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Citizen Science's Influence on Public Policy for Addressing Complexity: A Systematic Review of Tech-Based Projects in Higher Education

Berenice Alfaro-Ponce[1], Jorge Sanabria-Z[2], Luis Francisco Rivero-Zambrano[3] & Cristopher Muñoz-Ibáñez [4 5]

Abstract

Citizen science's (CS) deployment and benefit over the last ten years have been remarkably substantial in their contributions to the massification of citizen participation in tech-based CS projects. Insights into how CS projects influence community changes through proposals of actions and public policies are essential to understanding how they facilitate citizens' advocacy in decision-making at various ecosystem levels. To this end, we conducted a systematic literature review of tech-based CS projects published between 2017 and 2022, in which the participation of the tertiary education sector played a central role. We used a guideline that education plays a fundamental role in developing technology-based CS projects. The more educational processes, such as incorporating activities that strengthen complex thinking in citizens, the greater their involvement in decision-making to propose public policies that address their current problems. Findings suggested that a) there is significant involvement of the educational system with CS; b) CS projects do not comply with the innovation helixes; c) tech-based CS projects usually indirectly develop competencies and sub-competencies of complex thinking, and d) social actions are clearly articulated through these competencies and sub-competencies that determine the complete cycle of tech-based CS projects, which result in organized actions or public policies. To sum up, this study serves as a call for long-term co-design projects that consider both the individual development of the participants and the integral impact on decision-making at all levels.

Keywords: *Citizen science, higher education, educational innovation, tech-based methodologies, complex thinking, public policies.*

Introduction

Citizen science (CS) originated with the massive participation of citizens in data collection processes for scientific projects. This socially focused concept has been evolving and taking various forms over time, thus becoming flexible (Kullenberg & Kasperowski, 2016). This flexibility has shown as authors have incorporated new elements to this concept or the typology of the projects, and the citizen activities in particular types of projects have increased (Haklay, 2013,

[1] *Dr., Tecnologico de Monterrey, Institute for the Future of Education, Monterrey, Mexico,* berenice.alfaro@tec.mx
[2] *Dr., Tecnologico de Monterrey, Institute for the Future of Education, Monterrey, Mexico,* jorge.sanabria@tec.mx
[3] *Dr., Escuela Nacional de Biblioteconomia y Archivonomia del IPN, México,* luis.josue.jiasu@gmail.com
[4] *Dr., Tecnologico de Monterrey, Mexico.,* cristopher_antonio@tec.mx
[5] *Dr., Universidad Autónoma del Estado de Hidalgo, Hgo. Mexico,* cristopher_munoz@uaeh.edu.mx

2018; Miller-Rushing et al., 2012; Sanabria et al., 2022). ECSA (2015) emphasizes this complexity and points out that it is subject to the diverse contexts and disciplines that employ CS. They define at least ten principles of CS, which synthesize vital citizen roles and interactions at various levels, benefitting both researchers and participants, producing scientific products, feedback, and citizens' participation in dissemination processes. Thus, CS projects are guided by researchers' scientific interest in massive data collection and analyses or impact on other functions, where it is essential to emphasize that citizen interventions may vary.

Public participation in CS projects tends to be either active or passive, mainly following the educational interest embedded by the researchers developing the project, typically affiliated with higher education institutions. In such scenarios, researchers entrust their research projects into the hands of citizens, intending to massify the data collection process (Strasser et al., 2019), which is particularly welcomed when there are insufficient financial resources to carry out traditional field research efforts for this purpose. Information and communication technologies (ICT) have facilitated the interaction between citizens and scientists, allowing more generation, collection, and data processing for their analyses and applications. The result has been the creation of policies, legislative instruments, management and monitoring tools, educational and awareness programs, and facilitating partnerships and agreements among stakeholders (Brenton et al., 2018). Users may participate at a basic level either by sharing their computer equipment for collective processing or as mere data collectors, increasingly becoming more engaged, including the conception and analysis of the initiatives (Haklay, 2013, 2018). However, there is an ongoing debate regarding the reliability of the data obtained by the wide variety of participants. The issue of how projects can scaffold citizens' transition from mere data collectors (sensors) to active and empowered stakeholders has also been discussed.

Thorough research on CS projects in the last decade has shown specific desirable and undesirable characteristics of CS. Accordingly, there are still various conceptions of CS (Kullenberg & Kasperowski, 2016) where the actors' roles are no longer ambiguous and allow a better understanding of the importance of their contributions to the entire process (European Commission, 2020) and CS' role and impact in social problems (Heilbron et al., 2017). Bearing this in mind and the characteristics and impact of the initiatives (Sanabria-Z et al., 2022), we have deduced the importance of the citizen engagement discussion and the function and relevance of the educational system for the overall success of CS projects.

Thus, we established the following research question: How does the interaction of tertiary education affect the development of CS projects and participants' sub-competencies of complex thinking, where the results implemented or advanced organized actions or public policies?

We determined it was necessary to study the synergies between citizens, scientists, and the environment when conceptualizing tech-based CS projects (Sanabria-Z et al., 2022). We also considered the importance of contributing to the participants' development, actors, and the entire ecosystem (Asingizwe et al., 2020), particularly incorporating complex thinking, a relevant benefit to participants' personal and professional progress (Ramírez-Montoya et al., 2022) during 21st-century changes. Thus, educators could establish the CS methodology for this purpose by understanding the correlations of collaboration in tech-based CS projects and the development of participants' sub-competencies.

Importance of complex thinking for a better understanding of the phenomena

Complex thinking is considered an essential meta-competency to understand the phenomena around us. The world's complexity can hardly be understood or partially understood if a multi-referential approach is not used (Ardoino, 1991, 2005; Ardoino & Acevedo, 2003). Multireferentiality allows us to study complex reality, understood as multiple dimensions of facts, which for Morin (1996), are circumstances with diverse facets where chaos and order converge. Nowadays, the vertiginous changes brought about by globalization and the related complex interactive dynamics make it necessary to approach these phenomena from a perspective that responds to these challenges.

The continuous development of ICT has opened new opportunities in research, interaction, and improvement in education. Recent studies have determined the necessity of fostering knowledge, skills, and competencies to address the challenges of the 21st century (Ramírez-Montoya et al., 2022) (UNESCO, 2016) and the technological and environmental challenges of the Anthropocene era (UNDP, 2020), which compels us as a society to establish strategies to achieve SDG 2030 (European Commission, 2021). In this consideration, many of the participants in CS projects are not students, but they can strengthen their lifelong learning through non-formal educational pathways by developing their sub-competencies throughout the projects.

We commonly use “lifelong learning” to address adult education, especially knowledge acquired in diverse ways and stages. Considering this, international organizations have discussed lifelong learning as significant for the positive transformation of the labor market (OCDE, 2016; OECD, 2021; UNESCO, 2022) and other structural changes in societies. For the OECD (2021), lifelong learning enables cohesive societies to cope with today's vertiginous changes by developing skills, knowledge, and aptitudes. This notion certainly contributes to the progress and flourishing of individuals, thus establishing the means for them to have greater and better participation in their social environments and become involved in decision-making.

Citizen science and its influence on Education

Educational intervention strategies have conventionally sought to reduce the under-representation of citizens in scientific careers worldwide. Participatory project-based learning has proven to be effective in actively engaging participants in gaining scientific knowledge following the research process (Bradforth et al., 2015; Ferreira et al., 2019). CS has gained recognition in this area as a powerful tool for engaging students in real-world projects, addressing the goals of both scientists and educators (Bonney et al., 2009) and those of umbrella frameworks, such as the Sustainable Development Goals (Fritz et al., 2019). For instance, it has contributed to raising awareness and attitudes that change behavior (Kelemen-Finan et al., 2018). Likewise, another advantage of the connection between CS and education is its implementation as a strategy for citizenship education (Estelles et al., 2021). However, there are notable differences between informal science education (ISE) and formal science education (FSE) projects regarding participants' achievable engagement and learning outcomes.

