

Review

Engagement and Social Impact in Tech-Based Citizen Science Initiatives for Achieving the SDGs: A Systematic Literature Review with a Perspective on Complex Thinking

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Abstract: Recent years have witnessed significant achievements and technological advances in citizen science (CS) projects; nevertheless, significant global challenges are present. Proof of this is in the joint efforts of international organizations to achieve the 2030 SDG agenda in a complex environment. Thus, UNESCO has recognized CS as being among the initiatives that could bridge the Science, Technology, and Innovation gap as a substantial resource, given its power to bring the general public closer together. Although tech-based CS projects keep rising, there is limited knowledge about which type of projects might allow participants to develop higher-order complex thinking skills. To that end, this study describes a systematic literature review (SLR) and analysis of 49 CS projects over the last 5 years concerning the technology utilized, the level of citizen involvement, and the intended social impact. The results of the analysis evidenced: (a) broad implementation in Europe on issues of the built environment, disaster risk, and environmental and animal monitoring; (b) prevalence of helix configurations other than the triple, quadruple, and quintuple helix innovation models; (c) a focus on technological developments to improve living conditions in cities; (d) an opportunity to develop applied native technologies; (e) limited development of participants' complex thinking, when constrained to low levels of involvement; and (f) an opportunity to develop native technologies and promote a higher level of citizen participation, leading to more significant impact whilst developing complex thinking.

Keywords: participatory science; technology; complex thinking; higher education; sustainable development goals; information and communication technologies; quintuple helix innovation model; revised Bloom's taxonomy; RBT; critical thinking; innovative thinking; industry 4.0; educational innovation; transversal competencies

1. Introduction

1.1. Background and Context of Citizen Science Initiatives

The European Commission and international organizations recognize the increasing need to involve various actors such as citizens, communities, and civil societies in research initiatives to promote trust in science. Likewise, they consider that citizens should be part of choosing the scientific role and direction that technologies will assume and the best practices that encourage and reward transformative participatory actions for more significant social impact [1,2]. This perspective is consistent with that of the OECD [3], which has pointed out the imperative need to incorporate Science, Technology, and Innovation (STI) in addressing

various social and environmental problems in the Anthropocene era [4,5]. The OECD has shown how regional and global megatrends require the intervention of skilled citizens with a knowledgeable perspective on the issues, a force becoming the prevalent power that defines the future.

Within this framework, citizen science (CS) becomes critical because it is an approach that intrinsically brings individuals closer to science and fosters their awareness of their surroundings [6,7]. Also known as participatory science or community science, CS is a research process that involves citizens as active agents at different levels of engagement [8,9]. CS is a strategy to address current challenges, one based on a scientific approach supported by technology [10], mainly addressing the issues associated with the environment and linked to the SDG 2030 agenda [11–13]. It places the participating citizens at the center and empowers them to know, reflect upon, participate in, and address these challenges whilst interacting with various stakeholders.

Science, Technology, and Innovation (STI) are required to address contemporary social phenomena. These phenomena can hardly be understood if not seen from a multi-referential approach [14]; therefore attention to environmental and social problems requires articulating fragmented knowledge and liaising with the various actors involved. Since social phenomena are inherently complex, to reach a comprehensive understanding, it appears increasingly necessary to approach social phenomena from the vantage of social and positive sciences and, ideally, to observe them from a multi-angled, transdisciplinary perspectives, without trying to reduce them, but rather attempting to understand how each part complements the whole [15]. In this context, CS can be a practical approach that provides citizens with the tools necessary for accessing science and solving the problems associated with complex phenomena.

1.2. Citizen Science: An Ally of an Open Science Society

CS is a core component of Open Science's attempt to address the complexity and reduce inequalities in STI [16], given the richness of its methodology, and ability to change mindsets through applied experimentation. UNESCO's Open Science Recommendation recognizes the urgency of addressing the complexity of challenges and wicked problems. Among the issues this normative tool seeks to tackle, we find the emphasis on accelerating scientific progress toward sustainable development [16]. Notably, the aim is for science processes to transcend their level of impact and launch enhanced scientific practices and more coherent factual knowledge. Through this more efficient enterprise, quality improvement, reproducibility, and scientific impact enhance the reliability of the evidence supporting robust decision-and-policy making whilst reinforcing trust in science [16].

Considering the challenges of sustainable development, it would be helpful for the public decision-making process to be anchored in a framework connecting actors, knowledge, and innovation with the environment. This is fittingly the promise of the analytical framework of the quintuple helix innovation model [17–20], which seeks to bring the impacts of societal performance to the natural environment through sustainable knowledge [21]. However, although helix models are widely recognized, the shaping of their dimensions has often been criticized [22,23]; for instance, Barcellos-Paula et al. [24] have pointed out that in applying the quintuple helix innovation model to initiatives, one must have a good understanding of the relevance of the causes and effects of the variables that affect decision making while seeking to achieve harmony among the participating entities. Likewise, Andryeyeva et al. [25] identified methodologies that shed light on developing initiatives focused on the SDGs and using the quintuple helix innovation model when regional singularities are due to legislative discrepancies. Therefore, there are limitations to developing complex schemes in different regions involving different helices. Moreover, although there are diverse alliances under the helix definition, they might happen in different configurations, as pointed out by Leydesdorff [22]. From this perspective, the role that citizens play in the decision-making process and in defining the public agenda is relevant because, as stated in the UNDP [26], human activity has caused the social and environmen-

tal problems currently faced by humanity; therefore, greater citizen participation in the decision-making process among diverse stakeholders is compulsory. Additionally, citizen participation has a potential impact where alliances among all the stakeholders converge to benefit society based on scientific cooperation and openness.

1.3. Tech-Based Citizen Science and Complex Thinking in the Achievement of SDG 2030

Applying new technologies in CS projects has aroused great interest among scientists and citizens, awakening the possibilities of bringing citizens closer to science, empowering them, and opening possibilities for collecting and sharing data and information that can scale scientific projects whilst advancing science. For CS projects to achieve the most significant impact, it is imperative to consider the various contextual elements and those individuals involved in the initiatives. Thus, Sanabria-Z et al. [27] defined the Threshold of CS Projects framework, a roadmap of three key dimensions to ensure a comprehensive outcome: Bounded CS, Threshold CS, and Full-cycle CS. A typology of eight components was cross-combined with these dimensions, depending on the project type, which, when levelled appropriately, promotes the gradual involvement of the participants whilst meeting the objectives. The main characteristics of CS frameworks and typologies were considered a baseline for its construction, among which the complex thinking component stands out, along with contextual awareness, citizen engagement, infrastructure leverage, technological innovation, educational innovation, outreach and scale, and network building. Within this scope, complex thinking is recognized as the macro-competency comprised of the sub-competencies of critical, innovative, systemic, and scientific thinking [28]. According to Suherman et al. [29], the proper implementation of projects that promote the development of such sub-competencies, such as critical thinking, contribute to the participants' unfolding of creative solutions to decision-making challenges, among other benefits.

Notwithstanding the visible progress in engaging individuals in tech-based CS projects, there are still conceptual limitations when determining how their voluntary participation should affect the underlying purposes of such projects [30]. Consequently, regarding the intellectual development of the participants, it is still questionable whether tech-based CS projects can achieve this transformation, which is undoubtedly very ambitious, since most of this line of infrequent studies focuses on citizen engagement rather than tapping into other benefits of the participants' experience. Few research studies have explored developing citizen scientists' complex thinking, skills, abilities, and attitudes whilst enrolled in a CS project and how these key elements might help them understand the problems better and devise solutions using them.

