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How can we transform citizens into 'environmental agents of change'? Towards the citizen science for environmental citizenship (CS4EC) theoretical framework based on a meta-synthesis approach

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ABSTRACT

Environmental Citizen Science (CS) initiatives are argued to provide a promising vehicle for involving citizens in the investigation of various socio-environmental issues. However, environmental CS initiatives have often been criticized for merely focusing on the achievement of their scientific goals and outcomes (science-oriented), rather than on empowering and transforming the participants into 'environmental citizens' (citizen-oriented). This study adopts a meta-synthesis approach to synthesize evidence from three recent systematic reviews, seeking to extract a set of design principles for the development of an integrated theoretical framework enabling Environmental Citizenship (EC) in environmental CS initiatives. The proposed framework lies on the intersection of three main research areas: (a) Participation in CS, (b) Pedagogy in CS, and (c) Education for Environmental Citizenship. Grounded on the conjunction of the aforementioned areas, the Citizen Science for Environmental Citizenship (CS4EC) framework puts forward the transformative capacity and the participatory learning aspects of environmental CS initiatives. Overall, the proposed framework lays the foundations for the design of environmental CS initiatives capable for the empowerment and transformation of citizens into 'environmental agents of change'.

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Introduction

Defining citizen science

Citizen Science (CS), defined as the participation of citizens in scientific research initiatives, has a long history in the field of ecological and environmental sciences. Environmental CS initiatives have become even more popular, due to the rapid growth of Information and Communication Technologies (ICT), which allow the recruitment of people across the globe (Tsivitanidou & Ioannou, 2020).

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CS initiatives are grounded on partnerships between non-scientists and experts and they provide a vehicle for lay people to engage with the scientific process (Eitzel et al., 2017). These collaborative arrangements have been framed as a two-way street from which both scientists and non-scientists benefit (Chase & Levine, 2016; Kloetzer et al., 2021). In addition, the citizens (including students) who participate in the CS initiatives contribute to environmental management and ecological conservation.

Environmental CS is an umbrella term, which refers to participatory science initiatives that involve non-scientists in the scientific process to advance scientific knowledge and/or their community (NASEM, 2018). Both perspectives are well-reflected in the historical definitions of Bonney and Irwin, who provided different perspectives on what CS entails. Bonney (1996) defined CS as a movement focused on professional scientific projects in which citizens are mainly perceived as data collectors. In this way, CS becomes a method for the collection of large datasets by the participating nonscientists (Oesterle et al., 2019). On a different vein, Irwin (1995) had framed CS as a golden opportunity for shortening the distance between science and the public, while also considering people's concerns. According to Lewenstein (2022) this definition was well-aligned with the background of Irwin as a sociologist 'concerned with the relation among citizens, experts, and sustainable development in democratic systems' (p. 185).

Irwin's vision for CS was built around the notion of scientific democracy. According to Oesterle et al. (2019), Irwin envisioned CS as a process which would allow the active engagement of non-scientists in all the stages of the research process (i.e. from the formulation of the research questions to policy-level action). In addition, Irwin used the term *citizen science* 'to describe ways that sustainable development could be enhanced if more authority were to be exercised by actors beyond the scientific elite' (Lewenstein, 2022, p. 185). These ideas have also pushed forward the field resulting in the emergence of community-based CS initiatives; these initiatives are more responsive to community needs as they are more inclusive and involve to a greater degree the lay people (Woolley et al., 2016). This type of CS initiatives may provide a path towards a more democratic and justice-oriented science (Oesterle et al., 2019). However, in the midst of an unprecedented socio-environmental crisis, we argue that CS initiatives should proceed a step further towards investing more into their educative affordances, aiming at the transformation of the non-scientists into *environmental citizens*.

Citizen science for environmental citizenship

We envision environmental CS initiatives, as a vehicle for citizens' transformation into *environmental agents of change*, who may contribute to the mitigation, or even resolution, of various socio-environmental challenges. Such a conceptualization of CS is aligned with the notion of Environmental Citizenship (EC) which has gained ground in recent years. EC is based on the notion that 'each of us is an integral part of a larger ecosystem and that we need to embrace the challenge to live more sustainably, act responsibly and positively toward our environment' (Van Wyk, 2015, p. 26). EC seems to be therefore of crucial value, as we are in urgent need of environmentally empowered citizens, who can deal with the current environmental crisis (Georgiou et al., 2021; Hadjichambis et al., 2020). However, a challenging question is how we foster EC through CS initiatives.

Recent studies have pointed out that environmental CS initiatives may provide a transformative learning approach, which is a prerequisite for EC (Bela et al., 2016; Jørgensen & Jørgensen, 2021; Van Wyk, 2015). As the argument goes, environmental CS initiatives may develop citizens' EC by fostering knowledge generation, stimulating action-taking, and enhancing civic participation in collective and collaborative decision-making. Environmental CS holds great promise in supporting EC, to raise environmental awareness based on the notion of environmental rights and responsibilities, democratic education, inclusion and co-creation approaches (Hadjichambis & Hadjichambi, 2022).

However, the majority of environmental CS initiatives tend to be more science – rather than citizen-oriented. That is, beyond their scientific goals, CS initiatives are not aiming at the transformation of participants into environmental citizens who can act as *agents of change* (Jørgensen & Jørgensen, 2021). In this way, the transformative learning capacity of environmental initiatives remains largely unexploited (Bela et al., 2016). As supported by Oesterle et al. (2019), research in CS has not focused on how these initiatives could really empower lay people 'understand and value the power of science for sociopolitical and sociocultural action' (p. 2).

On a different note, an ever-increasing corpus of research has stressed that the majority of CS initiatives have been far away of being inclusive, as they have mostly attracted White males, above the median income, with a college degree (Pateman et al., 2021; Plunk et al., 2014). These trends are not surprising, given that science has been dominated by for those who are in power – mostly White and highly-educated men (e.g. Ceci et al., 2014; Oesterle et al., 2019; Woolston, 2020). The problem though, according to Cooper et al. (2021), is that many organizations rebrand their initiatives into community-based as a way to address this issue. However, as Cooper et al. (2021) highlight, re-naming is a meaningless action; instead, a fruitful way to go forward is the design for justice and equity, diversity and inclusion. These suggestions highlight the need for the explicit design of CS initiatives with a straightforward focus on the notion of democratic citizenship, as a central component of EC.

Problem statement

Environmental CS initiatives may have a significant effect in promoting EC, only if they are intentionally designed to do so (Jørgensen & Jørgensen, 2021). Nevertheless, a theoretical framework guiding the successful design of CS initiatives for EC has not yet been developed. This is not surprising, given that limited research has focused on the design principles that may enhance the effectiveness of CS initiatives (Senabre Hidalgo et al., 2021; Wald et al., 2016). At the same time, prior studies which presented frameworks to guide the development of CS initiatives (e.g. Chase & Levine, 2016; Gharesifard et al., 2019; Shirk et al., 2012; Wandersman, 2003), had not a clear focus on providing a framework aiming at the empowerment of the participants' EC.

This study adopts a meta-synthesis approach to synthesize evidence from three recent systematic reviews, seeking to design an integrated theoretical framework enabling EC in environmental CS initiatives. The Citizen Science for Environmental Citizenship (CS4EC) framework aspires to put forward the transformative capacity of environmental CS initiatives, to empower citizens to act as *environmental agents of change*. Overall, this study is guided by the following two research questions:

- **RQ1:** What are the main structural design principles contributing to the building of the CS4EC framework (Structural model of the CS4EC framework)?
- **RQ2:** How are these design principles related to promote citizens' EC (Procedural model of the CS4EC framework)?