It is commonly understood that CS in ISE projects does not lean towards the deep development of the individual but towards the achievement of a scientific research objective. Nevertheless, educational services in museums and other informal learning institutions such as zoos and aquariums have active CS (Kloetzer et al., 2021). Some key issues identified by Jordan et al. (2012) regarding attaining learning outcomes when engaging the general public on such scientific experiences include planning for quality evaluation. In their user’s guide for evaluating learning outcomes in CS, (Phillips et al., 2014) point out that the scope of CS projects in ISE should be tailored to the objectives and needs of the entities involved and be assessed through internal or external evaluations. They propose a framework for evaluating individual learning outcomes with six aspects: interest in science and the environment, self-efficacy, motivation, knowledge of the nature of science, scientific inquiry skills, and behavior and stewardship.

Concerning FSE projects, Zoellick et al. (2012) state that for a "scientist-teacher-student partnership" (STSP) to be successful, the learning objectives for scientists (e.g., the attitude toward the science of volunteers collecting and interpreting data to answer a research question) vs. those of educators (e.g., decision-making from long-term sampling in real scientific research) must be differentiated. Moreover, they propose a logical model for implementing FSE projects in which, in addition to scientists and students, a neutral entity is integrated (e.g., a higher education institution) to facilitate interactions and achieve an overall project goal, balancing scientific and learning interests, albeit evaluated from different perspectives (Zoellick et al., 2012). Recognizing that formal education structures narrow the expected goals in the curriculum framework, Roberts et al. (2019) indicate that CS results in student education are arguably more effective than in informal education. Among the benefits of CS learning through ESF, Harlin et al. (2019) highlight the school's capacity to recruit and retain students and motivate them to participate in real projects that advance science. Furthermore, they argue that teachers also benefit from opportunities for personal development and the chance to link the curriculum to the projects.

Whether in the context of ISE or FSE, it is central to remember that the educational impact of CS projects intertwines with others; this must be considered from the moment of conceiving the initiatives. With this in mind, and in line with Jordan's et al. (2012) notion of an impactful holistic approach to learning assessment, Sanabria-Z et al. (2022) proposed the "Threshold for CS Projects," which comprises eight strands for achieving comprehensive project impact, among them educational innovation, citizen engagement, and complex thinking. However, there are still transversal challenges for ISE and FSE in monitoring the development of the individual, especially in the long term, and reducing inequity issues to promote social justice in participatory projects (Roche et al., 2020). The insufficient synergy between scientists and educators in CS initiatives is a call to strengthen the co-design of projects aligned with relevant international frameworks and consider global social gaps to generate positive educational experiences.

Citizenship as a critical component for citizen participation and public policy

The idea of citizenship is a concept with crucial theoretical acceptance in democratic societies because it is associated with fundamental human rights. However, according to Kabeer (2007), there is currently a relevant debate that this theoretical discussion occurs in the face of an empirical absence. Thus, several authors (Kymlicka, 2010; Marshall, 1997; Marshall & Bottomore, 1998; Ramírez-Sáiz & Juan M, 2006) question the concept of citizenship, suggesting a crisis of social representation mainly in the political arena that impacts human rights. This shows us that in both the academic and real-world spheres, little has been achieved to shape inclusive societies, thus reducing the role of citizenship only to the vote.

This condition is not a new phenomenon; at least since the eighteenth and nineteenth centuries, citizenship has not been able to guarantee social rights. In this context, Marshall (1997) and Marshall & Bottomore (1998) divide citizenship into three parts: civil, political, and social:

- Civil rights are characterized by being proper to the individual condition and guaranteeing the citizen the possibility of owning property, having a job, professing religion, and demanding justice.
- Political rights derive from civil rights, which are regularly associated with the governed and the rulers; specifically, the possibility for individuals to vote, to be voted for, and to guarantee the vote.
- Social rights focus on the distribution of wealth in a community spectrum and guaranteed access to education, health, housing, employment, and others.

Citizenship allows individuals to share, be community members, be recognized, and receive guaranteed state benefits. Marshall asserts that citizenship is understood as a status of equal rights that generates a counterbalance to the existing inequality among community members.

Although the classical theory of liberalism indicates the universality of rights for all people, in practice, it remains a theoretical approach. For example, we can mention that education is still pending for a large part of the world's population in at least two aspects: coverage and equity (OCDE, 2018). According to data from (UNESCO-UNEVOC, 2020), in at least 20 countries, almost no young people from poor areas complete the second year of secondary school. In this sense, education plays a vital role in developing citizenship in formal or non-formal settings or throughout life, so both rights have a profound relationship.

It is essential to understand that citizen action is necessary for citizenship to be successful. Nash & Wiley (2010) indicates that the first movements that demanded their rights were the women's movements and LGBT groups, where the model of citizen rights was contested and led to the construction of other models. Other movements focused on inclusion and exclusion involving race and ethnicity (Oliver, 2017; Schierup & Ålund, 2018); they were used to respond to cultural policies. Immigration was also part of those social movements about racism and, thus, multicultural rights (Janoski, 2021). The various actions coming from citizens contribute to the global civil society. They generate new international laws that impact social and environmental issues.

Citizen actions can constitute institutional structures and spaces for political intervention and influence developed through association and collective action. For Cohen and Arato (2000), collective action is a mass movement based on material interests; these movements can be generalized because they are not local, moving from one place to another, and are of two types:

- Institutional-conventional is not oriented by existing social forms but comes together to deal with undefined or unstructured situations.
- Non-institutional-collective has a life cycle, open to causal analysis, and goes from spontaneous action of the crowd to the formation of public and social movements.

From this perspective, CS cannot be oblivious to citizens' role as participants and a fundamental part of movements because they can act as agents of change, among other duties.

Citizen organization is thus an element that dynamizes social learning and generates identity, incorporating new identities and democratic norms into social practices. This can create processes that significantly impact the public agenda (Cohen & Arato, 2000). Incorporating communication technologies also fosters citizens' participation and engagement (Chong et al., 2021) and, consequently, the decision-making process for bottom-up public policies (Hjern & Hull, 1982; Hjern & Porter, 1981). These actions are rights citizens have in everyday life, and the movements and organizations generated from them aim to their social position in the State. Thus, citizens can involve the various actors required to recognize and solve environmental problems through active participation.

Purpose of study

The research aimed to identify tech-based CS projects where the participation of the tertiary education sector (not only scientist intervention) was crucial. Likewise, it discerned the sub-competencies of complex thinking developed by participants and where the results included developing or implementing organized actions or public policies.

Method

The scientometrics meta-analysis method was used for this literature review, and a qualitative approach was used to analyze the concepts addressed. The database selection process was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol guidelines (Page et al., 2021) (see Figure. 1) to plan this systematic literature review (SLR) and present the results. We scrutinized articles published in Scopus and Web of Science from 2017 until 2022 because the best scientific journals are found in these databases. Therefore, we selected studies published in Q1-ranked journals to analyze tech-based CS projects.

