 1,435 total keywords, only those appearing at least three times were included, leading to 99 keywords meeting the threshold.

CITIZEN SCIENCE PLATFORMS TERMINOLOGY EVOLUTION

The examination of 450 articles identified 98 unique terms used to describe CSPs and COs, emphasizing the heterogeneity and complexity of the terminology in this field. The complete list of terms is available in Supplemental file 2: Appendix B. Among these 98 terms, four key components emerge, forming the structure displayed in Figure 5: a defining characteristic (e.g., open), a thematic focus (e.g., biodiversity), a practical application (e.g., citizen science), and a technical feature (e.g., platform). For instance, the term “open biodiversity citizen science platform” incorporates all four elements. While some terms utilize the full structure, others include only two components, typically a technical feature paired with another element (e.g., “community science platform” combines a practical application with a technical feature). Notably, the use of CSPs and COs terms has increased since 2015 and 2017, respectively, with CSPs being more frequently employed and appearing to be more consolidated in their positioning. Despite this trend, academic research and conceptual discussions have predominantly focused on CO, highlighting an imbalance between practical usage and scholarly attention. This variation in terminology reflects the evolution of the field but also reflects methodological challenges. The lack of standardized terms complicates research synthesis, makes it harder to identify comparable initiatives, and obscures the true spectrum of existing CSPs, raising questions about whether this diversity of terms implies fundamentally different platforms or merely represents different terminology for similar purposes.

A PURPOSE-BASED TAXONOMY FOR CITIZEN SCIENCE PLATFORMS

To close the gap created by the growing diversity of CSPs and their overlapping labels, a purpose-based taxonomy was built from a review of 450 peer-reviewed studies. Each platform was classified by its founding mission, on the understanding that a platform’s original purpose—more than any later add-on features—guides its technical design and community culture. The resulting taxonomy displayed in Figure 6 identifies nine categories, each describing a distinct way in which platforms support citizen science projects.