Theoretical background

The theoretical foundations underpinning the development of the CS4EC framework are related to the aspects of (a) Participation in CS, (b) Pedagogy in CS, and (c) Education for Environmental Citizenship (EEC). Below, we briefly explain how each aspect is fueling the development of the CS4EC framework.

Participation in citizen science

CS refers to the participation of non-scientists in scientific research. However, participation in CS initiatives can take different nuances (Bonney et al., 2014), and as such, the level of citizens' involvement in a CS initiative can be classified as contributory, collaborative, or co-created (Figure 1).

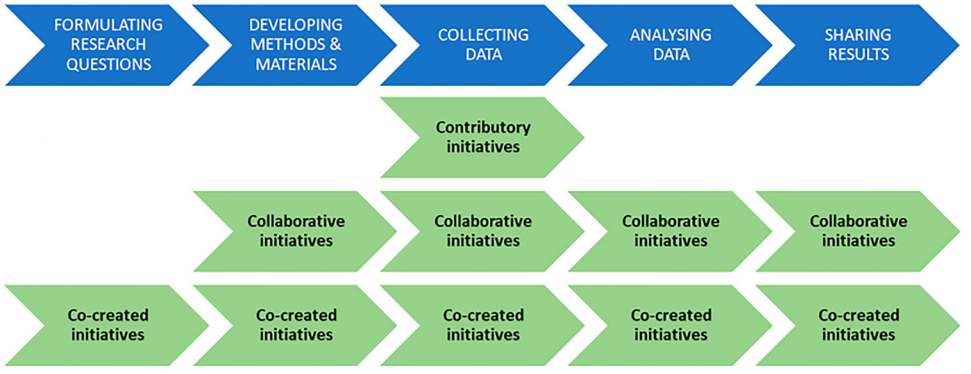

Figure 1. Classification of CS initiatives according to the levels of Citizens' involvement.

According to Oesterle et al. (2019), the CS community is more familiarized with the idea of public participation in CS initiatives as a way to collect large datasets to be deployed by scientists. This form of participation is aligned with the contributory vision of CS – that is environmental CS initiatives are seen as a way to ensure the collection of large swaths of data through participation. On the other hand, public participation in CS initiatives can be seen as a medium for ordinary people to design and enact, in collaboration with the scientists, valid and robust research processes (Kimura & Kinchy, 2016). In this form of participation, 'citizens are not considered qualified research assistants, but rather coresearchers' (Senabre Hidalgo et al., 2021, p. 202).

Despite the central role of participation in CS, little is yet known regarding how participatory arrangements in environmental CS initiatives support their transformative effects for the benefit of the environment (Bela et al., 2016). We expand this argument supporting that there is also lack of knowledge regarding what participatory aspects in environmental CS initiatives may contribute to the promotion of EC.

Pedagogy in citizen science

Over the last twenty years, educational research in CS has focused on the investigation of the learning outcomes derived in various CS initiatives (Lüsse et al., 2022). Overall, most documented learning outcomes are related to the increase of factual knowledge, development of science skills or understanding of the scientific processes (Brossard et al., 2005; Evans et al., 2005). However, affective learning outcomes have been largely neglected, even though environmental CS initiatives can also support attitudinal change toward socio-environmental problems.

It has been therefore argued that research should focus on how environmental CS processes could increase CS participants' environmental awareness and empower them to act towards place-based and also global environmental stewardship (Ballard et al., 2017a; Bela et al., 2016). For instance, as Mueller et al. (2012) have pointed out, we must '… promote youth activism through citizen science as a pedagogy in which teachers and their students gather information to make the most informed decisions about potential consequences …' and '… we need to find ways to include youths not only in pedagogy that heightens epistemic development but also in schooling where they have opportunities to engage with real issues through their activism' (p. 11).

Despite these arguments, limited research has been invested into how attitudinal and action-related learning outcomes can be produced in environmental CS initiatives. Research regarding the underpinning pedagogical aspects and the dynamics of learning in CS has been limited (Kloetzer et al., 2021). Considering the absence of formal curricula and the inconspicuous nature of the learning processes underpinning CS projects (Van Wyk, 2015), research efforts should be devoted to mapping the pedagogical structures, provoking attitudinal and behavioral changes to achieve EC.

Education for environmental citizenship

CS has many definitions, with most prioritizing the *science* component over the *citizen* one (Jørgensen & Jørgensen, 2021). However, Cooper (2016) has noted that a more citizen-oriented definition is needed, to emphasize that CS is about citizens deploying science to inform their activism on socio-environmental issues they care about. Such a definition reflects that citizens are able to 'use science to wield power but also to have a more critical understanding of their world' (Kenyon et al., 2020, p. 86). This definition is also the closest one to the notion of EC, which is about citizens' active participation in addressing current and future socio-environmental challenges (Dobson, 2007).

Jørgensen and Jørgensen (2021) have pointed out that environmental CS initiatives could serve as an educative vehicle aiming at the empowerment of EC. However, it is only recently that EEC has started to gain traction. During the last two years, more than 150 experts have joined their forces, in the European Network for Environmental Citizenship (ENEC) (Hadjichambis et al., 2020), trying to reach an integrated conceptualization for EEC. More specifically, according to ENEC (2018):

> Education for Environmental Citizenship is defined as the type of education that cultivates a coherent and adequate body of knowledge as well as the necessary skills, values, attitudes and competences that an Environmental Citizen should be equipped with in order to be able to act and participate in society as an agent of change in the private and public sphere on a local, national and global scale, through individual and collective actions in the direction of solving contemporary environmental problems, preventing the creation of new environmental problems, in achieving sustainability as well as developing a healthy relationship with nature.

Grounded on this conceptualization, Hadjichambis and Paraskeva-Hadjichambi (2020), have proposed the EEC model that paves the way to promote EC in an integrated educational approach (Figure 2).

In this model, they have summarized the competences (knowledge, attitudes, skills, values, and behaviors) that shape citizens' personal development (inner circle), allowing them to act as *agents of change*, as well as the potential actions an environmental citizen may undertake in different spheres (private or public), dimensions (individual or collective), and scales (local, national and global). Private sphere actions refer to actions that affect the relations between individuals and societies,