Regarding technological advances that facilitate CS, we can highlight microcomponent technology, which has evolved since 1965 as Gordon E. Moore predicted (Moore's law) [31]. He noted that every two years, the number of transistors in a microprocessor would double, increasing the functionality of electronic devices by means of its complexity. This law is no longer veridical, because the components' physical and chemical properties change when nanomaterials are developed. Interestingly enough, these constraints have not discouraged the semiconductor industry from pursuing the downsizing of micro devices to astonishing dimensions (e.g., a technology process has been developed in semiconductors to eventually make two-nanometer (nm) nanosheet technology (nm) [32]). Concurrently, technological evolution has led to significant efforts in education, such as programming embedded electronics or designing low-cost CMOS circuits under the Open Science paradigm, using freeware to build portable sensors for various applications [33,34]. Consequently, the increased availability of low-cost sensors allows their commercialization to reach citizens in ambitious CS projects involving technologies. Some examples of the diverse application of sensing technology at a low cost and in a portable way to analyze species of clinical or environmental interest can be shown in precise electrochemical devices [35], or in the development of lab-on-a-chip devices such as the study of a single cell for diagnostic purposes [36]; the significant effort to carry out the development of sensors also seeks their energy autonomy with green energies, such as the development of thin films of photovoltaic

sensors of controlled and affordable manufacturing with electrodeposition techniques [37]. Consequently, the advancement of low-cost sensors allows their commercialization to reach citizens in ambitious CS projects involving technologies.

In terms of understanding how tech-based CS projects address societal challenges, especially those referred to in the SDG 2030 agenda, international organizations have continuously stressed that global effort and alliance are indispensable. The SDGs are a turning point for the comprehensive achievement of human rights by ensuring solutions for critical social issues such as poverty, equality, welfare, and health [38]. Although it might be simplistic to think that tech-based CS projects can achieve SDG goals by merely establishing this resolution, one can assume that the participants might be able to delve into these subjects further, generate awareness about the environment, and consequently become empowered and willing to propose ideas. Advocating for an informed society open to science can be a strategy that improves communities' mindsets for attaining the SDGs. In this respect, it is most valuable to identify features that characterize non-academic skills development and citizen involvement, as well as to determine the social impact that this may have, to gain an insight into how citizens can solve environmental and other problems.

Hence, considering this background, we established a holistic theoretical framework to guide this study, constructed around the Threshold of CS Projects typology [27], which uses four pillars: the recognition of the SDGs as a joint target to be attained; the UNESCO Recommendation on Open Science that guides the strategies for achieving these goals; the challenges faced by education models to develop transversal competencies as stated in UNESCO's [39] classification and as defined in the Education Research Institute Network; and the role of disruptive technologies underpinning the Fourth Industrial Revolution [40]. Figure 1 diagrams how the Threshold of CS Projects represents the researched themes of citizen engagement, technological innovation, networking building, and complex thinking, surrounded by the frameworks described above.

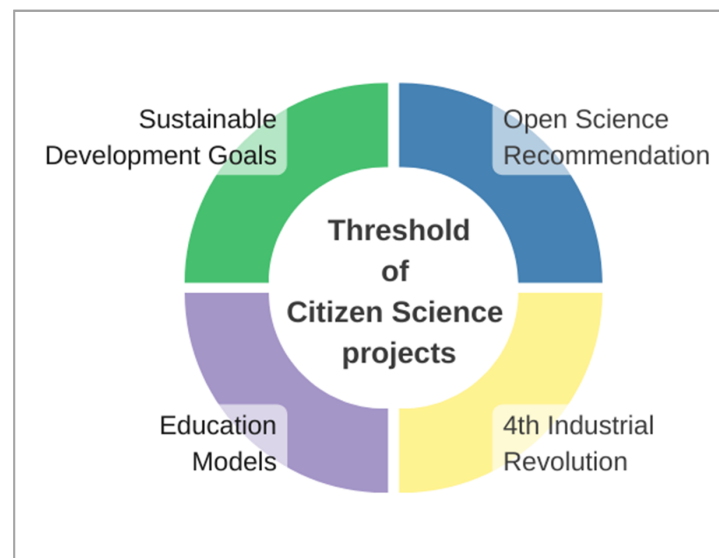


Figure 1. The theoretical framework of the literature review.

The review was conducted to identify common ground in tech-based CS project studies, looking at the technology utilized, the level of citizen involvement, and the social impact of their interventions. We focused the study on five main inquiry areas: (1) journal metrics in terms of regions, journals, citations, and keywords with the highest rates of occurrence; (2) projects' overview and scope vis a vis the helices of the innovation model and the SDGs; (3) analysis of the role of information and communication technologies (ICT) components in developing CS projects by their tangible nature and source of development; (4) assessment of the participants' role based on the transversal competencies developed

per the complex thinking approach, their level of participation, and their cognitive and knowledge classification; and (5) the degree of social impact intended by the projects.

2. Materials and Methods

Under this research's approach to analyzing tech-based CS projects, we used the SLR method presented by Kitchenham [41] and complemented it with the Garcia-Peñalvo [42] proposal. The SLR allowed us to explore a wide variety of studies and their results reported in scientific journals, which revealed trends in CS initiatives. The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) protocol [43] was taken as a guide for the systematic review in four phases: (1) identification, articles identified during the database searching and other sources from 2017 until 2021; (2) screening, articles screened, number of duplications removed and exclusions; (3) eligibility, articles eligible and excluded per particular criteria; and (4) analysis, a qualitative and quantitative synthesis.

Overall, three stages in the development of the analysis were carried out:

- (a) Research questions were defined according to the main objective of the SLR.
- (b) The search method was determined by defining the inclusion and exclusion criteria for the leading databases.
- (c) Selected items resulting from the screening were analyzed in detail.

2.1. Search Strategy

We decided to search the Web of Science and Scopus databases, given their scope and prestige among international scientific publications. Table 1 shows the search descriptors used in the study.

Table 1. Search descriptors in this SLR study.

Web of Science	Scopus
TS = ("Citizen Science" AND technology) Document type = article Time period = 2017–2021 Index = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC. Language = English	TITLE-ABS-KEY ("Citizen Science" AND technology) Document type = article Time period = 2017–2021 Language = English

Once the descriptors were applied in both databases, inclusion and exclusion criteria were established according to the study's objectives. The inclusion and exclusion process was carried out in three stages (see Table 2). In the first stage, the concepts, or keywords, for the search in databases were defined, making it possible to filter the articles that address the topic of CS and the use of technology. The second stage involved reviewing the abstracts of those filtered articles that complied with this incorporation of key concepts. In this process, a filter was made based on the review of the article's title, abstract, and body, where both keywords ("citizen science" and "technology") had to be mentioned in at least one of these elements. The abstract review also considered visualizing the methodology (not always explicitly indicated) and whether it was a project that generated new data. The third stage consisted of reviewing full-text articles in a more detailed way to verify that they were CS projects conducted using technology and involving citizen participation. The articles that used the CS methodology but which were not CS projects were discarded; likewise, those that only used CS databases from third-party projects for discussion or formulating a theoretical framework were also excluded.

Table 2. Criteria for inclusion and exclusion of articles on this SLR study.

Inclusion Criteria	Exclusion Criteria
Articles including both keywords in either the Title, Abstract, or Body. Articles published between 2017 and 2021 Applied technology CS studies. Articles ranked in the first quartile of WoS and Scopus. Explicit use of technology in CS projects. Citizens' participation in the project.	Absence of one or both keywords ("technology" and "citizen science") Theoretical or review articles (e.g., CS survey, data analysis, discussion about frameworks or future scenarios) Studies that did not use or develop any technologies. Studies related to CS but which were not CS projects. Studies that only discussed or used CS approach and methodology.

2.2. Research Questions

Some examples of the PRISMA methodology (Figure 2) were applied in the following review studies [44,45], in which research questions (RQs) were made based on the targeted problem to identify and clarify the key concepts and to determine the strategy for data search, review, and analysis. In our review, we divided the RQs into five dimensions: (1) journal metrics, aimed at providing an overview of the geographic areas where CS projects were addressed and information related to the number of publications and topics; (2) projects' overview and scope, aimed at showing the participating entities of the innovation ecosystem and the aligning of projects with the SDGs; (3) type of ICT, which indicates a generic notion of the use of technology commonly used in the CS projects; (4) participants' complex thinking, which reveals the contribution that CS projects have on the intellectual development of individuals according to their competencies, skills, attitudes, and beliefs; and (5) social impact, where the aim was to identify the scope of tech-based CS projects in terms of their societal reach (See Table 3).