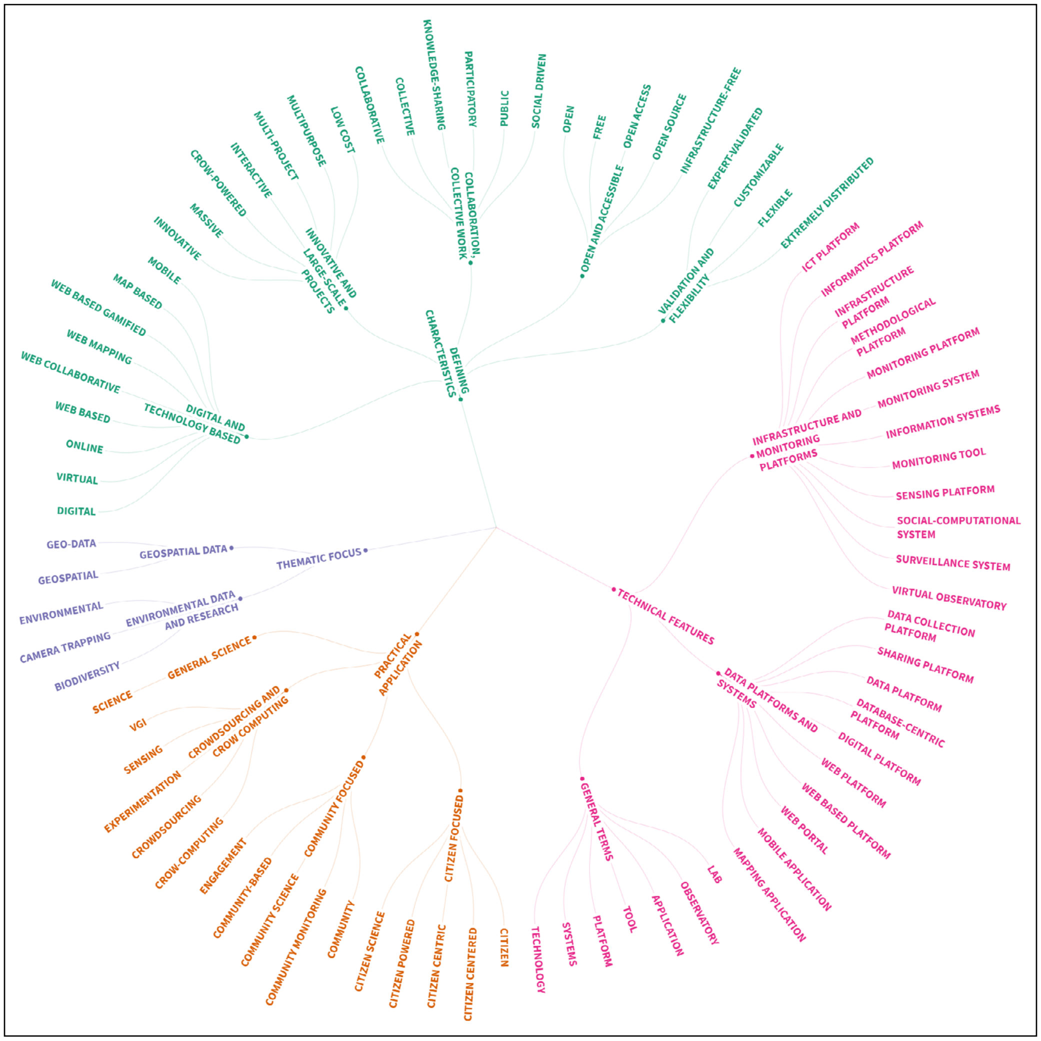


Figure 5 An analysis of 98 expressions used to denominate citizen science platforms (CSPs) and citizen observatories (COs) extracted from the titles, abstracts, and keywords of a list of 450 papers. The analysis identified four key categorical elements: defining characteristics, thematic focus, practical applications, and technical features. Interactive visualization of this graphic is available at: https://public.flourish.studio/visualisation/17878604/.

Project discovery platforms: These platforms serve as gateways for individuals to discover and engage with active citizen science projects across various domains. They offer directories and search functionalities that allow users to find projects that match their interests, skills, or geographic location. This category aims to enhance visibility and participation in citizen science by simplifying the process of connecting volunteers with projects in need of their contributions (e.g., SciStarter, Hoffman et al. 2017).

Resource collection platforms (knowledge hubs): These hubs operate as central repositories for tools, resources, and training materials crucial to the citizen science and open science communities. They aggregate and disseminate knowledge, best practices, and methodological guidelines to support the implementation and advancement of citizen science projects (e.g., EU-citizen.science [Wagenknecht et al. 2021], CIVIS [Witt and da Silva 2022]).

Insight platforms: Platforms in this category are dedicated to analysing and interpreting the evolving landscape of citizen science. They offer insights into trends, challenges, and opportunities within the field by reviewing best practices, evaluating project impacts, and fostering discussions among practitioners, policymakers, and funders. They often serve as bridges between theory and practice, contributing to the strategic development of citizen science as a field (e.g., measuring the impact of citizen science [MICS] [Sprinks et al. 2022], Observatorio de Ciencia Ciudadana [Serrano et al. 2017]).