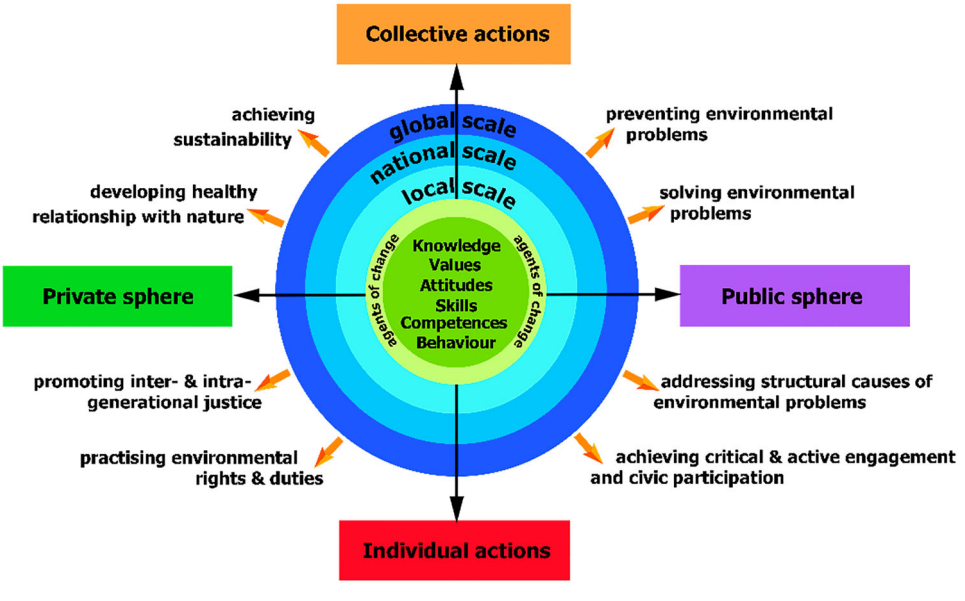

Figure 2. The Education for Environmental Citizenship (EEC) model. Source: Hadjichambis and Paraskeva-Hadjichambi (2020).

whereas public sphere actions refer to actions that affect the relations. Individual actions are those referring to personal actions, whereas collective actions are the more participatory ones. Applied actions of EC differ in terms of their impact and scalability, as they take place locally (e.g. within a community, village, town), nationally (e.g. within a country), and globally (e.g. within more than one country). Finally, the main environmental outcomes are related to (a) solving existing environmental problems, (b) preventing new ones, (c) addressing their structural causes, (d) developing a healthy relationship with nature, (e) practicing environmental duties and rights, (f) achieving active and critical engagement/civic participation, (g) promoting inter/intra-generational justice, as well as (h) achieving sustainability.

Hadjichambis and Paraskeva-Hadjichambi (2020) have also developed a pedagogical approach for the promotion of EEC, comprising of six stages (Figure 3): (a) Inquiry, (b) Planning actions, (c) Civic Participation and Critical Active Engagement, (d) Networking and Sharing in Scales, (e) Sustain Environmental and Social Change, and (f) Education and Reflection. These stages are not always meant to be followed in linear sequence; instead, a starting point can be any one of the six stages, according to the case. In addition, considering the nature of the environmental problem which is under investigation, the learning context, and the educational level, the necessary adaptations can be made.

EEC has a lot to contribute to the education of future environmental citizens (Hadjichambis et al., 2022). The EEC pedagogy provides a comprehensive approach which includes stages designed to promote EC (Hadjichambis & Hadjichambi, 2022). However, little is known regarding whether environmental CS initiatives are aligned with the EEC model and pedagogy, or how environmental CS initiatives should be designed to integrate EEC for the development of EC.

Methodology

This study adopted a meta-synthesis approach to synthesize the findings of three recent Systematic Literature Reviews (SLRs), given that 'the goal of the meta-synthesis is to produce a new and integrative interpretation of findings that is more substantive than those resulting from individual

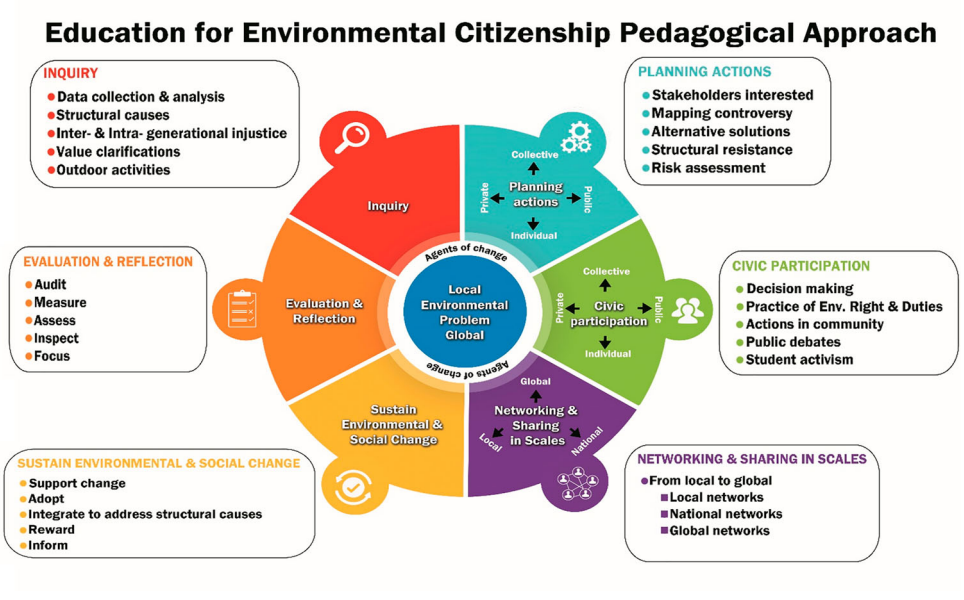

Figure 3. The Education for Environmental Citizenship (EEC) pedagogical approach. Source: Hadjichambis and Paraskeva-Hadjichambi (2020).

investigations' (Finfgeld, 2003, p. 894). A meta-synthesis can lead to new interpretations of research and is often deployed as a way to develop new theoretical frameworks. It was therefore adopted in this study which aimed at developing the CS4EC theoretical framework.

The selected SLRs (Adamou et al., 2021; Paraskeva-Hadjichambi et al., 2023; Vasiliades et al., 2021) were, according to our knowledge, the only available reviews which focused on environmental CS initiatives in relation to EC, seeking to shed light to on the research areas of: (a) Participation in CS (target groups, types of contributions, level of data collection, frequency of participation, forms of engagement), (b) Pedagogy in CS (learning context, learning focus, learning mechanisms, learning tools/resources), and (c) EEC (EC competences, actions, outcomes). Figure 4