Table 3. Research questions and answers on this SLR study.

Inquiry Area	Research Question	Possible Answers
Journal metrics	RQ1a: In which countries or regions were the projects implemented?	Name of country or region.
	RQ1b: Which are the journals with the most publications?	Names of journals.
	RQ1c: Which are the most cited articles?	Title of articles; Authors
	RQ1d: What are the most frequent keywords mentioned in the articles?	Authors' keywords (cloud).
Projects' overview and scope	RQ2a: Which helix-innovation model systems are identified in the studies?	Quintuple Helix innovation model systems (Carayannis & Campbell) [17]: Education, Economic, Political, Public, Natural environment.
	RQ2b: What type of helix-innovation model system configurations are represented in the studies?	Quintuple Helix innovation model systems (Carayannis & Campbell) [17]: Triple, Quadruple, or Quintuple Helix; Other combinations.
	RQ2c: On which Sustainable Development Goals do the proposals focus?	Sustainable Development Goals (United Nations) [46]. SDGs 1-17.
Type of ICT	RQ3a: What type of ICT was mainly used in the citizen science projects?	Software; Hardware; Both
	RQ3b: Was the applied technology native or from a third party?	Native technology; Third-party technology; Both.

Table 3. Cont.

Inquiry Area	Research Question	Possible Answers
Participants' Complex thinking	RQ4a Which transversal competencies are considered or intended in the studies?	The six domains of the ERI-Net working transversal competencies (UNESCO) [39]: Critical and innovative thinking; Interpersonal skills; Intrapersonal skills; Global citizenship; Media and information literacy; Others.
	RQ4b What level of citizen participation was undertaken or was intended?	Levels of participation in Citizen Science (Haklay) [47] Crowdsourcing; Distributed Intelligence; Participatory science; Extreme Citizen Science.
	RQ4c Which classification do the projects fit into according to cognitive process dimensions from the citizen participation perspective?	Revised Bloom's Taxonomy (RBT) cognitive process dimensions (Anderson) [48] Remember, Understand, Apply, Analyse, Evaluate, Create.
	RQ4d Which classification do the projects fit into according to the knowledge dimensions framework from the citizen participation perspective?	Revised Bloom's Taxonomy (RBT) knowledge dimensions (Anderson) [48] Factual, Conceptual, Procedural, Metacognitive. Ashoka's 4 Levels of impact (Ashoka Scandinavia) [49]
Social impact	RQ5a What impact do the initiatives have on society?	Direct service; Scaled direct service; Systems change; Framework change.

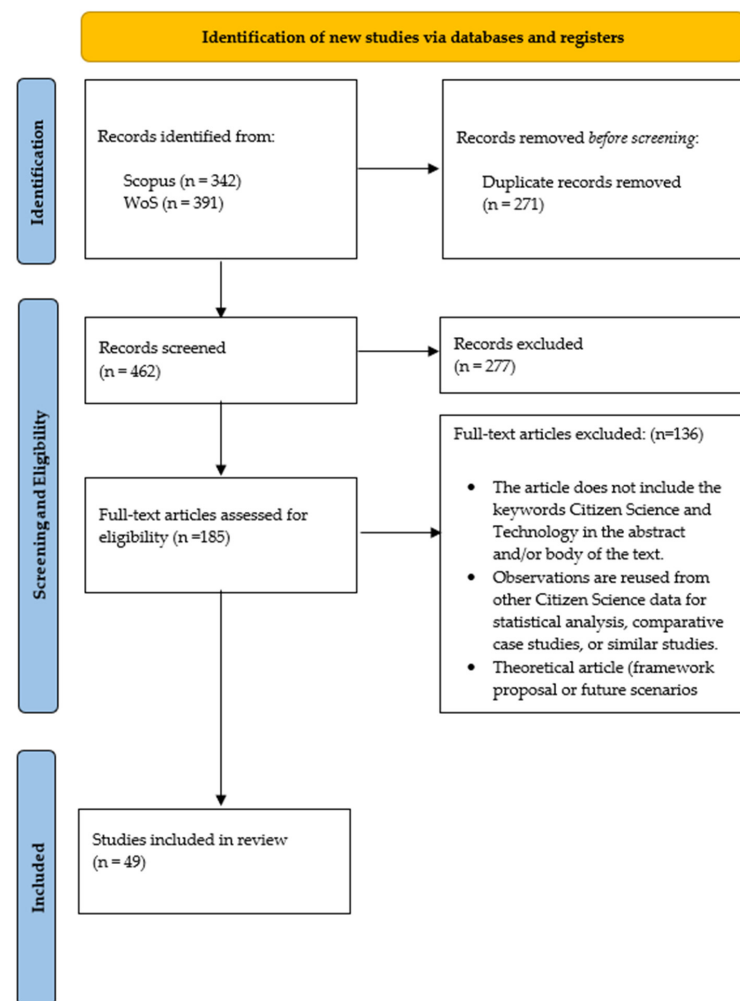


Figure 2. PRISMA Flow diagram.

A Google spreadsheet was used for data collection and analysis to generate the metadata from all the selected studies. The link is provided in the Supplementary Materials section and here <https://doi.org/10.5281/zenodo.6836976> (accessed on 13 July 2022). Additionally, the ggplot2 graphical system (<https://ggplot2.tidyverse.org/>, accessed on 10 July 2022), version 3.3.5, from the R programming language (<https://cran.r-project.org/>, accessed on 10 July 2022), version 4.2.1, was used to generate the figures.

3. Results

In the case of Journal metrics, we divided research question one into four entries:

RQ1a: In which countries or regions were the projects implemented?

Figure 3 displays a world map indicating each epicenter or region where tech-based CS projects have been developed in the last five years, identified with blue dots. In more detail, it is observed that larger blue dots on the world map represent places with more initiatives. The United States stands out as the leading country with more than 15 projects, followed by European countries, including the UK, Spain, and the Netherlands, with close to 5 projects each. However, it was noted that some projects reported regions with multiple countries, most notably in Europe and Africa, or started with a pilot in one country and later expanded globally, for instance [50].

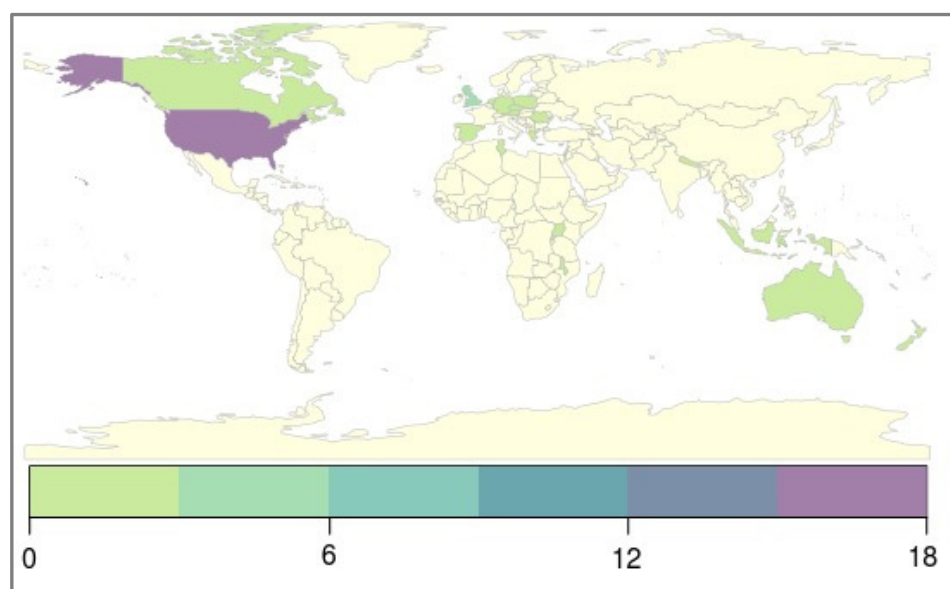


Figure 3. World map with the geographical locations where tech-based CS projects were developed from 2017 to 2021.