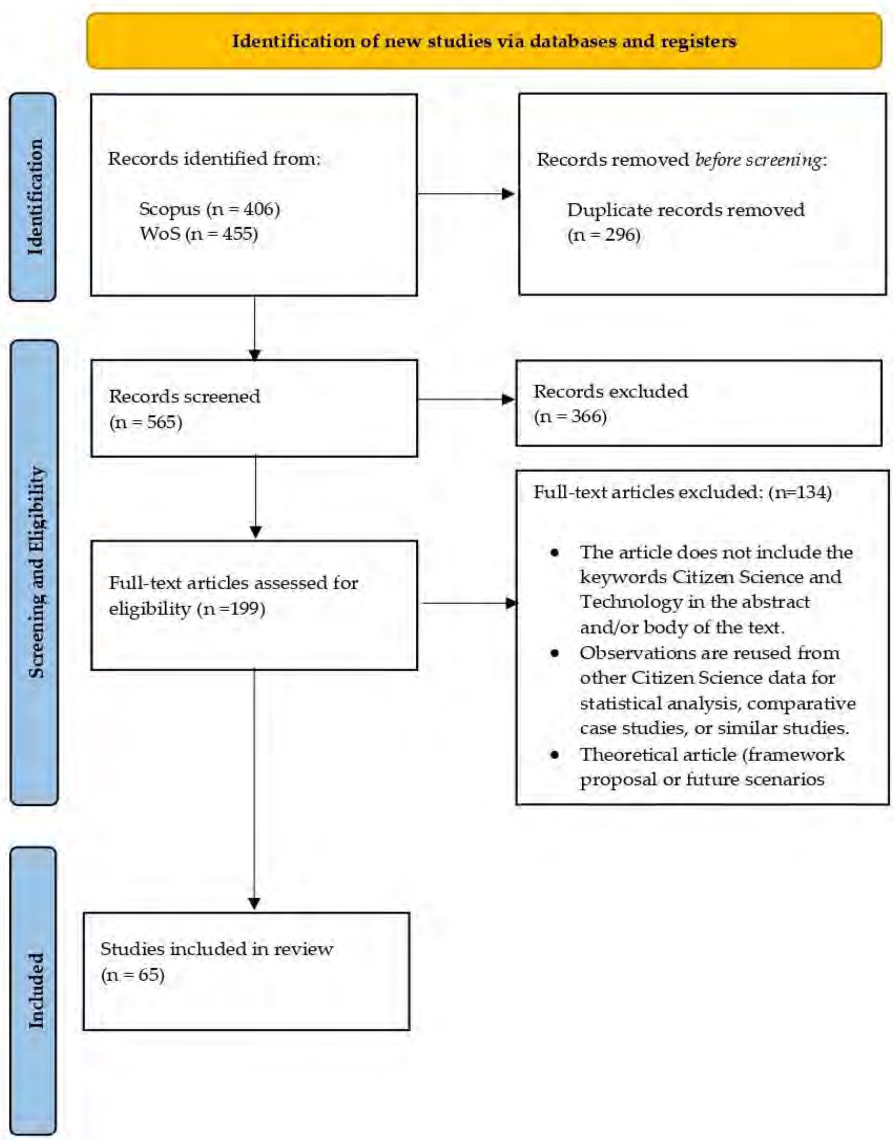

Figure1. SLR analysis from PRISMA protocol (Page et al., 2021)

The inclusion and exclusion criteria were applied in the meta-analysis of the articles. We examined the following criteria for the SLR:

- The research questions were formulated according to the problem of interest and the aim of the SLR.
- The search method was determined using the most relevant keywords of the topic of interest, articulated with the problem posed, in both Scopus and WoS databases.
- The proposal's design for the homogeneous exporting of the information from the database was planned for a better subsequent analysis.

Literature search strategy

We decided to conduct a thorough search in Scopus and WoS because of the relevance and prestige of the databases. The search descriptors are described in Table 1.

Table 1

Search descriptors

Web of Science	SCOPUS
"Citizen Science" (Topic) and Technology (Topic) and 2022 or 2021 or 2020 or 2019 or 2018 or 2017 (Publication Years) and Articles (Document Types) and English (Languages)	(TITLE-ABS-KEY ("Citizen Science") AND TITLE-ABS-KEY (technology)) AND (LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English"))

Research questions

It was necessary to develop a series of questions to determine how tertiary education influences tech-based CS projects and eventually contributes to the generation of organized actions and public policies. Based on the background framework presented, we considered five dimensions to analyze in the final database (see Table 2):

1. Educational system interaction helps us determine which educational levels interact in the CS projects, regardless of participants' status as scientists, professors, students, or even management staff.

2. Project scope allows us to understand the interaction among helixes, the CS project's objective, the range of interests according to SDGs 2030, and the technologies used.

3. Participants' development provides insights about the competencies that the CS projects intend to develop in the participants, according to the level of engagement and complex thinking sub-competencies to be developed.

4. Social action captures the final outcomes of the projects and their influence according to the participants' engagement and possible ways of organizing.

5. Journal metrics assist us in identifying the journals, countries, and authors most prone to research this topic.

Table 2

Research questions

Dimension	Research question	Possible answers
Educational System interaction	RQ1. Considering participants, which level or levels of educational attainment were involved in the project?	0. Not mentioned 1. Early childhood education 2. Primary/elementary school 3. High school 4. Tertiary education.
	RQ2. Who participated on behalf of the educational entity (the project coordinator)?	0. Not clear 1. Researchers 2. Researchers and administrative staff 3. Researchers and students 4. Students 5. Researchers, administrative staff, and students
Project Scope	RQ3: Which Innovation Model helix systems were identified in the studies? (Carayannis 2010)	1. Education system 2. Economic system 3. Political system

		4. Public 5. Natural environment
	RQ4. What Sustainable Development Goals do the proposals focus on?	1. No poverty; 2. Zero hunger; 3. Good health and well-being; 4. Quality education; 5. Gender equality; 6. Clean water and sanitation; 7. Affordable and clean energy; 8. Decent work and economic growth; 9. Industry, innovation, and infrastructure; 10. Reducing inequality; 11. Sustainable cities and communities; 12. Responsible consumption and production; 13. Climate action; 14. Life below water; 15. Life on land; 16. Peace, justice, and strong institutions; 17. Partnerships for the goals.
	RQ5 What type of ICT was mainly used in the Citizen Science projects?	0 n/a 1. Software 2. Hardware 3. Both
Participants' development	RQ6 What transversal competencies are considered or intended in the studies from the author's perception? (UNESCO-ERI)	0. n/a; 1. Critical and innovative thinking: creativity, entrepreneurship, resourcefulness, application skills, reflective thinking, reasoned decision-making; 2. Interpersonal skills: communication skills, organizational skills, teamwork, collaboration, sociability, collegiality, empathy, compassion; 3. Intrapersonal skills; self-discipline, ability to learn independently, flexibility and adaptability, self-awareness, perseverance, self-motivation, compassion, integrity, and self-respect; 4. Global citizenship: awareness, tolerance, openness, responsibility, respect for diversity, ethical understanding, intercultural understanding, democratic participation, conflict resolution, respect for the environment, national identity, and sense of belonging; 5. Media and information literacy: ability to obtain and analyze information through information and communication technology (ICT), ability to critically evaluate information and media content, ethical use of ICT; 6. Others: skills and competencies as defined by countries/ economies.

	RQ7 What level of citizen participation and engagement was undertaken or intended? (Haklay, 2013)	0. n/a 1. L1 Crowdsourcing (Citizens as sensors; Volunteered computing) 2. L2 Distributed Intelligence (Citizens as basic interpreters, Volunteered thinking) 3. L3 Participatory science (Participation in problem definition and data collection) 4. L4 Extreme Citizen Science (Collaborative science - problem definition, data collection, and analysis
	RQ8 What sub-competencies of complex thinking were developed by the citizens? (Ramírez-Montoya et al. 2022)	0. None 1. Innovative thinking: the capacity for creativity, implemented with a high degree of success; they delineate four levels: “incremental” innovation, “modular” innovation, “architectural” innovation, and “radical” innovation 2. Scientific thinking: higher-order thinking that helps students face the era of global competition to overcome various problems. It involves logical, analytical, systematic, inductive, and deductive thinking to solve problems. It includes defining, identifying, and formulating alternative proposals and determining the best solutions 3. Critical thinking is the intellectually disciplined process of actively and skillfully conceptualizing, applying, analyzing, synthesizing, and evaluating information acquired or generated by observation, experience, reflection, reasoning, or communication as a guide to belief and action 4. Systemic thinking is the underlying reasoning that students must develop to analyze and understand complex global systems and phenomena
Social action	RQ9. As a result of the participation, was there any action organized by the participants, and did it lead to any public policy that addresses their problems?	0. No 1. Organized action 2. Public policy

Journal Metrics	RQ10. In which countries or regions were the projects implemented? Which are the journals with the most publications? What are the most frequent keywords mentioned in the articles?	Name of country or region Names of journals, Authors' keywords

Findings

The results are presented according to the analyzed dimensions to determine the forms of conceptual interactions and how these can be determinant for a tech-based CS project in complex environments to contribute to the development of social actions and, in the best of cases, to facilitate the proposal of public policies.