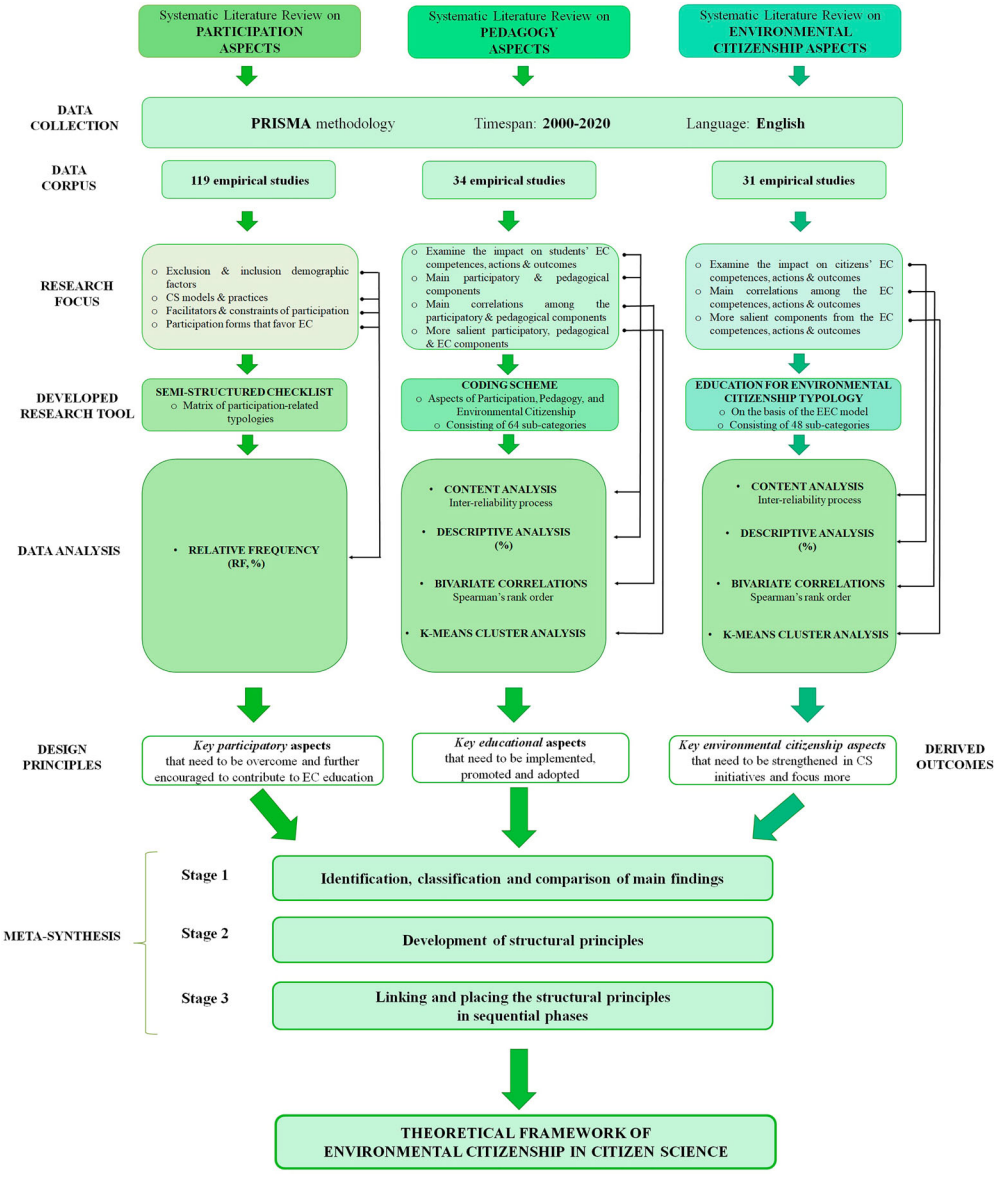

Figure 4. Diagrammatic representation of the methodology followed and the SLRs.

provides a methodological overview of the three SLRs deployed along with the adopted meta-synthesis approach.

Stage 1: classification and comparison of main findings

The first stage of the meta-synthesis approach focused on exploring, analyzing, and compiling the descriptive analysis findings from the three SLRs in concise and meaningful categories. In this stage we identified the main participatory, pedagogical, and EC-related concepts, derived from the descriptive analysis of each reviewed study, and we classified them into 15 themes. Next, we compared our findings between the three SLRs focusing on their similarities and differences.

Stage 2: identification of structural principles and keystone concepts

During the second stage, we synthesized these findings per theme across the SLRs to obtain a more comprehensive insights for each theme. Each theme was then situated and discussed in the context of EC. Thus each theme was reformed into a key structural principle, to be considered in the redesign of environmental CS initiatives. Finally, we deployed the findings derived from the correlational analysis conducted in the second and third SRL between the participatory, pedagogical and the EC-related concepts, to identify the most salient concepts playing a critical role in our model. Overall, this stage led in the development of the structural model of the CS4EC framework (see Section 4.1).

Stage 3: linking and placing the structural principles in sequential phases

During the third stage, we identified possible links between our structural principles seeking to place them in a timeline of sequential phases. Each phase was related to a distinct role allocated to the citizens participating in an environmental CS initiative (i.e. Citizens as *Co-designers*, *Scientists*, *Environmental agents of change*). Overall, this stage led in the development of the procedural model of the CS4EC framework (see Section 4.2).

Findings

Structural model of the citizen science for environmental citizenship framework

The classification of the findings of the three SRLs resulted in fifteen (15) themes: (1) Type of initiative due to citizens' contribution, (2) Target group, (3) Level of data collection, (4) Frequency of citizens' participation, (5) Form of engagement, (6) Learning context, (7) Learning focus, (8) Learning mechanisms, (9) Learning tools/resources, (10) EEC pedagogy, (11) EC actions (per dimension), (12) EC actions (per sphere), (13) EC actions (per scale), (14) EC competences, (15) EC outcomes. Table 1 presents the similarities and differences, per theme, between the three SRLs.

Next, according to our findings, we have identified a total of fifteen (15) structural principles (i.e. one principle per theme), guiding the development of the structural model of the CS4EC framework (Table 2). What follows is a brief presentation of these structural principles, in relation to EC, per aspect: participation, pedagogy and EEC.

For each of these principles we shortly present the 'status quo' of environmental CS initiatives, as this emerged in the three SLRs preceding this meta-synthesis effort. Then, we further reflect on the significance of each design principle in the context of environmental CS initiatives for EC. In this way, we further deepen how each structural principle is related to the envisioned structure of environmental CS initiatives.

Table 1. Comparative findings from the SRLs focusing on the participation, pedagogical, and EEC aspects of the reviewed environmental CS initiatives.

#	Themes	SLR 1: Focus on participation	SLR 2: Focus on pedagogy	SLR 3: Focus on EEC
		Main findings		
1	**Type of initiative due to citizens' contribution**	• Contributory initiatives		N/A
2	**Target group**	• Highly educated adult participants • Gender balance	N/A	
3	**Level of data collection**	• Single person	• Small groups	N/A
4	**Frequency of citizens' participation**	• Multiple Times over an extended time period		N/A
5	**Form of engagement**	• Conducting and monitoring observations • Gathering samples and submitting data/samples	• Gathering samples and submitting data/samples • Receiving Training • Doing data analysis & interpreting results	N/A
6	**Learning context**	N/A	• Non-formal settings	N/A
7	**Learning focus**	• Scientific literacy	• Environmental awareness	• Environmental awareness
8	**Learning mechanisms**	N/A	• Contributing to the task • Interacting With others • Using project documentation	N/A
9	**Learning tools/resources**	N/A	• Educational resources • Expert mentors	N/A
10	**EEC pedagogy**	N/A	• Inquiry	N/A
11	**EC actions (per dimension)**	• Individual over collective actions		
12	**EC actions (per sphere)**	• Private over public sphere actions		
13	**EC actions (per scale)**	• Local over national and global scale actions		
14	**EC competences**	• N/A	• Skills and knowledge over attitudes, values, and behaviors	
15	**EC outcomes**	• Development of a healthy relationship with nature • Solution of environmental problems • Prevention of new environmental problems		

Participation in citizen science

Co-creation. Most of the reviewed environmental CS initiatives were characterized as contributory initiatives, as they were pre-defined by the experts (i.e. scientists), and citizens' participation was limited to the data collection process. However, we propose a co-creation approach, which legitimates citizens to collaborate with scientists through all the steps of the process (e.g. the creation, the implementation, and the evaluation of an environmental CS initiative). In this way, CS

Table 2. Structural principles per aspect and theme.

