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Beyond reliability: towards a broader epistemic evaluation of citizen science

Para além da confiabilidade: rumo a uma avaliação epistêmica mais ampla da ciência cidadã

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Abstract

Citizen science has been one of the main forms of public participation in scientific research. The inclusion of non-professional scientists in this context has, however, generated concerns about the reliability of its results, and a great part of the literature has been investigating it. In this paper, we aim to provide a more comprehensive epistemic evaluation of citizen science by discussing standards other than reliability. To do this, we refer to Alvin Goldman's social veristic epistemology and its five standards for epistemically evaluating social practices or

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institutions: reliability (the ratio of results to total number of results and errors fostered by a practice), power (the practice's ability to help cognizers find results that answer the questions that interest them), fecundity (the practice's ability to lead to large numbers of results for many practitioners), speed (how quickly a practice leads to results), and efficiency (how well a practice limits the cost of getting results). By applying it to the citizen science literature and by relying upon its contributions, this framework enables the integration of various theoretical reflections on citizen science, encompassing trade-offs among these standards and addressing ethical concerns. Furthermore, it also allows one to respond to common criticism about citizen science and to draw some important implications. In particular, we show how citizen science's fecundity is crucial for mitigating the challenges associated with unseen science, i.e., research whose results are never shared outside an institution boundary, thus highlighting its significance in the growing landscape of public participation in scientific research.

***Keywords**: Philosophy of Science. Social Epistemology. Citizen Science. Public participation in scientific research. Unseen science.*

Resumo

A ciência cidadã tem sido uma das principais formas de participação pública na investigação científica. A inclusão de cientistas não profissionais neste contexto tem, no entanto, gerado preocupações quanto à confiabilidade dos seus resultados, e grande parte da literatura tem-se debruçado sobre esta questão. Neste artigo, pretendemos fornecer uma avaliação epistêmica mais abrangente da ciência cidadã, discutindo outros padrões para além da confiabilidade. Para tanto, referimo-nos à epistemologia social verista de Alvin Goldman e aos seus cinco padrões para avaliar epistemicamente práticas ou instituições sociais: confiabilidade (a proporção entre os resultados e o número total de resultados e erros promovidos por uma prática), poder (a capacidade da prática em ajudar os cognoscentes a encontrar resultados que respondam às questões que lhes interessam), fecundidade (a capacidade da prática em conduzir a um grande número de resultados para muitos praticantes), velocidade (a rapidez com que uma prática conduz a resultados) e eficiência (a forma como uma prática limita o custo da obtenção de resultados). Ao aplicá-los à literatura sobre a ciência cidadã e ao basear-nos nas suas contribuições, este referencial permite a integração de várias reflexões teóricas sobre a ciência cidadã, englobando compensações entre estas normas e abordando preocupações éticas. Para além disso, ele também permite responder a críticas comuns sobre a ciência cidadã e tirar algumas implicações importantes. Em particular, mostramos como a fecundidade da ciência cidadã é crucial para mitigar os desafios associados à ciência não vista, ou seja, a investigação científica cujos resultados nunca são partilhados para além dos limites de uma instituição, destacando assim a sua importância no panorama crescente da participação pública na investigação científica.

Palavras-chave: Filosofia da ciência. Epistemologia social. Ciência cidadã. Participação pública na pesquisa científica. Ciência não vista.

Introduction

Practices that fall under the concept of "citizen science" have been happening for at least two centuries but have grown exponentially in the last three decades, when the very concept emerged, became institutionalized and projects spread (Haklay *et al.*, 2021; Kullenberg; Kasperowski, 2016; Mahr; Dickel, 2019; Teixeira *et al.*, 2014). Despite their diversity in the scientific field, locality, and kind of contribution made by the public, citizen science projects can advance scientific knowledge, improve science education, and impact social-political issues (Bonney *et al.*, 2009b; Koffler *et al.*, 2021; Ottinger, 2010). Due to this growing importance and the participation of non-professional scientists in scientific research, it is not surprising that considerable attention has been given to the reliability of data generated by citizen science initiatives (Balázs *et al.*, 2021).

Despite receiving less attention, other elements of citizen science have been under epistemic scrutiny by the citizen science literature. Accordingly, in this paper, we aim to give a broad epistemic evaluation of citizen science by relying upon and integrating more standards than reliability. To do that, we refer to Alvin Goldman's (1992, 1999) social veristic epistemology and its five standards for epistemically evaluating social practices or institutions: reliability, power, fecundity, speed, and efficiency. While the next section is devoted to presenting this framework, the second section applies it in dialogue with the citizen science literature, and the third section draws some implications. As we will see, the application of Goldman's standards integrates several epistemically relevant aspects of citizen science, highlights potential benefits and worries, and counterbalances common criticism. It also allows one to see citizen science's connection to other themes, such as unseen science.