Dimension of Educational System interaction

RQ1. Considering participants, which level or levels of educational attainment were involved in the project? RQ2. Who participated on behalf of the educational entity (the project coordinator)? This dimension attempts to identify the relevance of the educational system in CS. Figure 2 shows that 77.6% of the projects analyzed do not mention the participants' educational level; thus, it is understood that they were citizens in general and that their educational level was irrelevant. 9% of the projects involved primary, elementary, or middle school participants. 7.5% of the projects had participants with high school education, while higher education represented 6%.

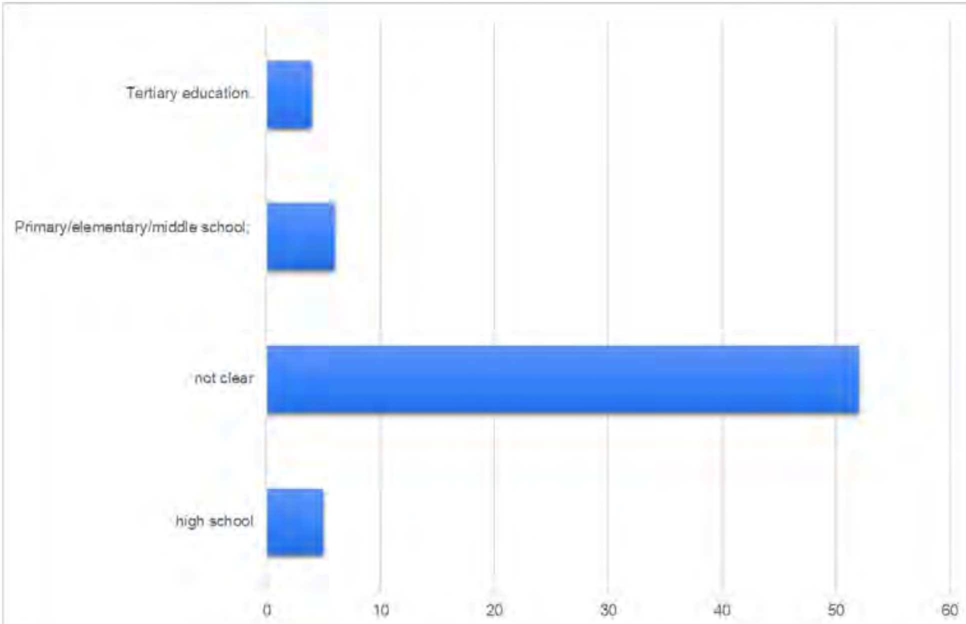

Figure 2 Participants' level of education while participating in tech-based CS projects.

Although the highest percentage of tech-based CS projects do not focus on active students as participants ("not clear," see Figure 3), this does not mean there is no significant influence from the educational system when discussing CS. The participation of the educational sector is indicated by those who lead the projects, where 35.4% are researchers affiliated with research centers or institutions of higher education. 32.3% are researchers and other actors, a combination of academia and the political or public sectors, 10% are researchers, students, and other actors, 9.2% are researchers and students, 4.6% researchers, administrative staff, and students, 4.6% other actors like government, and associations, 1.5%. There were no tech-based projects organized by students.

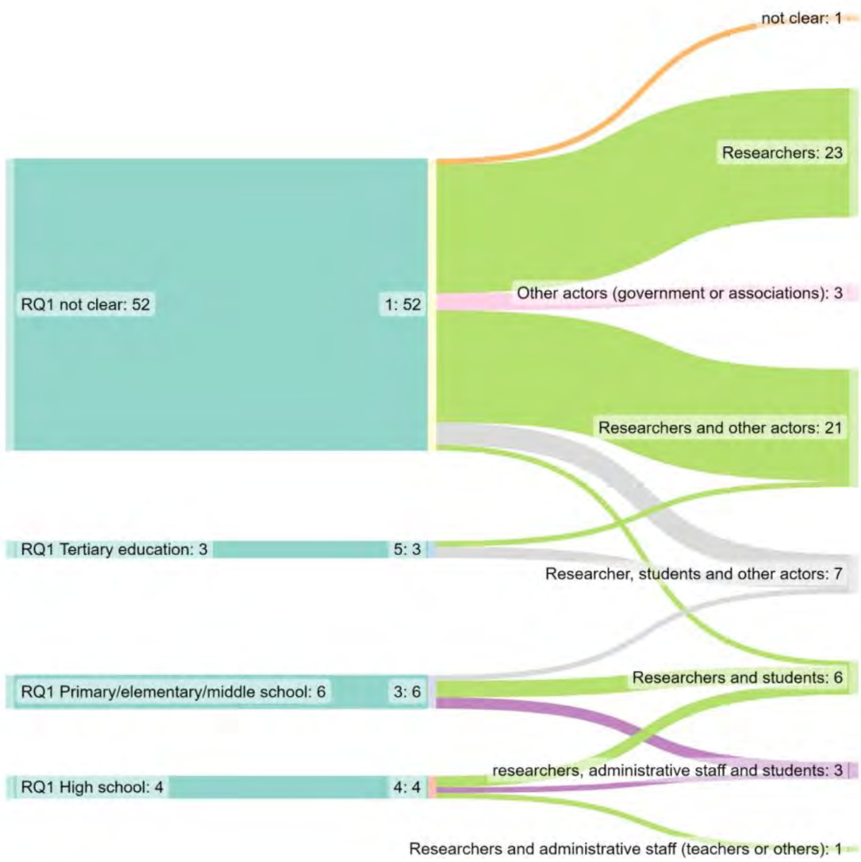

Figure 3 Interaction between participants (and their level of educational attainment) and participants on behalf of the educational entity (project coordinator).

Dimension of Tech-Based CS Project Scope analyzed

RQ3: Which Innovation Model helix systems were identified in the studies? (Carayannis 2010); RQ4. What Sustainable Development Goals do the proposals focus on? RQ5 What type of ICT was mainly used in the Citizen Science projects?

This dimension allows us to observe the intended scope of the CS projects. It was expected that the CS projects would address combinations of the helixes, understanding these as the elements that integrate a social ecosystem, according to Carayannis et al. (2012). However, no interactions between triple, quadruple and quintuple helixes were identified. We noted that systems collaborated with other combinations; in this regard, we remark that the educational system, combined with the public sector, acquired a fundamental role in tech-based CS projects (34%), as well as the combination of the education system with the political system and public sector 34%). Other varieties can be noted (see Figure 4).

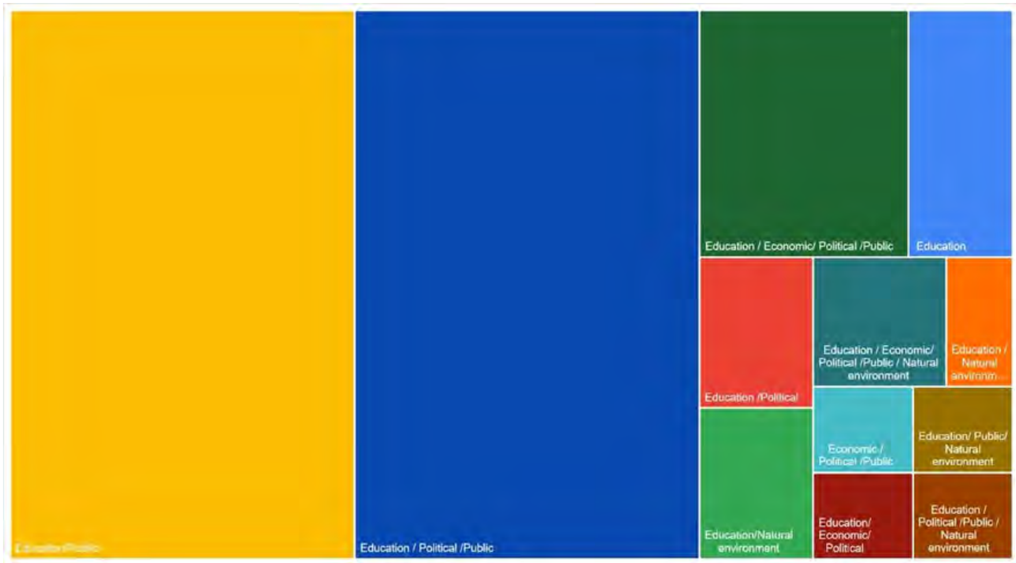

Figure 4. Systems combinations in tech-based CS projects.