Onsite data collection platforms: This category includes platforms designed to

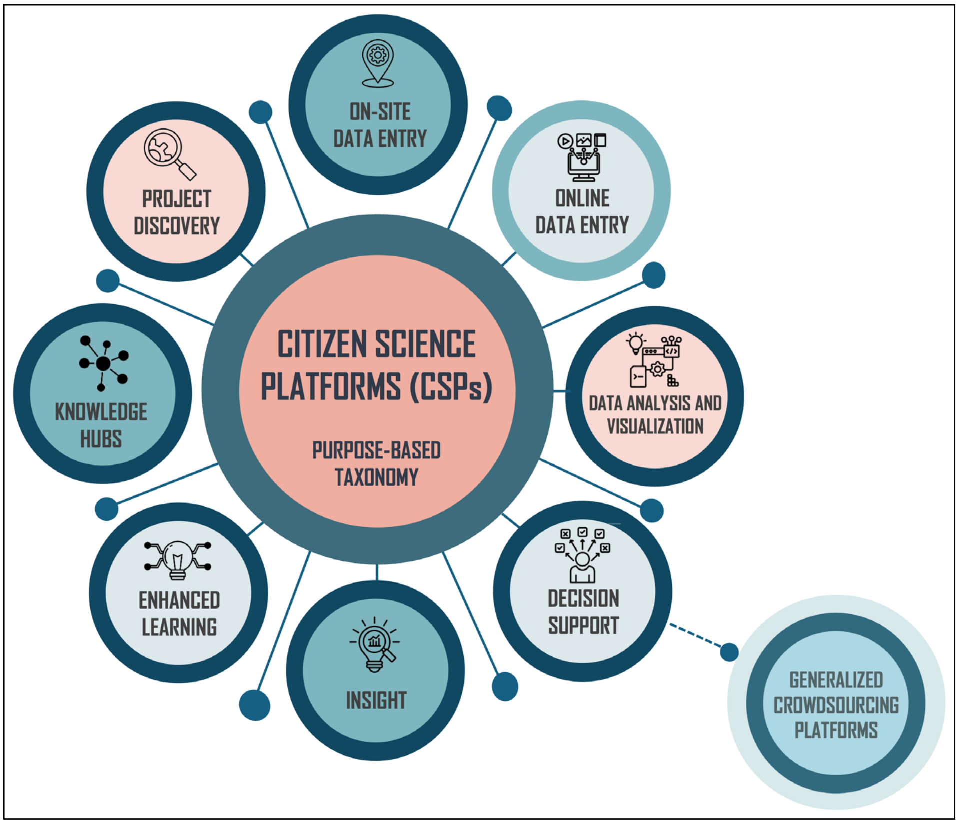


Figure 6 Purpose-based taxonomy for citizen science platforms (CSPs). A framework built on 450 academic records to categorize platforms by foundational intent and operational modalities.

facilitate the collection and management of data generated through citizen science activities usually in a predefined area. They range from mobile applications for field data collection to web-based interfaces that support data entry, validation, sharing, and publication. These tools are characterized by their focus on enhancing the quality and efficiency of data gathered by citizen scientists, incorporating features for real-time data submission, geographic information system (GIS) integration, and data collaborative validation (e.g., CitSci [Lynn et al. 2019], Anecdata [Disney et al. 2018], MINKA [EMBIMOS research group 2024], eBird [Sullivan et al. 2014], iNaturalist [Biodiversidata 2019]).

Within the ambit of onsite data collection platforms, a subcategory meriting specific mention encompasses sensing platforms, which are adept at aggregating and processing data from an array of low-cost sensors, microscopes, and high-level instrumentation, thus democratizing access to sophisticated data collection tools for the public. These platforms facilitate the acquisition of granular environmental, biological, and observational data, leveraging cost-effective technological solutions such as drones (e.g., DroneShark App [Pirotta et al. 2022]) and smartphone-based microscopes (e.g., EnLightenment), employing low-cost objective lenses [Wicks et al. 2017]).

Online data entry platforms: Streamline the gathering, processing, and analysis of data through collaborative online efforts. Zooniverse (Simpson, Page, and De Roure 2014), a leading and pioneering platform, exemplifies this category through its extensive utilization of diverse data sources, including videos, historical museum records, and camera trap images. It engages online communities in scientific inquiry by harnessing collective efforts for data analysis and categorization.

Data analysis and visualization platforms: These platforms facilitate the interpretation of collected data by researchers, citizen scientists, and the broader public through advanced graphical displays, interactive maps, and statistical analyses. The goal is to convert raw data into actionable insights and disseminate knowledge broadly. Platforms such as Mudi's web-based GIS enable intricate information visualization (Mudi et al. 2021), and Flukebook.org (Blount et al. 2022) provides an open-source solution integrating photo-identification algorithms with data management for marine research.

Enhanced learning platforms: This category spans interactive technologies such as gamification, 3D applications, and machine learning to elevate the learning experience and engage users in citizen science. For example, nQuire-it (Scanlon et al. 2020), an initiative by the Open University, utilizes digital tools to support educational goals, enabling deep engagement with scientific processes. Gamification platforms like Foldit (Curtis 2015) and Stall Catchers (Michelucci et al. 2022) transform complex scientific challenges into engaging activities, contributing to significant research findings in fields like protein folding and Alzheimer's disease. The SETI Breakthrough Listen project (Valluri and Dillikar 2021), for instance, uses gamification to involve the public in astrobiology and exoplanet detection research. Pl@ntNet (Affouard et al. 2017) demonstrates how machine learning and automated identification tools can support scientific and educational objectives by facilitating species identification and data collection.