RQ1b: Which are the journals with the most publications?

Journals with the most publications on tech-based CS projects are listed and numbered in Figure 4. The large circles (purple) represent the journals with the most publications (3 items), followed by the medium-sized ones (green) (2 items), and then the small ones (blue) (1 item).

The journals that published the most tech-based CS articles are *Science of the Total Environment* and *Plos One* with three each, followed by *IEEE Access*, *Biological Conservation*, *Frontiers in Marine Science*, *Atmospheric Measurement Techniques*, and *ISPRS International Journal of Geo-Information* with two studies each. The publications indicated that issues related to the marine ecosystem, the development of sensors and telecommunications, the environment, and the atmosphere predominate. Likewise, in a more global vision, Figure 4 shows that in addition to the topics mentioned, the topics associated with pollution, public health, hydrology, ecology, and urban planning are also incorporated in tech-based CS studies.

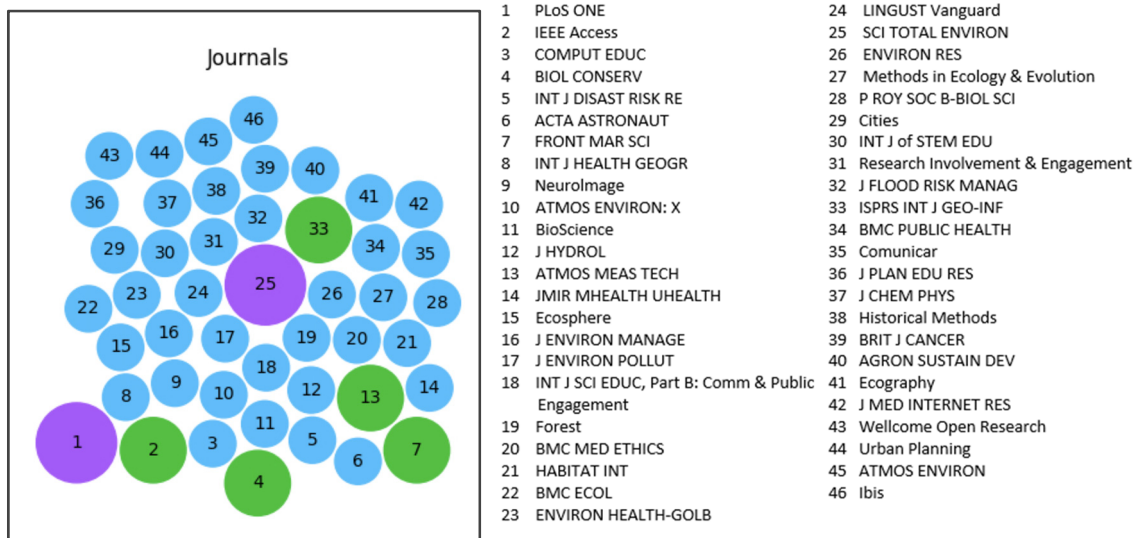


Figure 4. Journals (abbreviated names) with the most publications on tech-based CS projects.

RQ1c: Which are the most cited articles? And RQ1d: What are the most frequent keywords mentioned in the articles?

Here we identified the most cited groups of articles focused on tech-based CS projects, their study subjects, and the authors' common keywords. Thus, Table 4 identifies that the study with the most citations (154) was published in the *Cities* journal by Mueller et al. [51]; in this study, citizens were involved in the urban planning design process. Subsequently, the study by Jerrett et al. [52] in *Environmental Research*, with 112 citations, was of significant interest by connecting CS with air pollution sensors. Likewise, the study published in the *International Journal of Disaster Risk Reduction* by Bossu et al. [53], with 90 citations, related CS to the methodology for transmitting seismic risk information. In the remaining studies in Table 4, CS was associated with subjects such as ecology, information technology, animal transportation, built environment, and health. Furthermore, the number of citations associated with these studies reveals the scientific community's interest in studying high-impact applications of tech-based CS projects.

Table 4. List of most cited tech-based CS articles between 2017 and 2021.

Title	Journal	Year	Citations	Authors
Citizen Design Science: A strategy for crowd-creative urban design	<i>Cities</i>	2018	154	Mueller et al. [51]
Validating novel air pollution sensors to improve exposure estimates for epidemiological analyses and citizen science	<i>Environmental Research</i>	2017	112	Jerrett et al. [52]
LastQuake: From rapid information to global seismic risk reduction	<i>International Journal of Disaster Risk Reduction</i>	2018	90	Bossu et al. [53]
Long-term evaluation of air sensor technology under ambient conditions in Denver, Colorado	<i>Atmospheric Measurement Techniques</i>	2018	62	Feinberg et al. [54]
Amphibian and reptile road-kills on tertiary roads in relation to landscape structure: Using a citizen science approach with open-access land cover data	<i>BMC Ecology</i>	2017	60	Heigl et al. [55]
Testing the performance of sensors for ozone pollution monitoring in a citizen science approach	<i>Science of the Total Environment</i>	2019	53	Ripoll et al. [56]
Spatial data for slum upgrading: Volunteered Geographic Information and the role of citizen science	<i>Habitat International</i>	2018	49	Hachmann et al. [57]
Bring them aboard: Rewarding participation in technology-mediated citizen science projects	<i>Computers in Human Behaviour</i>	2018	48	Cappa et al. [58]
Field calibration of electrochemical NO ₂ sensors in a citizen science context	<i>Atmospheric Measurement Techniques</i>	2018	44	Mijling et al. [59]
Srazenazver.cz: A system for evidence of animal-vehicle collisions along transportation networks	<i>Biological Conservation</i>	2017	42	Bíl et al. [60]
Stress experiences in neighbourhood and social environments (SENSE): A pilot study to integrate the quantified self with citizen science to improve the built environment and health	<i>International Journal of Health Geographics</i>	2018	42	Chrisinger and King [61]

Concerning the keywords used in scientific articles, we found that the most often-used keywords in tech-based CS studies were “citizen science,” “smartphones,” “low-cost sensors,” “crowdsourcing,” “community science,” “community engagement,” and “machine learning.” Figure 5 shows the words most frequently found, although many other keywords also appeared to a lesser extent.

**Figure 5.** Word cloud distribution of the most frequently used keywords in the analyzed tech-based CS articles.

It can be presumed that most of the studies related to CS shown in Figure 5 used ICT, whether by using machine learning, cell phones, or social media, or by incorporating sensors.

About the projects’ overview and scope, research question two was divided into three sections:

RQ2a: Which helix-innovation-model systems were identified in the studies?

The types of helices were established according to the quintuple helix innovation model [17] in connection with tech-based CS projects. Carayannis & Campbell identified the following groups of actors represented in helices: academia, universities, and the higher education system (Education system/Edu.); industry, firms, and the economic system (Economic system); state, government, and political system (Political system/Polit.); media-based and culture-based public (Public system/Pub.); and natural environment, natural environments of society (Natural environment/Nat. envr.). Based on the review of the articles, the helices were identified according to their most significant involvement in CS projects. Except for one study [55], out of the forty-nine articles analyzed, all projects included the Education system helix, followed by the Public helix with forty-three studies, and the Political system helix with thirty-two studies. In contrast, the Economic system helix and the Natural environment helix were only included in ten and nine projects, respectively (see Figure 6). The preceding may be somewhat paradoxical since, despite not identifying the helix of the environment, CS projects historically began with initiatives relating to ecology, care for the environment, and flora and fauna. In fact, from the analyzed metadata of these studies, we found considerable representativeness of projects associated with these subjects.