Aspects	#	Themes	Structural principles
Participation	**1**	Type of citizens' contribution	Co-creation
	2	Target group (participating citizens)	Inclusiveness
	3	Level of data collection	Collaborative mode of data collection
	4	Frequency of citizens' participation	Extended participation
	5	Form of engagement	Integral & deep involvement
Pedagogy	**6**	Learning context	Focus on an environmental problem
	7	Learning focus	Authentic educational context
	8	Learning mechanisms	Active & social learning mechanisms
	9	Learning tools/resources	Use of multiple tools/educational resources
	10	EEC pedagogy	Holistic EEC pedagogy
EEC	**11**	EC actions (per dimension)	Both individual & collective EC actions
	12	EC actions (per sphere)	Both private & public EC actions
	13	EC actions (per scale)	Multi-scale actions
	14	EC competences	Focus on pro-environmental behaviors
	15	EC outcomes	Full coverage of EEC outcomes

initiatives may allow citizens to focus on socio-environmental problems related to their own communities and personal concerns, as well as to develop adequate solutions to address them (Bonney et al., 2014; Shirk et al., 2012). This principle is expected to increase the participants' active involvement and empowerment to act, which lies in the core of EC.

Inclusiveness. Over 110 empirical studies were analyzed in the first SRL, and the findings indicate that participation in environmental CS initiatives was not gender-discriminatory. However, most of the participants were White and highly educated adults. These findings indicate that CS initiatives leave out a large portion of citizens (e.g. people who lack scientific and digital skills) and this has an impact on the democratization of CS (Plunk et al., 2014). We therefore suggest the design of more inclusive environmental CS initiatives fostering the participation of the underrepresented groups (see also Oesterle et al., 2019), such as marginalized community members, people with disabilities, or even K-12 students who have a limited presence. This will ensure a more equal treatment for these populations, based on the notions of justice, equity, and democracy that characterize EC.

Collaborative Mode of Data Collection. In most of the environmental CS initiatives, the data collection took place either at the individual level or in small groups. However, we opt for a more collective mode of participation during the enactment of environmental CS initiatives. We suggest a shift towards participation in CS initiatives at whole communities, when possible, considering that to address socio-environmental challenges, there is a need for community-level responsibility. Building a sense of community-based responsibility, through collaborative data collection in environmental CS initiatives, encourages the citizens to work collectively toward the common good (Ballard et al., 2017b; Jørgensen & Jørgensen, 2021; Valencia Sáiz, 2005), which is a crucial aspect of EC.

Extended Participation. Another salient finding was citizens' participation on a multiple-time basis during the implementation of most of the CS initiatives. We agree with this finding, as citizens' extended participation constitutes an important aspect of an environmental CS initiative. If a CS initiative is about to promote citizens' environmental activism, then this should be reflected as a long-term process which requires perseverance, commitment, and effort (Reis, 2020a). Besides, EEC and its underpinned EEC pedagogy is a multi-stage process, which takes time to be enacted and completed.

Integral & Deep Involvement. The majority of the reviewed environmental CS initiatives reported that citizens were merely engaged with the data (e.g. conducting and monitoring observations), rather than being actively engaged with all the stages of the initiative. Therefore, we posit that environmental CS initiatives should primarily support citizens' integral and deep involvement throughout the process, not limited to the collection and submission of data. Considering that one of the main outcomes of EC is the achievement of critical and active engagement and civic participation (Schild, 2016), we argue for more participatory and meaningful forms of citizens' involvement throughout all the stages an environmental CS initiative.

Pedagogy in citizen science

Focus on an Environmental Problem. A significant portion of environmental CS initiatives aimed at improving participants' understanding of the scientific method by merely focusing on the data collection process, rather than improving knowledge on a given environmental problem. We are aligned with this latter focus, given that EC should be seen as a venue for supporting citizens' engagement with environmental problems. If environmental CS initiatives are simply structured around data collection, then they fall short in addressing this goal. We are opting towards environmental CS initiatives which are linked with sustainability issues and environmental problems, enabling the participants to get engaged with action (Jørgensen & Jørgensen), which if found in the core of EC.

Authentic Educational Context. The majority of the reviewed CS initiatives took place in non-formal settings which allowed the just-in-time and place-based data collection. This is not

surprising given that environmental CS initiatives are often viewed as a way of situating science in a local place. We highlight the significance of such practices, which may result in authentic educational contexts for the participants. If environmental CS initiatives take place in authentic educational contexts, they will motivate a sense of situated citizenship (Szerszynski, 2006) grounded in participants' connections, attachment, and caring about a specific environment. These elements are fundamental for fueling a form of place-based EC, anchored on specific places, areas and ecosystems, which are under various pressures and threats.

Use of Multiple Tools/Resources. The learning tools and resources deployed in environmental CS initiatives were also examined in the second SRL (i.e. focusing on pedagogy). According to our findings, the most prevalent forms of tools and resources used are educational resources (e.g. step-by-step instructions, student handouts, educational materials, and workbooks), as well as the help provided to students by expert mentors during the implementation of CS initiatives. However, we also propose the use of more scientific learning tools/resources and similar sources as experts (e.g. open access data, scientific resources and equipment). This can result in the formation of a more scientific identity, supporting citizens' actions towards addressing various environmental problems (Gaydos & Squire, 2012; Teo & Triantafyllou, 2020), as another pathway for connecting environmental CS initiatives to EC.

Active & Social Learning Mechanisms. Most CS initiatives reported that citizens' contribution to the data collection and analysis tasks served as the major learning mechanism. However, this learning process is quite limited, while its impact on EC is also quite restricted. We urge the need for more emphasis on active and social learning mechanisms in environmental CS initiatives (e.g. interacting with others, using project documentations, creating and sharing personal artifacts). These mechanisms are aligned with a socio-cultural view of learning (Kloetzer et al., 2021). Given that community building in environmental CS initiatives is a key aspect (Jørgensen & Jørgensen, 2021), we posit that these learning mechanisms could support EC.

Holistic Education for Environmental Citizenship Pedagogy. The majority of the reviewed K-12 CS initiatives were merely structured upon the inquiry stage. This finding is important given that inquiry is just one of the six stages composing the pedagogical model of EEC. On the other hand, we have found that the EEC pedagogy stages of *Civic Participation and Critical Active Engagement*, *Planning Actions*, and *Networking and Sharing in Scales* were adopted in a limited degree in the reviewed K-12 environmental CS initiatives, while the stages of *Sustain Environmental and Social Change* and *Evaluation and Reflection* were not reported at all. Considering the accumulative contribution of these stages to transforming citizens into *agents of change* (Hadjichambis & Paraskeva-Hadjichambi, 2020), we posit that future environmental CS initiatives should adopt all the stages of the EEC pedagogy.

Education for environmental citizenship

Both Individual and Collective Environmental Citizenship Actions. The reviewed environmental CS initiatives mainly included individual EC actions rather than EC actions situated in the collective dimension. However, limiting environmental work in the context of individual actions neglects the significance of collective systemic change. If future environmental CS initiatives are about to achieve more integrated forms of EC, they should also provide citizens with opportunities to engage with actions at the collective dimension. Collective environmental actions have a different dynamic as they highlight the significance of collective systemic change (Clover et al., 2013), and they are argued to support successful adaptation to environmental changes (Karlsson & Hovelsrud, 2015). For this reason, they compose an integral part of EC.