Decision support platforms: Platforms in this category are aimed at informing decision-making processes, offering real-time data and analysis to address public health issues and environmental problems, among others. Examples include digital health dashboards that enable households to manage COVID-19 risks effectively, providing community alert systems, bidirectional engagement mechanisms for citizen queries, and secure access to critical information. Platforms like Guerilla Sensing (Banse et al. 2021) act as early warning systems, utilizing citizen science data to respond to environmental threats promptly.

Generalized crowdsourcing platforms: This category covers platforms not exclusively designed for citizen science but that have been adopted for such purposes due to their broad utility and accessibility. These include generic crowdsourcing platforms like Google Maps, Google Earth, and Open Street Maps, which have been documented for their application in various citizen science projects. Additionally, open-source platforms like PyBossa demonstrate the versatility of these tools in supporting citizen-led research efforts. Platforms like Twitch have also been repurposed for citizen science activities, challenging traditional notions of participation and data collection methods. Participatory monitoring initiatives, such as the use of WhatsApp for a farmer field school program in Sarawak, Malaysia, illustrate the adaptive use of social media for community-based scientific research (Agnese et al. 2023).

DISCUSSION

CSPs and COs function as unique RIs (Momino, Piera, and Jurado, 2017) that transcend boundaries around knowledge production (Heaton 2022). These infrastructures provide essential resources, systems, and services for conducting scientific inquiry (European Commission 2020; Fabre et al. 2021) while fostering collaborative knowledge co-production between scientists and non-scientists (Momino, Piera, and Jurado 2017). Unlike traditional RIs serving specialized scientific communities, CSPs navigate a dual framework—addressing professional methodological needs while cultivating engagement with broader publics and their diverse knowledge systems (Baudry, Tancoigne, and Strasser 2022). CSPs and COs constitute what might be termed socio-technical infrastructures, entities that require a delicate balance between social engagement and technological capability (Maccani et al. 2020; Heaton 2022), shaped by environmental, social, and organizational factors (Fecher et al. 2021). This dual nature creates tensions and challenges in their implementation and management. However, it is precisely this unique positioning at the interface between professional science and public participation that enables these platforms to support distinctive contributions to the knowledge required by society—contributions that might remain inaccessible through conventional research approaches (Spasiano 2021).

Citizen science infrastructures encounter multifaceted challenges characterized by competing imperatives: reconciling standardization requirements with the preservation of contextual knowledge and methodological flexibility (Brenton et al. 2018; Hine 2020; Roger et al. 2023); addressing hierarchical scientific structures within participatory platforms that generate power asymmetries and governance tensions regarding data ownership, attribution mechanisms, and decision-making authority (Chen 2019); negotiating divergent validation mechanisms across scientific and lay knowledge systems (Hine 2020); balancing openness with privacy concerns (Lynn et al. 2019; Bailey et al. 2021); and navigating technological dependencies while acknowledging disparities in access, skills, and engagement (Newman et al. 2012).

These tensions contribute to explaining why CSPs have not achieved Star and Ruhleder's (1996) criterion of "Infrastructure invisibility" through seamless integration into established practices. Ottinger's (2022) analysis of citizen science disaster responses contexts demonstrates that socio-technical artifacts like CSPs remain infrastructurally peripheral precisely because their data products exist outside stakeholder decision-making routines and operational protocols. This marginalization reflects the contested legitimacy of citizen-generated data within established knowledge hierarchies (Hine 2020)—necessitating strategic interventions to incorporate citizen science contributions and their infrastructures into decision frameworks (Bowser et al. 2020; Dosemagen and Williams 2022).