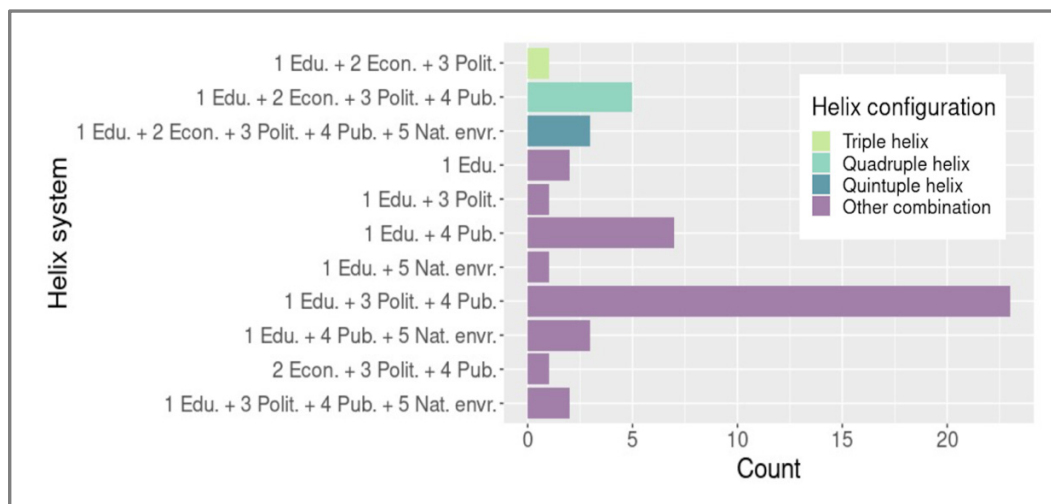


Figure 6. Classification of tech-based CS projects according to the triple, quadruple, and quintuple helix innovation models [17].

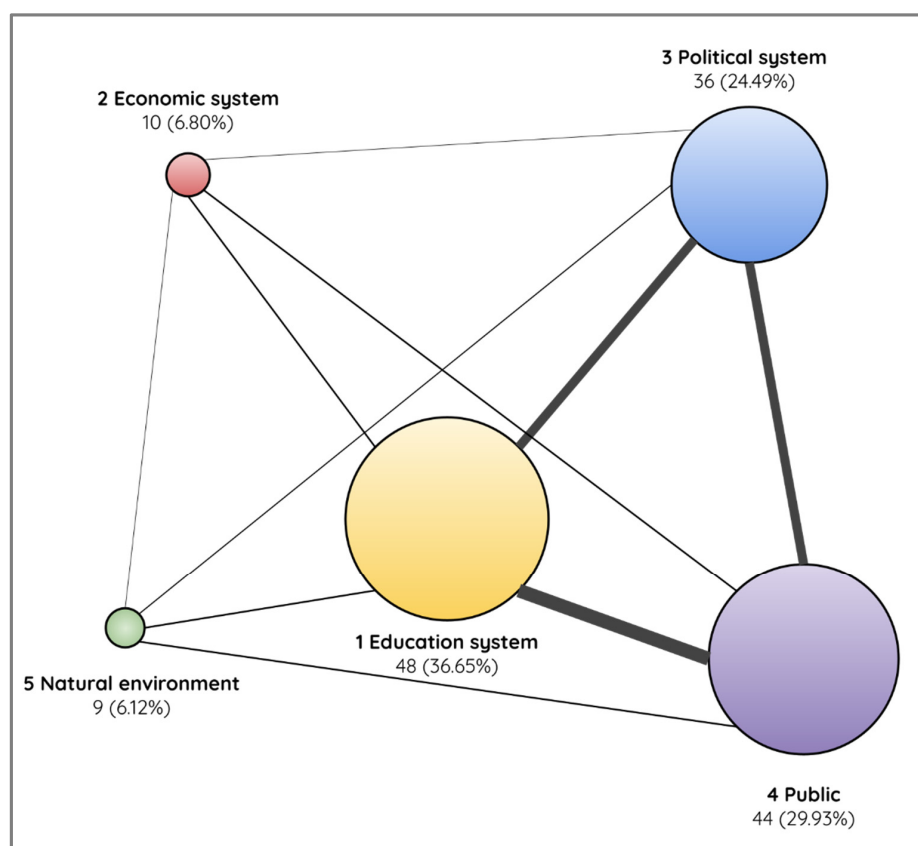
RQ2b: What helix-innovation-model system configurations are represented in the studies?

Following the importance of the helices' interaction, RQ2b is directed to the configuration of the helix innovation model that the projects represent. Carayannis & Campbell's [17] triple, quadruple, and quintuple helix innovation models were identified only in certain studies. Among them, with a minimum difference, the quadruple helix was found to be the most-addressed configuration in tech-based CS projects (seven times), followed by the triple helix (twenty-eight times) and the quintuple helix (three times) as shown in Table 5. The first column shows the number of helices interacting in the studies; Column Two shows the types of interactions that occur among the helices in these studies; Column Three shows the number of studies analyzed; and the last column shows the corresponding percentages.

Table 5. Helix interaction in the reviewed tech-based CS articles.

Number of Participating Helices	Helix Interaction Configuration	Number of Studies	%
One helix	1 Education system	2	4.1
Two helices	1 Education system; 3 Political system	1	2
	1 Education system; 5 Natural environment	1	2
	1 Education system; 4 Public	7	14.3
Three helices	2 Economic system; 3 Political system; 4 Public	1	2
	1 Education system; 2 Economic system; 3 Political system	1	2
	1 Education system; 4 Public; 5 Natural environment	3	6.1
	1 Education system; 3 Political system, 4 Public	23	46.9
Four helices	1 Education system; 3 Political system; 4 Public; 5 Natural environment	2	4.1
	1 Education system; 2 Economic system; 3 Political system; 4 Public	5	10.2
Five helices	1 Education system; 2 Economic system; 3 Political system; 4 Public; 5 Natural environment	3	6.1
	Total	49	100

Figure 7 shows the spheres associated with each of the five helices, where the thicker the bond between them, the greater the helix-to-helix interaction, as described in Table 5. In most studies, the configuration of the collaboration between helices did not correspond precisely to these models but was somewhat random in its combinations. Results by helix showed that the Education system helix appeared in 48 studies, representing 36.65% of the total number of helices, followed by the Public helix (44, 29.93%), and in third place, the Political system helix (36, 24.49%).

**Figure 7.** Distribution of helix innovation models in tech-based CS studies.

RQ2c: On which Sustainable Development Goals do the proposals focus?

Figure 8 shows a distribution of the SDGs addressed by the analyzed tech-based CS projects. From the graph, it is observed that the SDGs of sustainable cities and communities (eighteen projects), life on earth (thirteen), good health and well-being (nine), climate action (seven), clean water and sanitation (six), and justice and solid institutions (six), have the most closely related objectives within the CS studies. However, certain SDGs still appear not to have been addressed through tech-based CS studies, such as: no poverty, zero hunger, gender equality, decent work and economic growth, responsible consumption and production, and alliances for the objectives.