Both Private and Public Environmental Citizenship Actions. All three SRLs have shown that citizens' involvement in CS activities, had a positive impact on strengthening their EC actions mainly in the private sphere. On the contrary, public sphere actions were found to be of mostly deployed in K-12 environmental CS initiatives. We posit that future environmental CS initiatives should prioritize public environmental activism (Reis et al., 2020a), rather than focusing on private sphere

environmentalism. We therefore argue towards the design of environmental CS initiatives that will support citizens to undertake not only private EC actions, but also public EC actions.

Multi-scale Actions. Most of the reviewed environmental CS initiatives provided opportunities to the citizens to engage with EC actions situated in the local scale rather than in the national and global scale. In many cases, environmental CS initiatives adopted a place-based approach, aiming to develop a local community connection, and as such, they prioritized local civic actions. These findings agree with the notion of EC, which is often effectively practiced in local areas where citizens develop a sense of place, responsibility and ownership (Nash & Lewis, 2006). However, it is also important to support the citizens to draw connections between the data they collect and the broader socio-environmental challenges. This will allow connections between environmental CS initiatives, and the global sustainability problems we are striving for (Jørgensen & Jørgensen, 2021), allowing the development of a more global notion of EC.

Focus on Pro-environmental Behaviors and Competences. All three SRLs have shown that current forms of environmental CS initiatives have significantly less impact on the development of pro-environmental behaviors in comparison to the development of citizens' knowledge, skills, and attitudes. However, we posit that the formation of pro-environmental behaviors should be the central focus of CS initiatives. Put simply, EC is all about pro-environmental action and citizens' agency towards achieving sustainability. Therefore, this principle highlights that CS initiatives should place more time investment and concerted effort to enhance pro-environmental behaviors (Kenyon et al., 2020), in addition to the development of citizens' knowledge, skills, and attitudes.

Full Coverage of the Education for Environmental Citizenship Outcomes. Most of the environmental CS initiatives, contributed mainly to developing a healthy relationship with nature, solving environmental problems, and preventing the creation of new environmental problems. On the other hand, EC outcomes such as the promotion of inter/intra-generational justice, practice of environmental rights and duties, addressing the structural causes of environmental problems, achievement of critical and active engagement and civic participation, as well as achievement of sustainability were either promoted on a lesser extent or were not addressed at all. This finding signifies a gap in environmental CS initiatives, given that the degree of inclusiveness, the depth of democracy and participation, the issues of equality as well as the issues of intra- and inter-generational justice are of particular importance for the promotion of EC (Hadjichambis & Paraskeva-Hadjichambi, 2020). It should be highlighted that there is not EC without environmental justice – toward this direction future environmental CS initiatives should involve an internal motivation of justice; what Rodeiro (2020) calls *environmental transformative justice*.

Keystone concepts

We also focused on the number of the statistically significant moderate and strong correlations between the participatory, pedagogical and EC concepts. More specifically, a cluster analysis was deployed to set a cut-off point and divide these concepts in two categories: the concepts with the higher number of connections were defined as Keystone Components (KCs), while the rest were defined as the Peripheral Components (PCs). Based on this classification, the KCs refer to the most important ones, whereas the PCs included the less significant ones in support of the CS4EC.

As illustrated in Figures 5 and 6, we have identified 12 KCs, as follows: Willingness to Act in Society as Agents of Change, Political Systems Knowledge, System Thinking Skills, Constructive Participation Skills, Problem-Solving Skills, Public Sphere Actions, Collective Actions, Local Scale Actions, Solution of Environmental Problems, Communicating Findings, Planning Actions, and Civic Participation & Critical and Active Engagement.

These concepts should be considered when designing an environmental CS initiative for EC. Put simply, these KCs should be placed on the core of each environmental CS initiative. In addition, our analysis led in the emergence of semantic networks which were built around these KCs, deepening our structural principles.

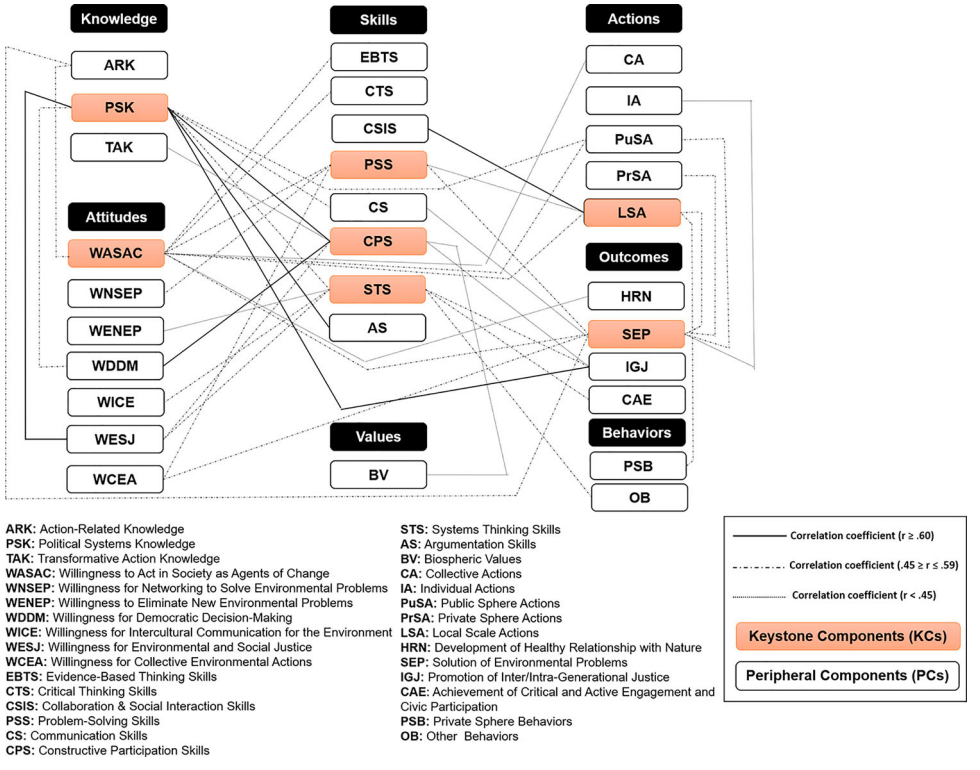

Figure 5. The keystone concepts and the semantic networks emerged in the second SRL.

Procedural model of the citizen science for environmental citizenship framework

Following up the extraction of the 15 design principles, we sought to identify any possible links between the principles to place them in a timeline of sequential phases, resulting in three (3) main phases. Each phase was related to a role allocated to the citizens participating in a given environmental CS initiative – citizens as (a) *Co-designers*, (b) *Scientists*, and (c) *Agents of change* (Figure 7).

We posit that the implementation of these phases contributes to (a) citizens' integral and deep involvement during the CS initiative, (b) the holistic accomplishment of the EC outcomes, as well as (c) the development of pro-environmental behaviors.

Citizens as co-designers

During this phase, citizens undertake the role of *Co-designers*, signaling the initiation of the collaboration between scientists with citizens for the co-development of the environmental CS initiative. In its essence, the co-developed environmental CS initiative encompasses the principles of *Inclusiveness*, *Focus on an environmental problem* and *Co-creation*.