Another relevant topic was associated with Sustainable Development Goals. The environmental systems were not sufficiently clear about the participation of organizations focused on these topics. Nevertheless, most tech-based CS projects focus on environmental issues. Therefore, we opted to analyze the interactions among SDGs, helix systems, and ICTs in those projects (see figure 5).

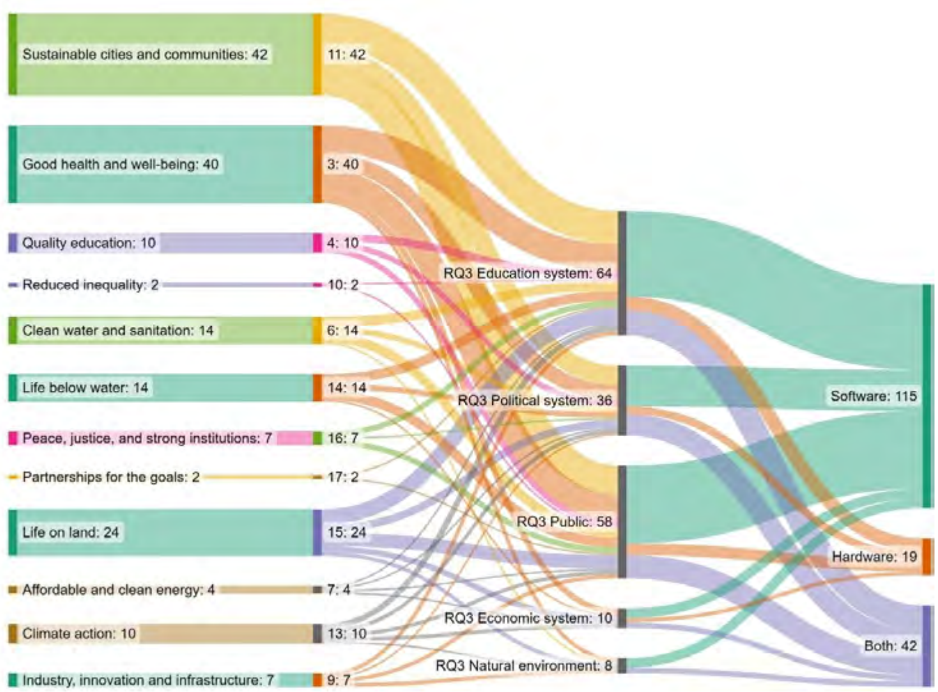

Figure 5. Interaction of SDGs with innovative helix systems and ICT in tech-based CS projects

Figure 5 illustrates 176 interactions between SDGs, helix systems, and ICTs. The interaction of tech-based CS projects mainly concentrated on SGD 11 (Sustainable cities and communities), followed by SDG 3 (Good health and well-being), and then SDG 15 (Life on land). Sustainable cities and communities were articulated only with the Educational, Political, and Public sectors, while Good health and well-being and Life on land were linked with the four sectors. Most of these interactions show that the projects used mainly software as ICT, followed by both (software and hardware), and in a few cases, projects only used or mentioned hardware.

Dimension of Participants' Development

RQ6 What transversal competencies are considered or intended in the studies from the authors' perceptions? (UNESCO-ERI); RQ7 What level of citizen participation was undertaken or intended? (Haklay, 2013); RQ8 What sub-competencies of complex thinking were developed by the citizens? (Ramírez-Montoya et al., 2022).

According to the authors' perception, this dimension is essential to understand how tech-based CS projects contribute to the training of citizens and the activities to be developed. This clarification is necessary because these projects do not indicate the intentionality of developing specific skills and/or transversal competencies in their participants. On the other hand, acquiring these cross-cutting competencies can guarantee their strengthening of lifelong learning. In Figure 6, we present the transversal competencies (UNESCO, 2016) that were intended to be developed from the analysis: 1. Critical and innovative thinking (27%); 2. Interpersonal skills (17%); 3. Intrapersonal skills (10%); 4. Global citizenship (27%); 5. Media and information literacy (17%); 6. Others, like skills and competencies defined by countries/ economies (2%).

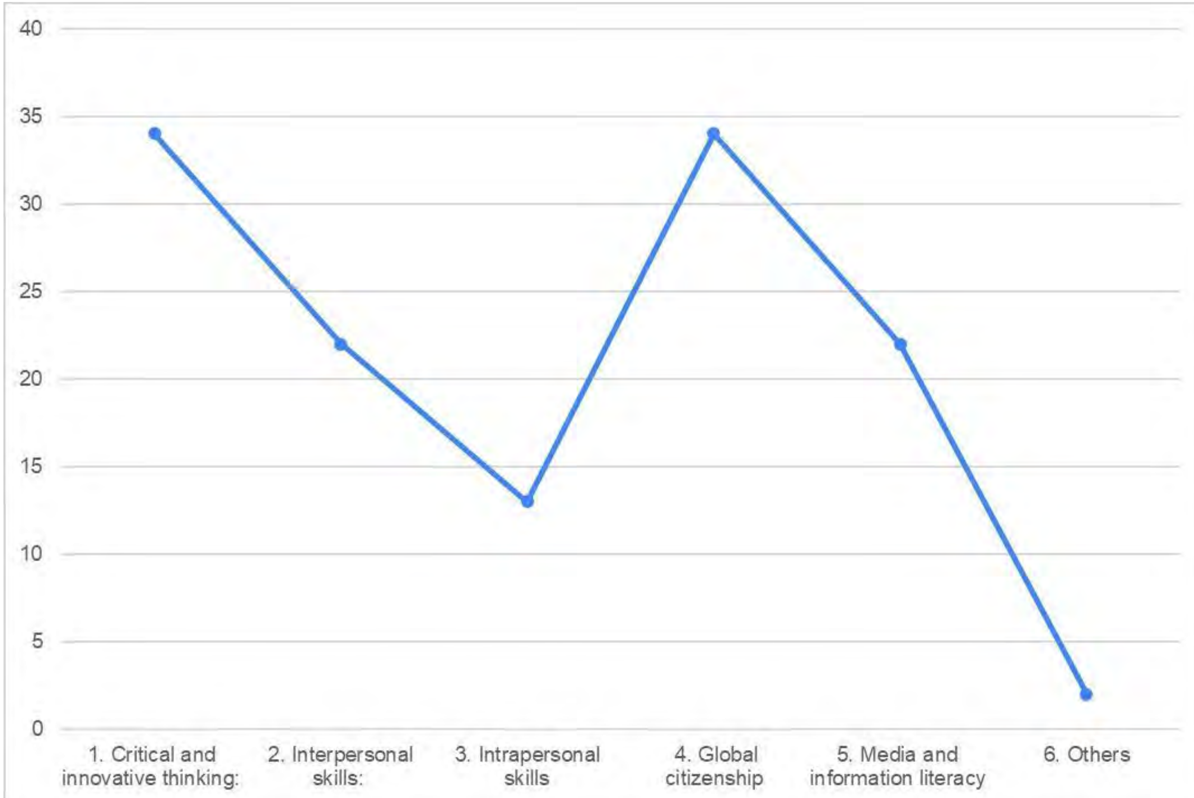

Figure 6. Transversal competencies from UNESCO (2016) intended to be developed in participants

It is important to emphasize that the participants did not necessarily succeed in developing these transversal competencies; however, the type of project and their interests could be aligned with them.