Goldman's social veristic epistemology and its five standards

Social epistemology is often contrasted with the traditional approach of epistemology according to which individual knowers in isolation from others are the focus of analysis. The emphasis on how an individual by herself can attain knowledge has been somewhat prominent also in the self-image of modern science, as we can infer, for example, from the Royal Society of London's motto "nullius in verba". A vast literature in epistemology and history, philosophy, and sociology of science has demonstrated, however, not only the importance of taking the social context (e.g., interaction with others, social norms, and institutions) of knowers into account but also how unavoidable this context is to a proper understanding of the pursuit of knowledge (Longino, 2002; Fricker *et al.*, 2021).

Alvin Goldman has been one of the main proponents of social epistemology. He calls his approach "veristic" because he takes true beliefs as the fundamental epistemic good. In other words, true beliefs have intrinsic value, and a practice has an instrumental value by fostering them (Goldman, 2002). Therefore, a veristic social epistemology investigates social practices or institutions' impact on the production of true beliefs in contrast with error (false belief) and ignorance (the absence of true belief) (Goldman, 1999, p. 5). One can perform this evaluation either from an absolutist or a comparative perspective by contrasting two practices dealing with the same intellectual tasks but in a different way (*ibid*., p. 92). Goldman (1992, p. 195) lays out five standards to do this appraisal: reliability, power, fecundity, speed, and efficiency.

Before presenting and commenting on them, it is important to briefly discuss the adequacy of the concept of "true beliefs" to our context, a concept that is also present in all standards. Indeed, one could legitimately worry about their presence in the realm of science due to several reasons, such as its fallibilism. Although we agree with Goldman (1999, p. 246) that this is an avoidable worry, we will use Thagard's (1997, p. 247) way of reframing Goldman's standards by substituting "true beliefs" for "scientific results". Here, a scientific result can be an empirical or a theoretical claim whose minimal requirement is its potential publication in a peer-reviewed journal. Accordingly, an error would be a result that would be rejected by peers, and ignorance would be the lack of a result. We believe that this way of reframing Goldman's standards is more adequate to the context of citizen science, and it also deflects important epistemic and metaphysical questions that we could not consider here. Either way, the five standards are presented by Thagard (1997, p. 247) in the following way:

1. *Reliability*. The reliability of a practice is measured by the ratio of results to the total number of results and errors fostered by the practice;
2. *Power*. The power of a practice is measured by its ability to help cognizers find results that answer the questions that interest them;
3. *Fecundity*. The fecundity of a practice is its ability to lead to large numbers of results for many practitioners;
4. *Speed*. The speed of a practice is how quickly it leads to results;
5. *Efficiency*. The efficiency of a practice is how well it limits the cost of getting results.

These standards were applied, for example, by Thagard (1997) to diverse kinds of scientific collaboration (employer/employee; teacher/apprentice; peer-similar, and peer-different) and, more specifically, to the bacterial theory of ulcers and the multiconstraint theory of analogy. More recently, they were also applied by Fallis (2011) and Frost-Arnold (2018) to Wikipedia. Below, we comment on them by drawing upon this existing literature.

Reliability's main motivation is the avoidance of errors and, consequently, it is not surprising that it is one of the main epistemic worries about citizen science and science in general. As non-specialists or peers with comparatively less expertise get into a practice, its reliability can decrease although other standards may increase. This is the case, according to Thagard (1997, p. 248), in the situation of a scientific researcher collaborating with a laboratory technician (employer/employee relationship) where reliability may decrease or stay the same, but speed and power increase since the scientific researcher has more time to focus on other questions, for example. In the case of Wikipedia, the case is somewhat similar: studies have shown that Wikipedia is fairly reliable as other alternative encyclopedias, but it is different from them thanks to its higher power: Wikipedia had around 3,800,000 articles in 2018 while Encyclopedia Britannica, in its last edition of 2012, 65,000 (Frost-Arnold, 2018, p. 32).

If a practice fosters a certain number of results only about a specific subject, it would be a very reliable practice, but it would not score well in power. Also, if it answers to irrelevant questions, it would not be powerful either. In other words, while reliability is an antidote to error, power is an antidote to ignorance (Goldman, 1987, p. 122). We shall see that citizen science also scores well in power and combats important forms of ignorance.

Regarding fecundity, Goldman (1992, p. 195) states that a scientific practice may score well in power if it produces many truths (results) by a scientific elite, but fecundity may be lacking for "public education in the culture may be weak, so the bulk of the populace is mired in superstition and ignorance". In a paper on communication control, he refers to fecundity when discussing how simplified messages in the media may increase the audience size, thus increasing fecundity in terms of "the number of people acquiring true beliefs [results]" (Goldman, 1991, p. 123). There seems to be, therefore, an active and passive interpretation of fecundity working on these passages: fecundity can either happen when many practitioners get their results during an investigation or when many practitioners get results by dissemination processes. Both interpretations appear in later applications of fecundity: Thagard (1997, p. 249) argues that the teacher/apprentice increases fecundity in the sense that the apprentice is being trained and will eventually get results on their own; and the online and free access properties of Wikipedia make it very fecund since a lot of people can access its entries according to Fallis (2011, p. 305) and Frost-Arnold (2018, p. 32).