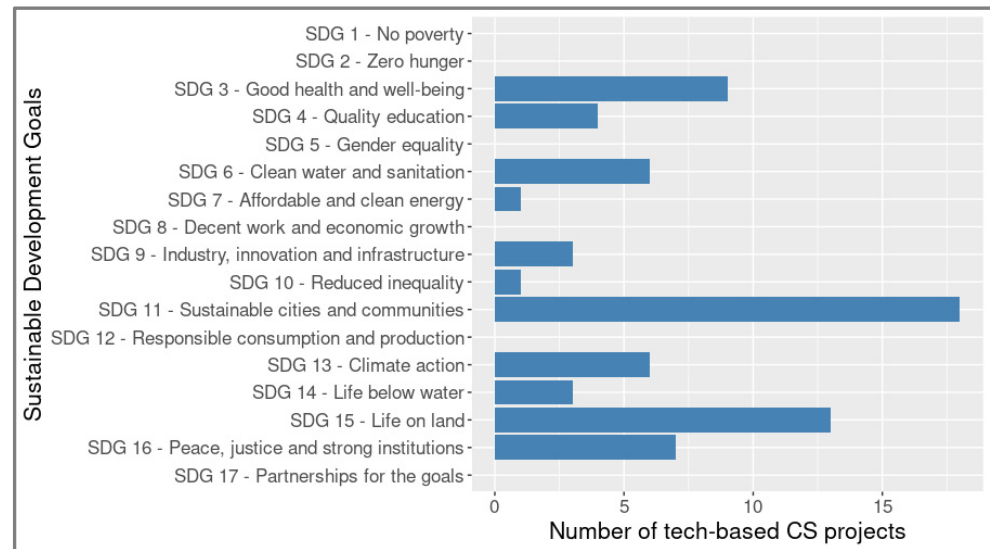


Figure 8. Distribution of SDGs identified in tech-based CS studies.

On the subject of the type of technologies, research question three was divided into two sections

RQ3a: What types of ICT were mainly used in the Citizen Science projects?

We considered whether projects emphasized using hardware, software, or both during implementation (see Figure 9). In the case of hardware, devices such as cameras, measuring devices (sensors), and smartphones were considered, whilst software could be featured as video games, mobile applications, or websites, among others. Out of the forty-nine articles analyzed, thirty-two used software as the primary tool in their study, and only five used hardware. However, 12 cases of hardware-software combinations were found, e.g., the case of the trio developed by NASA with the FluidCam artefacts and MiDAR, together with the NeMO-Net software [62]. In this case, the devices were not intentionally developed for CS projects. The NeMO-Net software does integrate this approach and takes advantage of the data collection benefits of the FluidCam and MiDAR artefacts.

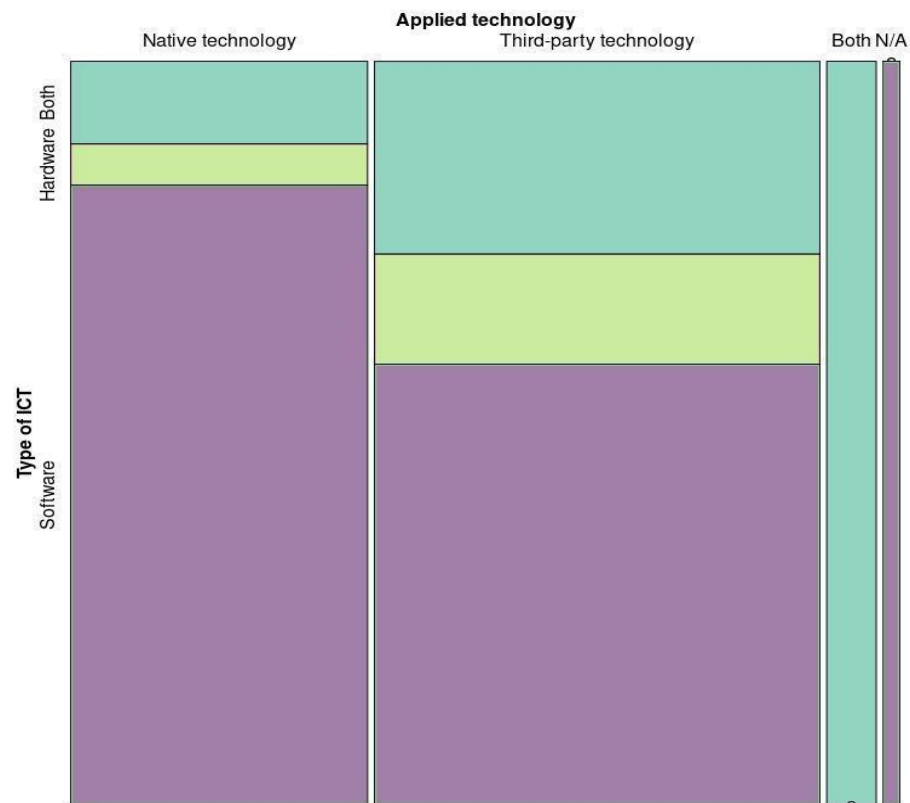


Figure 9. Correlation matrix graph in the distribution of applied technology vs. ICT type in the CS studies analyzed.

RQ3b: Was the applied technology native or from a third party?

Figure 9 shows the types of ICT (hardware, software, or both) in correlation to its application (native/in-house or third-party development). In the case of applied hardware, artefacts (stationary or mobile instruments and sensor-based devices for measuring and sampling) and other devices for personal use (wearables) for self-development or commercial use were considered. Commercial and self-developed programs and applications for websites or mobile devices were considered in the applied software area. A total of eighteen projects corresponded to native developments; twenty-eight used third-party technologies, and only three combined both.

Regarding the participants' complex thinking competencies, research question four was divided into four sections, the first two referring to participants' competencies and involvement, whilst the latter two focused on cognitive processing and knowledge dimensions. At the end of this section on complex thinking, a Sankey diagram (see Figure 10) reflecting the relationships between the results of the four related questions is presented.

RQ4a: What transversal competencies are mentioned in the studies?

Noting that not all studies refer to tech-based CS implementation projects, but some are still in a proof-of-concept or pilot stage (e.g., to test a future campaign, an artefact, or app), we decided to consider the transversal competencies intended in the studies. Regarding the transversal competencies mentioned in the studies, we based the analysis on five of the six domains of the ERI-Networking transversal competencies [39]. The overall results for each domain and their predominant key skills, competencies, values, and attitudes are presented.

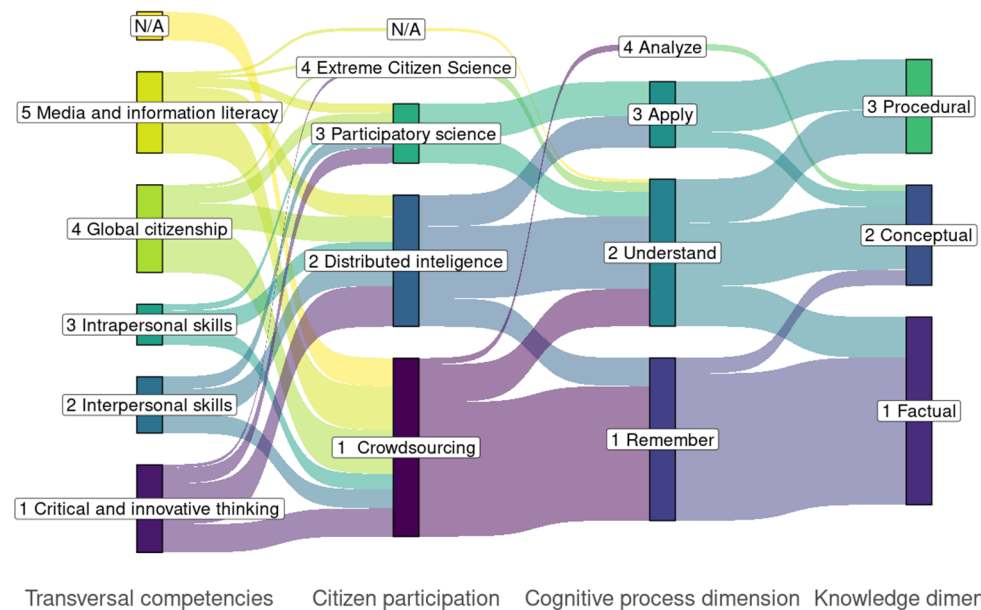


Figure 10. Sankey diagram of the association of tech-based CS studies, including assessment of participants' transversal competencies (RQ4a), participation level (RQ4b), cognitive processes (RQ4c), and knowledge dimensions (RQ4d).