One of the most relevant elements analyzed relates to the engagement of the participating citizens (see Figure 7). In this context, we used the engagement levels defined by Haklay (2013): L1. Crowdsourcing as the most basic form of participation (48%); L2. Distributed intelligence (29%), with some interpretations from the participants; L3. Participatory science, where the participants' intervention goes further with analyzing the problem, its definition, and the collection process (18%); and finally, L4. Extreme CS, where it is possible to say that there was an appropriation of the project and citizen participation in the decision-making process, better known as a collaborative science (2%).

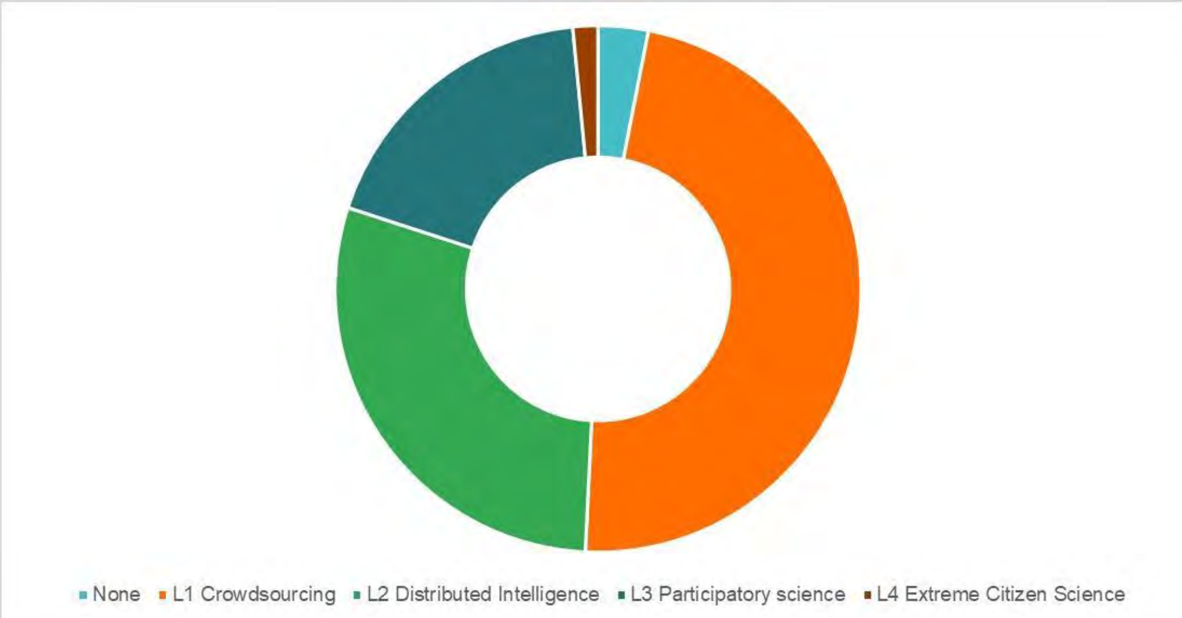

Figure 7. Citizens' levels of engagement in tech-based CS projects.

Another element to address due to citizen participation in these projects was which sub-competencies of complex thinking were explored or developed during these projects. These can contribute to their lifelong learning and trigger more and better-informed citizen participation in future decision-making. According to Ramírez-Montoya et al. (2022), the sub-competencies of complex thinking are critical, innovative, scientific, and systemic thinking, and each contributes to and impacts the personal development of participants. We observed that sub-competencies were not developed in most projects (56%). The sub-competencies that mainly were attended to were critical thinking (34%), followed by scientific thinking (5%), and the least relevant was systemic thinking (3%). We did not find interaction with innovative thinking (see Figure 8).

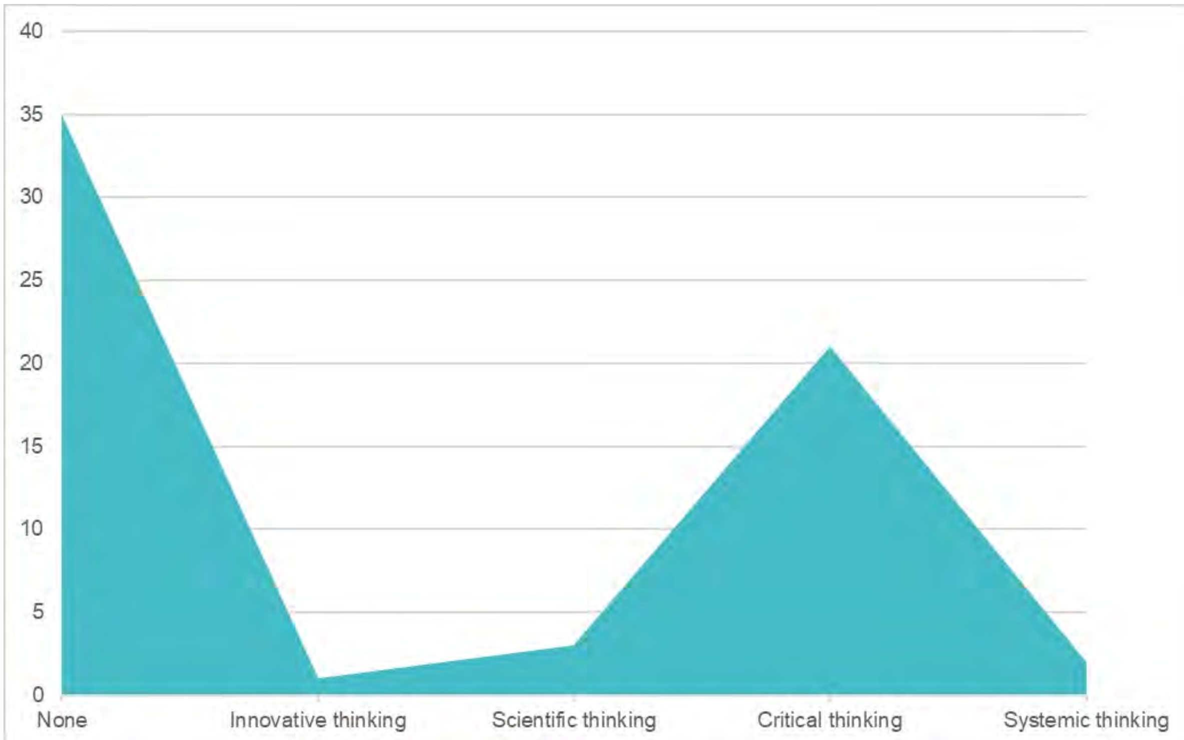

Figure 8. Sub-competencies explored or developed by participants

Dimension of social action

RQ9. As a result of the participation, was there any action organized by the participants, and did it lead to any public policy that addresses their problems?

Social action is a fundamental part of citizen activity. Therefore, citizens are expected to participate in various democratic endeavors and are not limited to voting or being voted for. In this sense, CS can strengthen citizen engagement if the project has established the value of citizenship since these participants not only collaborate in the project but also interact with the various actors, propose changes and improvements and, above all, take a position in the decision-making process through bottom-up action. In this SLR, we considered it essential to know whether tech-based CS projects fulfilled this purpose because the citizen exercise cannot be limited to simple data collection. Citizenship must aim for active participation that impacts the community.

According to the findings, only 27% of the tech-based CS projects achieved a complete and ideal Full-CS cycle, as Sanabria-Z et al. (2022) proposed (see Figure 9). This implies that most projects did not result in organized action or the proposal of public policies that comprehensively address the problems being studied.

In the foreground, Figure 9 shows the axes of citizen engagement, sub-competencies developed, and whether there was any organized action or proposed public policy. Based on the analysis, the higher the level of citizen engagement, the greater the possibility of developing complex thinking sub-competencies and having proposed organized actions or public policies. Likewise, the lower the level of citizen engagement, the lower the likelihood of participants developing any sub-competencies of complex thinking - since they were limited to data collection only - and the lower the possibility of organized actions or public policies as a result of such projects.