This phase begins with the recruitment of participants in a place-based CS initiative. Aiming to achieve inclusiveness, we recommend Cooper et al.'s (2021) strategy for 'centering in the margins'. Put simply, we envision an environmental CS initiative which starts with the inclusion of diverse and underrepresented groups of people and minorities, which have been traditionally excluded from CS. As Cooper et al. (2021) state 'If a project is accessible to the marginalized, it will be accessible to all' (p. 1388). In this way, the CS initiative may serve as a stage for those one, whose voices often go unheard.

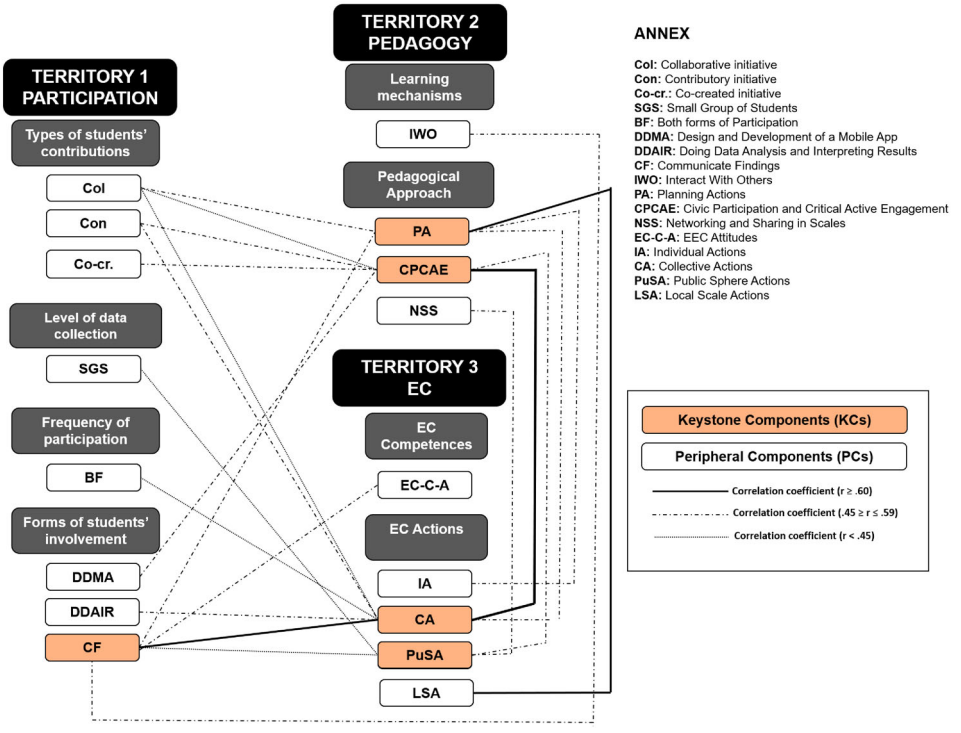

Figure 6. The keystone concepts and the semantic networks emerged in the third SRL.

This phase continues with focusing on an environmental problem which should be related with the community concerns for local environmental problems or for global environmental problems with local symptoms. This will motivate citizens to participate on a voluntary basis that will also serve as the springboard for action (Chari et al., 2019). The selection of an environmental problem will also serve as the starting point for the development of EC. For instance, according to Hadjichambis and Paraskeva-Hadjichambi (2020), EEC starts with 'local environmental problem which draws on students' interests and concerns, a problem that their community faces and they feel that they have to do something about it' (p. 250).

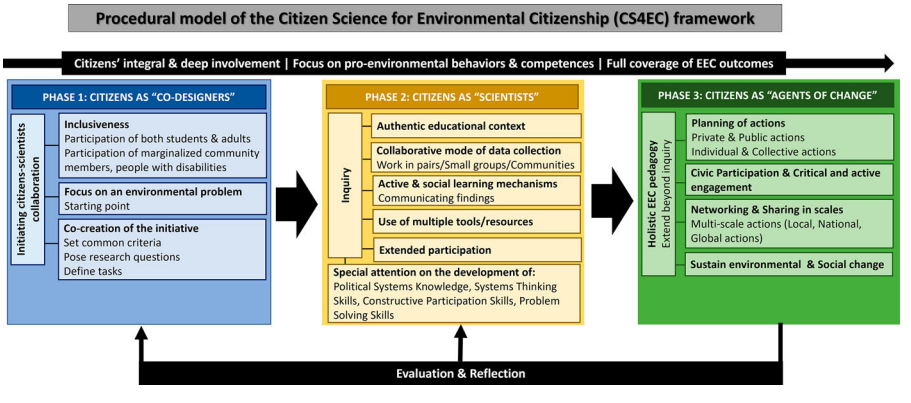

Figure 7. The procedural Model of the CS4EC framework.

Citizens as scientists

In this phase, the citizens undertake the role of *Scientists*. This phase is related to the social construction of knowledge regarding the selected environmental problem, through the adoption of scientific inquiry. As argued by Reis (2020a), the inquiry approach empowers participants to act 'as producers of contextualised and socially relevant knowledge, instead of being simple consumers of knowledge' (p. 144). In turn, the development of knowledge is a central aspect, given that knowledge serves as a precondition for pro-environmental behavior.

However, we argue that scientific inquiry should also adopt various design principles, as these have emerged from the meta-synthesis of the SRLs. Firstly, scientific inquiry should be situated in *authentic educational contexts*, to increase the citizens' feeling of relevance with their natural surroundings. It should be also underpinned by *collaborative forms of participation* as well as *active and social learning mechanisms*, allowing the gradual development of a Community of Practice (CoP) around the environmental problem under investigation. In addition, the *use of multiple tools and resources* contributes to authentic inquiry and action taking toward the investigation of environmental problems; this facilitates the kind of EC required for sustainability. Finally, the scientific inquiry should last over a period of time, allowing citizens' *extended participation*.

Citizens as environmental agents of change

In the third phase, the citizens undertake the role of *Agents of change*. According to this role, they link their inquiry-based findings with follow-up environmental actions. In this way, the CS initiative involves citizens in a series of follow-up stages, comprising the EEC pedagogy, such as *Planning of Actions* and *Civic Engagement*, *Networking in Scales*, *Sustain of Environmental & Social Change* as well as *Evaluation & Reflection*.

Firstly, in the stages of *Planning Actions* and *Civic Participation and Critical and Active Engagement* the environmental CS initiative encompasses the design and implementation of both collective and individual actions, as well as actions at the public and private sphere, by the citizens. Of course, environmental CS initiatives should be primarily grounded in public environmental activism and community building; these elements are found in the core of EC (Jørgensen & Jørgensen, 2021). More specifically, when planning the actions to be undertaken, citizens are expected to take into account the involved stakeholders and their arguments, examine alternative solutions for the environmental problem studied, and reach into a proposal. Next, citizens proceed with the implementation of various civic actions aligned with the selected proposal (e.g. organizations of campaigns-lobbies, volunteerism in campaigns, publishing in local newspapers). Overall, these stages facilitate civic participation for EC in three ways: decision-making, influencing and community participation (Schulz et al., 2016).

Next, in the stage of *Networking and Sharing in Scales* citizens are asked to develop local, national and global networks comprised of multiple stakeholders who did not have the opportunity to participate in the environmental CS initiative (Glasbergen, 2010). In these networks, participants can disseminate their findings and upgrade the discussion about their proposed solution at a national or even global level. The advancement of digital technologies and the widespread use of internet contributes to establishing of these networks, developing online communities and bringing together groups of people across the globe (Tsivitanidou & Ioannou, 2020). Therefore, the CS participants are empowered to act as global citizens, thus enacting the motto 'act locally, think globally'.