Among the six domains, *Critical and innovative thinking* hosted the majority of observations (twenty-eight), where the sub-categories of reflective thinking (eighteen) and reasoned decision-making (eight) stood out, next to a low incidence of creativity (four). Two domains followed with an equal number of entries, *Global citizenship* (twenty-six), which featured awareness (twenty-six), respect for the environment (eighteen), responsibility (ten), and a lesser extent, a sense of belonging (five) and democratic participation (four); then *Media and information literacy* (twenty-six), with a significant occurrence of the ability to obtain and analyze information through information and communication technology (twenty-six), and to a smaller degree the ability to critically evaluate information and media content (seven). In the *Interpersonal skills* domain (nineteen), collaboration (sixteen) was identified as the most frequent, and to a lesser extent, teamwork (four), sociability (three), compassion (three), and empathy (two). Lastly, within the *Intrapersonal competencies* (thirteen), limited observations were found in the ability to learn independently (five), self-awareness (five), and self-discipline (three). The sixth domain, called *Others*, dedicated to skills and competencies defined by countries or economies, was not considered during this review because of the ambiguity in pairing the regions analyzed.

In contrast, some of the skills that the CS studies did not address were: entrepreneurship, organizational skills, flexibility and adaptability, perseverance, self-motivation, integrity, self-esteem, tolerance, and conflict resolution. Therefore, it might be a pending issue to work on these competencies and incorporate them in future CS initiatives. Likewise, it is noteworthy that, although competencies for the development of ICT were quite popular in CS studies, the question of the ethical use of ICT was largely absent from the studies (1).

RQ4b: What level of citizen participation was undertaken or was intended?

In the case of citizen participation, we based the analysis on the four levels of participation in CS by Haklay [47], from "Crowdsourcing" to "Extreme CS," whose results are shown along with the type of applied technology identified. At level one, Crowdsourcing, a total of twenty-six projects were identified, of which nine corresponded to native developments, fourteen to third-party technologies, and one to both. As for level two, Distributed Intelligence, thirteen projects were found, of which three were native technologies, nine were third-party, and two used both. Level three, Participatory science, was identified in seven projects, including four in native technologies and three from third parties. Finally, in level four, Extreme CS, only one project was observed that featured a native technology.

A considerable number of projects were carried out in schools, either with students or also involving teachers. Some studies included a financial incentive as compensation for participants, as in the case of Jacobs et al. [63], although they argued that the intrinsic motivators of representation, being heard, and contributing were more potent motivators.

RQ4c: What classification do the projects fit into according to the RBT's Cognitive Process dimensions from the citizen participation perspective?

To address this and the next question, we chose the Revised Bloom's Taxonomy (RBT) [48,64]. RBT features cognitive categories that, in correspondence with the complex thinking perspective and Haklay's levels of engagement approach [47], allowed us to progressively distinguish the participants' development from lower-order thinking skills (LOTS) to higher-order thinking skills (HOTS) [65]. RQ4c was answered by considering the six Cognitive process dimensions in an ascending pyramid: remember (visualized at the base), understand, apply, analyze, evaluate, and create (visualized at the top). According to our interpretation, we sought to identify the cognitive process conducted by participants through the CS projects, as stated in each project or as intended. Results showed a tendency consistent with the ascending complexity of the thinking skills pyramid; these were "remember" (twenty-three), "understand" (seventeen), "apply" (eight), and "analyze" (one); there was no presence of "evaluate" (0), or "create" (0).

RQ4d: What classification do the projects fit into according to the RBT's Knowledge dimensions framework from the citizen participation perspective?

Also, based on RBT, the framework to answer RQ4d considered *Knowledge dimensions*, with thought processes ranging from concrete to abstract (factual, conceptual, procedural, and metacognitive). Similar to the previous question, we sought to identify the type of knowledge intended for the participants according to the nature of each CS project. Our analysis showed a trend similar to that of the previous question, where the majority of projects involved the factual knowledge type (twenty-seven), followed by procedural (twelve) and then conceptual (ten), with no consideration of the metacognitive type (0).

Figure 10 diagrams the overall integration of the four questions in this section, which refer to the participants' complex thinking competencies through the association of all the analyzed components. By its construction, the four questions can be seen as pillars for the items considered for ranking the answers.

Except for the first column (transversal competencies), the three columns to the right show ascending numbering that can be interpreted as the corresponding degree of complexity for each column, where "one" represents less complexity and "four" is the maximum level identified. Overall, the results revealed that the three columns of citizen science, cognitive dimension, and knowledge dimension coincide in the predominant proportion of the base (level one). This represents the low complexity in the citizens' involvement and cognitive processes, and of the activity requirements in CS projects. Comparably, level two implies a greater capacity for interpretation and construction of meanings. Under these two levels, most transversal competencies (left column) are identified as being developed.

Although the blocks at level three show a lower number of observations, the proportion and consistency between levels are maintained among the three columns, where the equal influence of transversal competencies (left column) remains prominent. At this level of inter-column associations, participants are expected to contribute to a greater degree to the collective that designs CS projects, which brings them closer to applying procedures, methods, and skills in a given situation. As a whole, we observed that participants do not reach the maximum levels of involvement in tech-based CS projects, which shows that they do not manage to collaborate integrally throughout the projects, undermining the possibility of developing the creativity and meta-cognition intended by the complex thinking competency.

RQ5a: What impact did the initiatives have on society?

To envision the impact of the analyzed tech-based CS projects on society, we employed Ashoka's levels of impact [49], which present a stepped classification starting with (1) Direct Service, innovation for basic needs; (2) Scaled Direct Service, which involves intervention

with efficient models; (3) Systems Change, which addresses the source of a problem through new models and behaviors in specific markets; and (4) Framework Change, where the mindset and behavior of people are transformed on a large scale within society. Figure 11 reveals Ashoka's social innovation levels of impact that were identified for each type of project, either stated or intended, based on the interpretation of the authors of this analysis. At the Direct service level, nineteen studies were identified, minimally surpassed by the next level, Scaled Direct Service with twenty-one studies, and finally, at the third level, Systems Change, eight studies were identified. As for the highest level of impact, Framework Change, no studies were found to consider this intention.

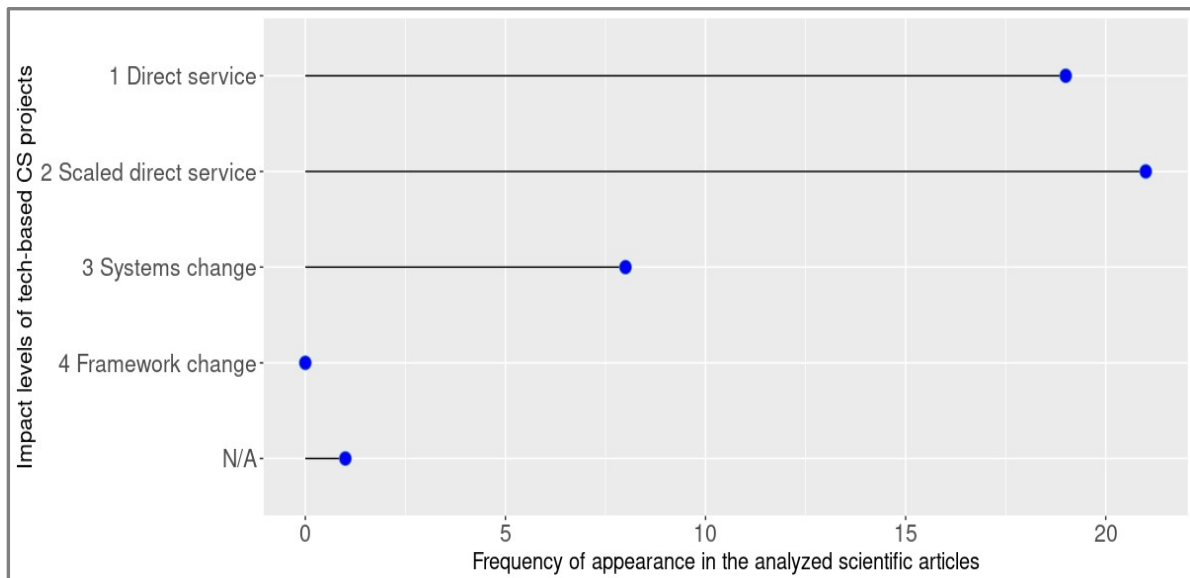


Figure 11. Ashoka's four levels of impact [49].