Our review reveals the transitional state of CSPs and COs within the research landscape. The body of literature, spanning fifteen years, demonstrates significant growth since 2021 and thematic diversification since 2017, though persistent imbalances exist between technological documentation and socio-technical analyses. Although research in COs has evolved from technological frameworks toward socio-technical systems—where software, data frameworks, and technologies intersect with participants, communities, and institutional contexts (Baudry, Tancoigne, and Strasser 2022; Heaton 2022)—this trend is not as prevalent for CSPs. Research has moved beyond engagement mechanisms (Cardoso 2017; Hoffman et al. 2017), gamification (Simeone et al. 2018), and data management (Berre, Schade, and Roman 2013) to address frameworks situating COs within environmental governance (Liu et al. 2014; Wehn and Evers 2014), earth observation systems (Grainger 2017), and SDG monitoring networks (Woods et al. 2022), while also addressing ethics (Lynn et al. 2019), responsible research and innovation (O'Grady and Mangina 2022), and privacy (Bailey et al. 2021). This research's developmental trajectory can also be characterized by three distinct waves: the "technological and engagement wave" (2016–2018), characterized by technical documentation and conservation activities; the "monitoring systems wave" (2019–2020), focused on biodiversity monitoring, air quality, water quality, and earth observation; and the "openness and frontier technologies wave" (2021–2022), marked by open science, open innovation, artificial intelligence, and connections to SDGs.

Despite the global presence of CSPs and COs, research remains concentrated in the E.U. and the U.S., raising concerns about the universality of existing frameworks. European policies largely shape CO development, embedding assumptions about participation and knowledge validation that may not translate across cultures (Escobar 2018). Emerging technologies can broaden participation, enabling data collection by historically underrepresented communities; however, digital divides, differing scientific traditions, and socio-political factors may hinder inclusivity (Newman et al. 2012; Fortson et al. 2024). Cross-cultural adaptation is essential to ensure citizen science infrastructures remain accessible, equitable, and context-sensitive (Maccani et al. 2020).

As the field evolves, the lack of categorization and common language in CSPs persists, with 98 unique terms across 450 articles reflecting conceptual uncertainties beyond linguistic inconsistency. Without standardization, knowledge aggregation and cross-learning remain challenging. A common language clarifies CSPs roles and improves coherence, contributing to a shared understanding of the diversity and interconnections among CSPs.

Previous categorizations, such as Liu et al. (2021), classify CSPs by institutional scope, though their Eurocentric focus limits global relevance, while Brenton et al. (2018) categorize CSPs by technological function within data infrastructure, but their framework requires updating to account for the current operational diversity of platforms. Building on Brenton et al., this paper introduces a purpose-based taxonomy with nine functional categories. The new taxonomy expands categories to reflect current technological developments, classifying CSPs by operational intent—emphasizing their core mission as the defining factor shaping structure and services. This approach seeks to resolve conceptual fragmentation and provides a globally adaptable framework for CSPs.

FUTURE RESEARCH DIRECTIONS

Future research on CSPs and COs must address critical gaps regarding the formulation of operational models (Hager et al. 2021), sustainability mechanisms, and their role in policy and decision-making (Liu et al. 2021). Business model development and implementation, particularly around cost-effective provision of public services and community-based data ownership models like data cooperative are needed (WeObserve Consortium 2021b). Research should focus on improving cloud-based and decentralized infrastructures that facilitate distributed data storage, reducing dependency on isolated, project-specific repositories (Roger et al. 2023). Additionally, there is a need to study adaptive infrastructures that can dynamically respond to evolving citizen science needs, incorporating real-time data ingestion, automatic metadata generation, and machine-assisted data curation (Maccani et al. 2020). Investigating new methods for ensuring data provenance, trustworthiness (Musto and Dahanayake 2019), and standardization—particularly for projects relying on heterogeneous, community-driven datasets—will be crucial for building infrastructures that can be widely adopted across disciplines and geographic scales (Brenton et al. 2018; Bowser et al. 2020). Studies should explore how to design user-centered platforms that accommodate diverse stakeholders, from volunteer contributors to policymakers and researchers. This includes improving user interfaces, optimizing mobile applications for real-time data collection, and developing tools that simplify data validation and annotation by non-expert users (Newman 2010; Liu et al. 2021; Skarlatidou et al. 2019). Artificial intelligence applications should move beyond image processing to include data validation, real-time feedback mechanisms, and human-machine collaboration (Ceccaroni et al. 2019).