Then, in the stage of *Sustain Environmental and Social Change* the environmental CS initiative continues with citizens' supplementary efforts to maintain the socio-environmental impact achieved. In this stage citizens can undertake activities for supporting and improving previous actions, such as keeping the issue in the news, adopting and reinforcing new measures, rewarding those who have helped with their actions, etc. These efforts provide the mechanisms for individual and collective human agency which can 'transform the systems and structures that create and sustain environmental change' (O'Brien & Barnett, 2013, p. 386).

Finally, during the stage of *Evaluation & reflection*, citizens reflect on and evaluate the effectiveness of their environmental actions. This stage is related to the transformative learning framework, which supports that critical reflection can promote a shift in citizen's socio-environmental worldviews (Kitchenham, 2008). As argued by Groulx et al. (2017), the theory of transformative learning gives particular attention on where and how this reflection can be translated into a dialogue that brings to the surface new opportunities for further collective actions.

Discussion

CS is an ever-increasing field, especially in the context of ecological and environmental sciences, and holds great promise for educational practice and research. What is still missing is 'an emphasis on the citizen aspects of citizen science and the perspectives of the non-professional or amateur scientists who are on the ground collecting and analyzing data' (Chari et al., 2019, p. 1). As the field expands, researchers have highlighted the need to consider the contribution of environmental CS initiatives to the transformation of citizens through learning and engagement (Bela et al., 2016). It has been argued that environmental CS initiatives may play a crucial role in the development of environmental citizens, who are able to take action toward the mitigation of current socio-environmental issues, thus serving as springboard for the cultivation of EC (Jørgensen & Jørgensen, 2021; Van Wyk, 2015). In the absence of prior frameworks focusing explicitly on this goal, the present study has synthesized evidence from three recent systematic reviews, seeking to extract design principles for the development of the CS4EC framework.

The proposed framework is grounded on fifteen (15) structural principles lying on the intersection of three research areas: (a) Participation in CS, (b) Pedagogy in CS, and (c) EEC. Firstly, five design principles have emerged in relation to participation, as follows: (a) Inclusiveness, (b) Co-creation, (c) Extended participation, (d) Collaboration (Collaborative mode of participation) and (e) Integral & deep involvement. Secondly, the design principles situated in the area of pedagogy, are the following ones: (a) Focus on an environmental problem, (b) Authentic educational context, (c) Active learning mechanisms, (d) Use of multiple tools/resources, and (e) Holistic EEC pedagogy. Finally, the EEC structural design principles highlight the following aspects: (a) Both individual & collective EC actions, (b) Both private & public EC actions, (c) Multi-scale actions, (d) Focus on pro-environmental behaviors, and (e) Full coverage of EEC outcomes.

These principles have served as the milestones in the structure of the CS4EC framework, as they contribute to the empowerment participants' environmental agency. More specifically, in this study, we are particularly interested in fostering citizens' agency through environmental CS initiatives to address current socio-environmental challenges and transform current unsustainable patterns into more sustainable ones. For this purpose, we have approached agency from a socio-cognitive point-of-view rather than as an individual attribute (Bandura, 2006; Stetsenko, 2017). Toward this direction, the principles comprising the CS4EC framework have a particular focus on the development of citizens' agency, as a transformation process (Mezirow, 2000), via leveraging the socio-cultural affordances of environmental CS initiatives.

Of course, it should be noted that, prior studies have also sought to shed light on how to facilitate citizens' active engagement and participation in CS initiatives (Paleco et al., 2021; Senabre Hidalgo et al., 2021), how learning outcomes are produced in CS initiatives (Kloetzer et al., 2021) or on how CS initiatives can result in positive environmental impact (Teo & Triantafyllou, 2020). However, none of these studies has provided a holistic theoretical framework focusing on CS for EC, grounded in the conjunction of citizens' participation, pedagogy and EEC.

In our study we have also sought to unveil how the identified structural principles should be ordered to result in the achievement of EC (i.e. procedural model of the CS4EC framework). To do so, we have presented how these principles could be sequenced to facilitate EC in the context of environmental CS initiatives. Each phase was therefore related to a distinct role allocated to

the citizens (including students) participating in an environmental based CS initiative, as follows: (a) Citizens as Co-designers, (b) Citizens as Scientists, and (c) Citizens as Agents of Change.

In this essence, this trajectory leverages the transformational capacity of environmental CS initiatives (Bela et al., 2016), and proposes a concrete pathway for transforming the non-scientists into environmental citizens. At the same time, the CS4EC framework is aligned with recent discussions on the potential of CS initiatives to enhance scientific literacy as this is conveyed in Vision III (Lüsse et al., 2022). Sjöström and Eilks (2018) have proposed a Vision III of scientific literacy, as a more praxis-oriented approach towards the development of socio-political action (Santos, 2009). Vision III focuses on critical reflection and action-taking aligned for the achievement of active citizenship and environmental sustainability (Birdshall, 2022). In the absence of other concrete paradigms of how CS initiatives can support scientific literacy for Vision III, the CS4EC framework may provide a learning trajectory of how environmental CS initiatives should be structured and evolve to get there.

Last but not least, even though the CS4EC may partially share some common grounds with the notion of Community Science (e.g. inclusiveness, co-creation approach, focus on local problems, etc.), what greatly differentiates our framework is its strong emphasis on various educative components in support of citizens' environmental agency. This is crucial given that little is known on how community CS research can be translated in forms of environmental agency (Chari et al., 2019; Jørgensen & Jørgensen, 2021). Opposed to the Community Science frameworks, the CS4EC model has also an additional focus on multi-scale actions which exceed the local scale, and reach the national and global scales. Finally, while there are ongoing debates on whether CS should be renamed into Community Science to adopt more inclusive language, we emphasize that in the CS4EC framework the term *citizen* is not referring to someone's national citizenship, and it is not deployed as legal term of *exclusion*. Instead, this term is adopted as a focal point of agentic empowerment for action-taking at a local, national, and global scale. Importantly though, we coincide with the position of Cooper et al. (2021) in that beyond the naming of these initiatives into CS or Community Science ones, it is essential to provide approaches which support citizens' inclusion and empowerment; and this is what the CS4EC framework is contributing to.

Limitations and future research

Even though the findings of this study may help flesh out a more comprehensive framework of how environmental CS initiatives should be designed to achieve EC, some limitations of this work are also important to note. Firstly, the framework is grounded on a theoretical basis, but it is not backed up with empirical testing. However, it is fully based on more than 180 empirical studies. Future studies should still enact and empirically investigate the CS4EC framework. At the same time, beyond merely exploring the design, implementation, and impact of environmental CS initiatives grounded on the CS4EC framework, future studies should focus on weighting each design principle according to its contribution to EC. In addition, future research could also focus on the development of an evaluation instrument, structured around the CS4EC framework.

Finally, it should be mentioned that our meta-synthesis approach was limited by the small number of SRLs being synthesized due to the novelty of this research area (i.e. EC in conjunction with CS is an emerging field of study), which may lead to selection and publication bias. However, with the merging of the three SRLs, we reviewed and compiled more than 180 empirical studies. Therefore, while the SRLs synthesized are, according to our knowledge, the first ones published in the field, they adequately cover the available corpus of literature.

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