4. Discussion

Strong interest has been observed in implementing tech-based CS projects across Europe on topics relating to both the physical and natural environments. Technological developments have been mainly directed to CS projects addressing the SDG of sustainable cities and communities (see Figure 8). Particularly in Europe, many tech-based CS projects have been carried out (see Figure 3). This activity level is in line with the momentum of European organizations such as the European Citizen Science Association [7]. Moreover, bodies such as the European Research Council [66] drive funding for environmental and welfare improvement issues. Europe's recent synergy in tech-based CS projects appears to result from cross-organizational partnerships promoting the self-management of researchers, backed by funding aligned to current societal challenges.

Tech-based CS projects in line with achieving SDGs tend to follow a different helix alliance configuration from that of the triple, quadruple, and quintuple helix innovation models. Of the 49 studies analyzed, only 24.8% complied with the helix innovation models proposed by Carayannis & Campbell [17] (see Figure 6), among which the most predominant form of collaboration was the education system, the political system, and the society (public) (see Figure 7). This finding is aligned with existing analyses of innovation models and SDGs which, whilst acknowledging the helices' influence, criticize how their dimensions are constructed, opening the way for more organic collaborations [22,23]. In the context of tech-based CS projects, the forms of cooperation among actors can be of diverse natures that do not necessarily coincide with the currently known helices of innovation models, a fact which opens up the possibility of research on the particularities of alliances in the field.

A noticeable focus on developing applications that aid in strengthening urban scaling through CS projects is noticeable. There is a perceived upsurge in the focus on SDGs, coincident with the attempt to improve life in the cities (see Figure 8). This concentration of projects makes sense from the perspective of urban scaling, which is concerned with urban sustainability, and emphasizes how life in the city implies the interconnection of elements and systems that simultaneously involve nature [21]. Challenges in the designs of tech-based CS projects that attempt to achieve sustainable urbanization call for reconsidering the technological potential to monitor and prevent consequent negative impacts.

Whilst the driving role of technology in recent CS projects is evident, there is a shining opportunity to develop native technologies to attain the SDGs. In the analysis of recent tech-based CS projects, the need for native development and hardware was evident (see Figure 9). Regarding the technologies identified in CS projects, the Fourth Industrial Revolution framework seems not yet to have had an overall effect on developing innovative applications [40]. The need for native technology development in CS projects becomes even more urgent when observing the rise of disruptive technologies such as IoT, IA, big data, and blockchain to assist in the development of smart cities [5]. Despite the creativity applied to tech-based CS projects, there is still a perceived lag in applying native technologies, which is even more evident in the disruption caused by the Fourth Industrial Revolution.

The development of complex thinking in tech-based CS projects is still restricted to the passive participation of citizens. The present review has revealed the relationship between the lack of deep involvement of citizens in projects and their consequent limited development of complex thinking in the activities to which they contribute; among the 49 studies analyzed, traces of the elements of critical and innovative thinking were only noted in 55% (see Figure 10). The participants' reduced involvement in tech-based CS project experiences leads to poor assimilation of knowledge, which truncates their chances of reaching a problem-solving stage potentially applicable in new situations [29]. Disregarding the development of complex thinking in CS projects can be addressed by basing project planning on frameworks and typologies that consider the role of technologies and the development of the individual [27]. For tech-based CS projects to achieve a holistic impact, including the development of complex thinking, it is necessary to plan with an awareness of participants' interactions.

CS projects that used native technologies and showed a higher level of citizen involvement achieved a more significant impact and may also have contributed to developing complex thinking. Regarding the 49 projects analyzed, 16.3% attained Ashoka's level three "Systems Change" (see Figure 11), which indicates that new models for addressing problems are generated; whereas out of the 16.3%, 75% incorporated native technology, and 62.5% achieved a high level of citizen participation. These results are consistent with the promise of the Fourth Industrial Revolution.

The Fourth Industrial Revolution promotes technologies to assist in developing skills and competencies for the future [40]. Indeed, the above results converge with the ladder promoted by Ashoka, where the involvement of CS participants might allow for systemic change by transforming the mindset of individuals and thus their behavior [49]. Furthermore, the design of projects must consider their impact on the various components to be developed to achieve a comprehensive result [27]. The contribution of CS projects to systems change has a significant social impact, as it reconfigures circumstances based on the implemented solutions. In this circular process, tech-based CS projects must also be guided towards developing critical and innovative thinking from a comprehensive perspective for participants to generate awareness of the significance of their learning about their immediate environment and achieve optimum benefits.

5. Conclusions

This review aimed to identify commonalities between CS projects and the technologies used, the level of participants' involvement, and the social impact achieved, by analyzing

49 relevant studies in the literature addressing issues related to the SDGs. By answering a set of strategic research questions, we found that the leading technologies used within the studies were the development of application-oriented software and machine-learning-based data management. Other studies employed and combined, at some point, hardware developments like sensors, computers, smart cell phones, and other types of devices. Some projects integrated the internet and social networks as well. Moreover, those CS studies' most related to SDGs associated with technology were mainly sustainable cities and communities.

Regarding the competencies where technology was present, citizens learned to evaluate information and media content critically, increased their literacy to handle media and information by building skills to obtain and analyze information through ICT, and became more meditative and thoughtful about reflective thinking. In terms of the level of involvement of the various stakeholders in innovation, a genuine interest existed in the design and implementation of tech-based CS projects in Europe and other regions of the world, highlighting topics like built space, disaster risk, and environmental and animal monitoring. We also observed that these projects followed a variety of helix alliance configurations, the most common being the Education-Political-Public and Education-Public combinations. It was also noticeable that the tech-based applications described in the reviewed articles were oriented to strengthen the city life of individuals. Many of these projects either adopted or customized third-party software. Still, there was a clear opportunity to devise native technologies for future proposals, given that these approaches have a significant impact on society and positively affect the aspect of complex thinking, which is a central point of this study. It was observed that the participation of citizens in the projects, in general, was still passive and limited.

The research presented here has been rigorous in its analysis, but we are aware that it can be made even more exhaustive by including other valuable sources of information that complement our findings. Nevertheless, we consider it a reasonable attempt to communicate what the literature offers by linking the relevant and trendy topics of CS, technology, and complex thinking. An additional limitation is perhaps that our work did not consider in its analysis the correlation between the level of involvement of the citizens and the length of implementation/application periods. Other relevant issues that were not possible to address were associated with public policies, governance, human rights, and social justice. These are undoubtedly viable lines of research for the near future. Other possible research avenues can be derived from our work: adding other sources of information and data from projects reported in journals with lower quartiles, Q2 for instance, could be considered; finding more detailed insights into the existing data, for example, parameterizing the real impact of tech-based CS projects on society; measuring the correlation on various combinations of SDGs observed in tech-based CS projects; conducting an analysis on the kind of competencies that citizens develop when involved in these kinds of projects; and evaluating the association of CS studies with the level of participation and involvement of citizens, the evolution of cognitive processes, and the knowledge dimensions. We strongly believe there are several research opportunities on these topics, especially for those aiming to advance science whilst impacting our society and people's well-being.

Supplementary Materials: The following supporting information can be downloaded at: <https://doi.org/10.5281/zenodo.6836976>, Table S1: metadata of the analyzed scientific articles of this SLR.

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