Research should explore how AI can support infrastructure improvements by addressing biases, enhancing multilingual accessibility, and strengthening ethical safeguards to improve inclusivity and reliability (Duerinckx et al. 2024). Additional studies on how citizen science infrastructures can better integrate with official governmental and scientific data systems will be key to maximizing the societal impact of citizen-generated data (Brenton et al. 2018).

CONCLUSIONS

Understanding CSPs and COs as RIs requires recognizing them as complex socio-technical systems that rely on an evolving specific body of knowledge, which demands further theoretical evolution and systematic documentation of operational models and practices. This study provides a broad overview of existing knowledge on CSPs and COs, identifying research trends, gaps, and future directions for advancing understanding in the field. It introduces a classification framework that addresses the lack of standardization in CSPs terminology. The proposed nine-category purpose-based taxonomy establishes a foundation for building a common language out of the existing diversity of platforms. Platform developers can expand and refine this taxonomy, using it as a basis to align functionalities and improve interoperability. Policymakers, researchers, and other stakeholders can use this classification to support comparative studies that inform CSPs development, strengthen long-term sustainability, and reinforce their formal recognition as RIs.

DATA ACCESSIBILITY STATEMENT

All data that support the findings of this study are included within the article (and any supplementary files).

SUPPLEMENTARY FILES

The supplementary files for this article can be found as follows:

- **Supplemental File 1.** Appendix A. Search strings used for this systematic review. DOI: https://doi.org/10.5334/cstp.831.s1
- **Supplemental File 2.** Appendix B. Spreadsheet that compiles all data used. Tab 1: list of 450 academic records selected for the bibliometric analysis. Tab 2: list of 98 terms used to refer to CSPs identified within analysed records. DOI: https://doi.org/10.5334/cstp.831.s2

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

KS led the conceptual approach, methodology, analysis, visualization of results, writing, and editing of the manuscript. PP contributed to the editing of the manuscript. AA contributed to the qualitative analysis of results. AG contributed to the design of the methodology and qualitative analysis. AL, XS, CR, DT, IR, MA, and JP contributed to the qualitative analysis and review of the manuscript.

AUTHOR AFFILIATIONS

Karen Soacha-Godoy orcid.org/0000-0002-4287-1256
EMBIMOS research group, Institut de Ciències del Mar (ICM-CSIC), Barcelona, Spain; Universitat Oberta de Catalunya (UOC), Barcelona, Spain
Pranesh Prakash orcid.org/0000-0002-5368-4827
Anekaanta Law and Consultancy Services, Chennai, India
Ana Álvarez orcid.org/0009-0003-2622-714X
EMBIMOS research group, Institut de Ciències del Mar (ICM-CSIC), Barcelona, Spain
Adriana Giraldo Tejada
Universidad de Barcelona, Máster de comunicación e investigación de mercados, Facultad de económicas, Barcelona, Spain
Alexandre López-Borrull orcid.org/0000-0003-1609-2088
Universitat Oberta de Catalunya (UOC), Barcelona, Spain

Xavier Salvador orcid.org/0000-0003-3039-7566
EMBIMOS research group, Institut de Ciències del Mar (ICM-CSIC), Barcelona, Spain
Carlos Rodero orcid.org/0000-0002-9331-6519
EMBIMOS research group, Institut de Ciències del Mar (ICM-CSIC), Barcelona, Spain
Diego Torres orcid.org/0000-0001-7533-0133
LIFIA, CICPBA-Facultad de Informática, UNLP, La Plata, Argentina; Depto. CyT, UNQ, Bernal, Argentina
Ivan Rodero orcid.org/0000-0002-0675-6728
Quanta Systems, S.L., Barcelona, Spain
Mabel Ayure
Secretaría de Educación del Distrito de Bogotá, Bogotá, Colombia
Jaume Piera orcid.org/0000-0001-5818-9836
EMBIMOS research group, Institut de Ciències del Mar (ICM-CSIC), Barcelona, Spain

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