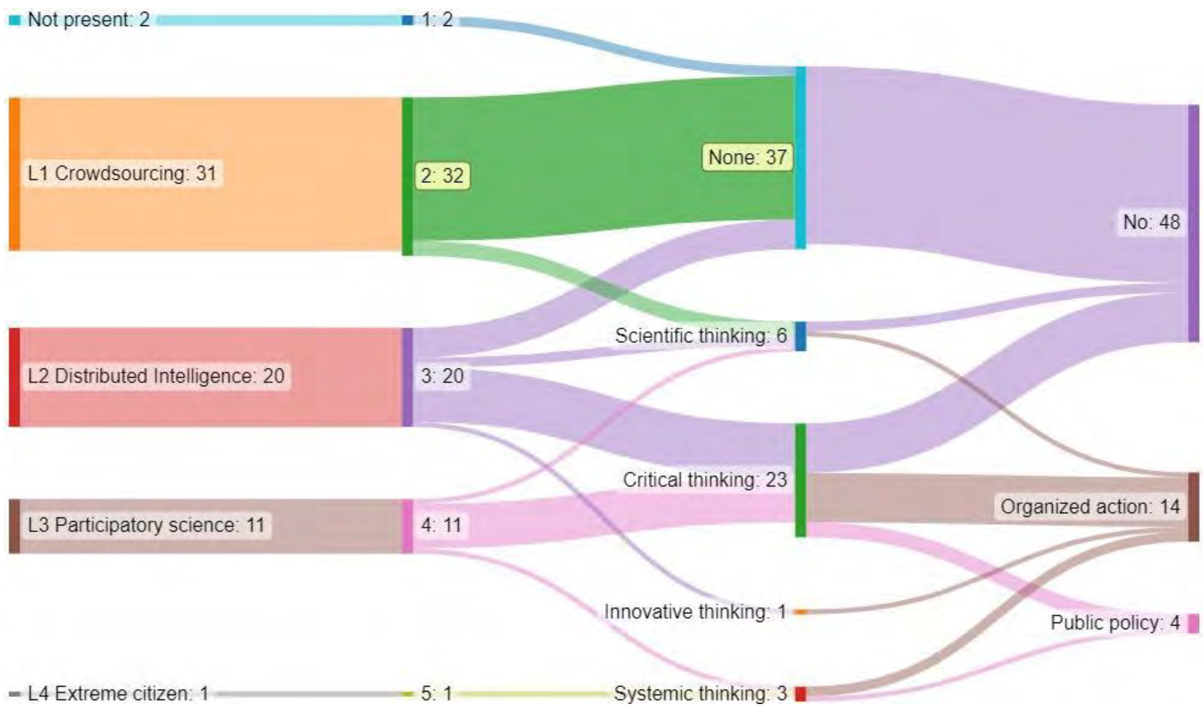

Figure 9. Relationship flows between the citizen engagement levels, sub-competencies, and social actions conducted.

Dimension of Journal metrics

RQ10: In which countries or regions were the projects implemented? Which are the journals with the most publications? What are the most frequent keywords mentioned in the articles?

This dimension helps us to identify trends of publications on CS projects. Accordingly, we observed that the countries with the most production on the topic were the United States of

America, with 33.8% of projects published; the United Kingdom (6.2%), and Greece (4.6%). The remaining countries were around 1.5% to 3.1% (see Figure 10).

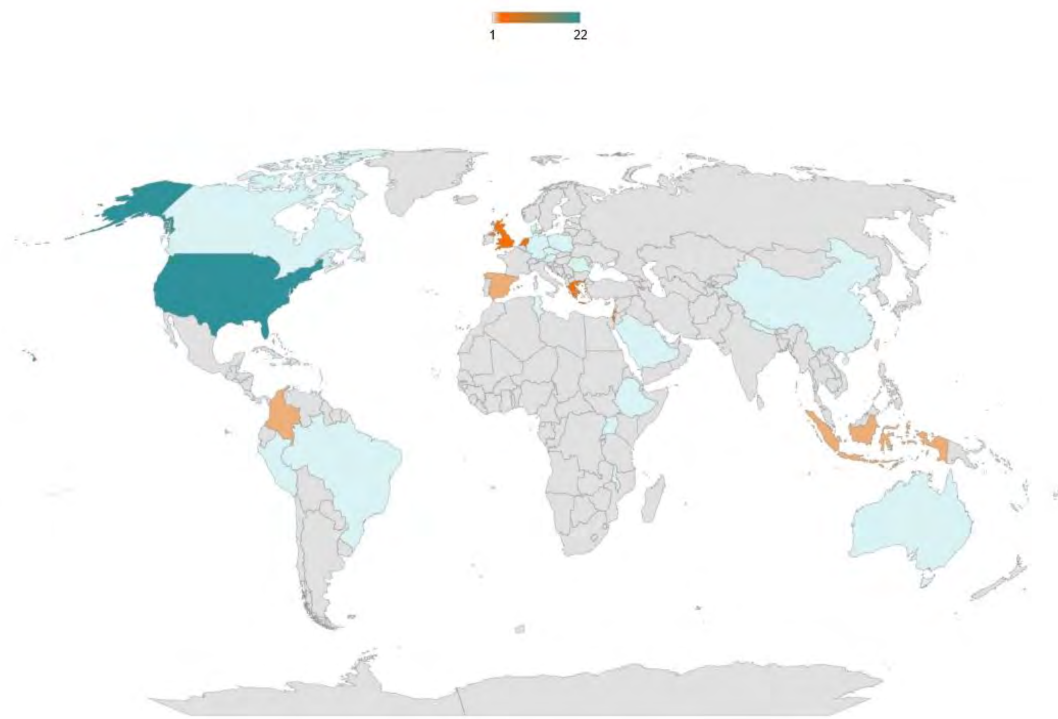

Figure 10. Countries with the most publications related to tech-based CS projects.

On the other hand, the scientific journals that most frequently addressed these topics were *Frontiers in Marine Science, PLoS ONE,* and *Science of the Total Environment* (see Figure 11).

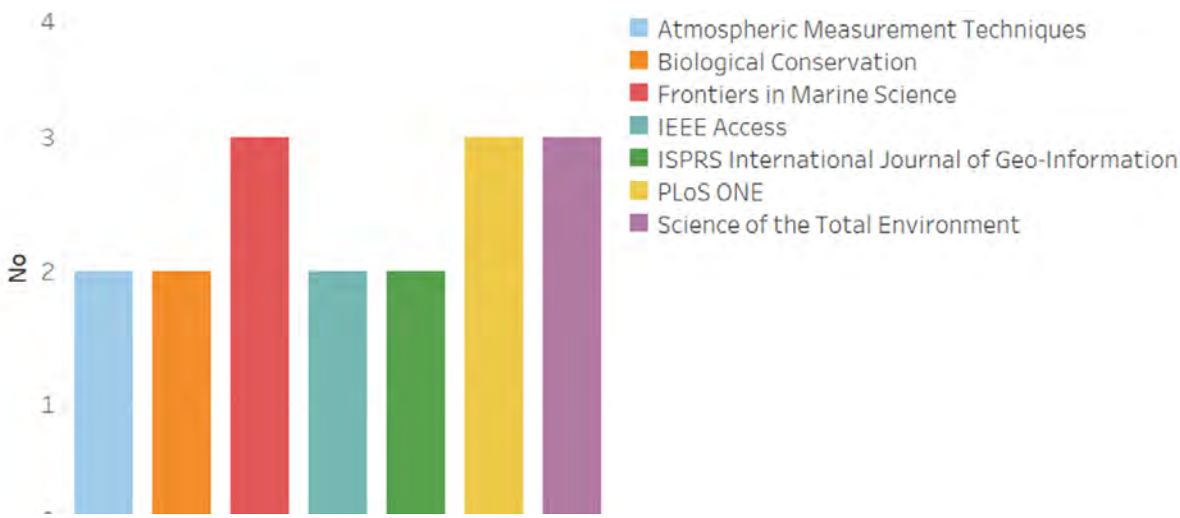

Figure 11. Academic journals that address the topic of tech-based CS projects.

Finally, a word cloud of keywords was elaborated to identify which terms were associated with CS (see Figure 12). *Citizen, science, monitoring, community, data*, and *air* were the most frequent words, and *engagement* and *participation* were found to a lesser extent.

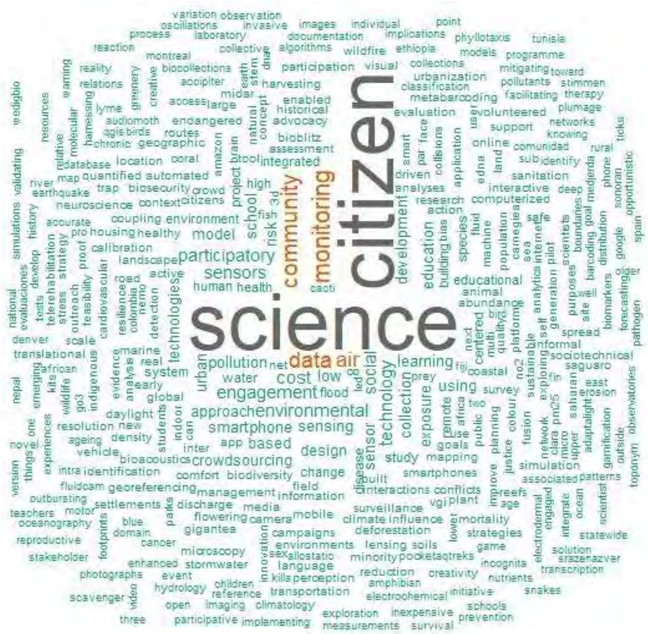

Figure 12. Word cloud with the most common keywords associated with tech-based CS projects.

With the help of text mining, we determined the most significant interactions between keywords, as shown in Figure 13.

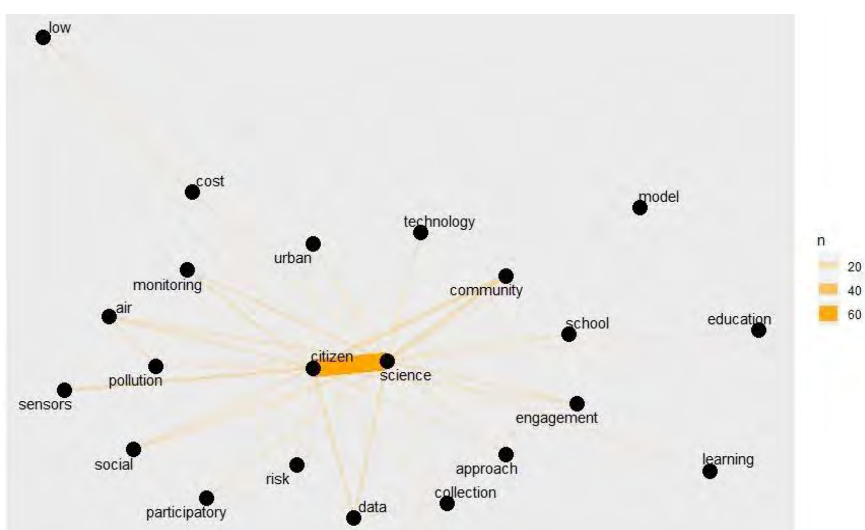

Figure 13. Interaction of keywords from text mining analysis.

We noticed that the most substantial interaction concentrated between *citizens* and *science*, and there were strong articulations with *data, community, technology*, and *involvement*.

Discussion, Conclusion and Implications

The main findings are presented below according to the five stated dimensions for the database analysis.

a) Educational system interaction: In the case of tech-based CS projects, education plays a crucial role at different stages linked to the associated objectives of the projects. The educational sector displayed its most significant intervention through the researchers coordinating projects (see Figures 2 and 3). In this framework, other academic actors have shown little interaction in this type of project, as seen in Kumar et al. (2020) and Musavi et al. (2018). Overall, the educational system is not currently clearly reflected through the actors involved in tech-based CS projects, which could be overcome by appointing researchers' as educational system representatives.
b) Project scope: In tech-based CS projects, the education system helix is often found to be combined with the political and public sectors. The project analysis showed that though there was no helix interaction involving triple, quadruple, and quintuple innovation models, other system configurations were found (see Figure 4). Additionally, Figure 5 demonstrated that among the most frequently addressed SDGs, only number 11 displayed exclusive interaction with education, political, and public sectors, which in turn were mainly associated with a preference for the use of software in tech-based projects. The preceding is consistent with Brenton et al. (2018), who argue how technologies are used in CS projects to facilitate data collection and processing that can be applied to educational programs, policymaking, and management strategies. Hence, it is assumed that the use of technologies facilitates the incorporation of the education system's helix in CS projects, especially concerning sustainability.
c) Participants' development: Deploying citizen participants in tech-based CS projects aims to identify and nurture competencies, sub-competencies, and forms of citizen involvement. For the most part, projects were found to have the support and backing of the educational system. However, this certainly does not mean that they were adequately integrated with

any educational strategy or had the purpose of influencing the formal, non-formal, or lifelong training of citizens (see Figures 6 and 8). In this respect, specific competencies were identified (UNESCO, 2016) in the analyzed studies, alongside sub-competencies of complex thinking developed in the assigned activities (Ramírez-Montoya et al., 2022). Mainstreaming participant development in competencies, involvement, awareness, and networking was embedded in CS project design guidelines such as the Threshold for CS projects (Sanabria-Z et al., 2022). From the analysis, we interpreted that most tech-based CS projects intended to develop specific participant skills. However, this intention was not declared relevant in the project's conception.

d) Social action: From the epistemological aspect of citizenship, participation in tech-based CS projects should be noted for more than merely crowdsourcing. The analysis clearly showed that the lower the level of citizen engagement in projects, the weaker the chances of achieving social action, as seen in Figure 9. From Marshall's (1997) social-political perspective, the role of citizens is fundamental to the process of social and community impact. Therefore, following Haklay's (2013) citizen engagement proposal, citizen participation in these projects should be at the most complex levels of involvement. Thus, in tech-based CS projects, a higher level of citizen engagement can contribute to the development of community-anchored projects through organized action or public policies, followed by achieving the projects' goals and the SDGs addressed.

e) Journal metrics: There is bold leadership of tech-based projects in the United States and European countries, with environmental and basic sciences prevalent. As shown in Figure 10, the United States maintains the hegemony of the CS projects that have been analyzed to date. Furthermore, Figure 11 shows a prevalence of environmental and basic science and engineering journals that dominate CS and technology topics. The low rate of social tech-based CS projects is consistent with Heilbron et al. (2017), who point out that one of the main reasons has to do with the relationship, where the concept of citizen science comes from the natural sciences and is a positivist approach (of natural sciences), which leaves out other paradigms of the Social Sciences.

Conclusion

Drawing on the questions and related results, we provided the main findings according to the five dimensions proposed regarding tech-based CS projects within the complexity framework. The process allowed us to explore the current role of education in CS and how projects enabled citizen participation to influence the development of organized actions and public policies. Overall, we hold that tech-based CS projects have certain limitations when discussing optimal citizen participation. They do not clearly contemplate a formative process contributing to citizens' formal or non-formal education based on their participation.

Implications from the lack of standardization of tech-based CS projects since their conception translates into limited comprehensive impact and, therefore, insufficient transcendence of the data and findings obtained for consideration by stakeholders. To overcome this shortcoming in practice and research, research designers should consider transversal frameworks to guide initiatives and evaluate them as they proceed. The Threshold for CS projects is one example; it seeks to align different types of project impacts to achieve Full-cycle CS, including the development of complex thinking in the participants (Sanabria-Z et al., 2022).

Based on the insights from this review, we highly encourage the scientific community to envision strategies to enhance comprehensive projects that integrate the role of the education sector in liaison with other helixes from the beginning of a CS quest. That said, future studies will be needed when aligning impact frameworks to identify how educational elements affect and interact with citizen engagement and result in citizen participation in decision-making to influence public policy.

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