Collaborations such as those which occur between a scientific researcher and a laboratory technician, between teachers and apprentices, or between similar peers may reduce in general the time of getting true answers – the standard of speed –, despite the need for some training. Cross-disciplinary collaborations (peer-different relationships), on the other hand, may be slower due to the necessity of forging a common vocabulary, but it may have a higher power (Thagard, 1997, p. 253). These forms of collaboration also have different costs: hiring employees may be expensive, but it will increase other standards. Wikipedia's voluntary design, on the other hand, makes it less costly and, therefore, more efficient (Frost-Arnold, 2018, p. 32).

Citizen science meets social epistemology

Before applying the above standards to citizen science and comparing it with more traditional forms of research, it is important to make explicit what we are considering to be citizen science. Now, not only the definition of citizen science is extensively disputed but the very term as well (Eitzel *et al*., 2017; Liebenberg *et al*., 2021). While acknowledging the importance of these debates, we will not develop them here and, instead, we will adopt the Brazilian Citizen Science Network's (RBCC) definition because of its wide scope and unification of several citizen science elements[1]. The RBCC (2023) defines citizen science as:

> […] a wide range of types of partnerships between scientists and those interested in science, for shared production of knowledge with the potential to promote: 1) public engagement in different stages of the scientific process; 2) scientific and technological education, and 3) co-elaboration and implementation of public policies on topics of social and environmental relevance.

To show how it unifies several elements of citizen science, consider how items (1) and (3) are present in two influential and initial characterizations of citizen science. (1) is present in Bonney's (1996) conception of it as public participation in scientific research, and item (3) in Irwin's (1995: xi) statement that "'Citizen Science' evokes a science which assists the needs and concerns of citizens" (cf. Ottinger, 2017). (2) is important because it also accommodates citizen science's relationship with education (cf. Lacerda *et al*., 2023; Lüsse *et al*., 2022).

For our purposes, it is also important to adopt a typology of citizen science that differentiates at which scientific stage people interested in science are participating. One useful way to do so is by dividing citizen science among contributory, collaborative, and co-created projects (Bonney *et al*., 2009a; cf. Ceccaroni *et al*., 2017 for other typologies). If people interested in science participate solely by contributing data, the project is defined as contributory; if, in addition to data collection, they also help in analyzing the data, refining the project design, and/or disseminating findings, the project is considered collaborative; finally, when participants are involved in these and additional stages (e.g., problem formulation), the project is classified as co-created.

Reliability

As previously stated, reliability has been one of the main worries about citizen science. This worry may be derived from a wide range of factors, such as the belief according to which non-professional scientists

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[1] Despite not being able to discuss definition issues further, it is important to acknowledge one feature of RBCC's definition that may not be present in other definitions: it does not cover citizen science activities without partnerships with scientists.

will necessarily decrease the quality of the result generated by a study or even scientists' own concerns about the wider scientific community's potential negative reaction to their findings (cf. Riesch; Potter, 2014). The preoccupation about reliability can also take multiple forms: Balázs and collaborators (2021), for example, list five categories including citizens not following data collection protocols or their incorrect implementation. Although those categories relate to contributory projects, there are legitimate worries about the reliability of all kinds of citizen science. For example, it has been a common criticism that some co-created projects about a public health issue may be treated by advocacy groups (Rise of the Citizen Scientist, 2015). There are, however, at least three main lines of replies to the worry with reliability.

First, as argued by Elliott and Rosenberg (2019) in dialogue with the philosophical literature on the aims of science and with the citizen science community's own reflection about data quality, it is unfruitful to put into question the general reliability of citizen science. Rather, one should evaluate whether the results of particular projects are adequate and epistemically sufficient for their particular objectives. Second, studies have shown that the reliability of citizen scientists' analyses is close to or similar to academic scientists' ones (cf. van der Velde *et al*., 2017; Jordan *et al*., 2012; Gillett *et al*., 2012), which is a reason to accept that citizen science's results would be published in peer-reviewed journals as our requirement states, a situation that has been happening. Third, there are strategies already implemented to alleviate potential worries about reliability before, during, and after a citizen science project (Balázs *et al*., 2021; Freitag *et al*., 2016). They vary according to the kind of citizen science project, but they include, for example, the training of citizen scientists (before), automatic quality assessments (during), and expert verification or statistical analysis (after). Those strategies are important because they alleviate the chance and number of errors.

One can, however, present a rejoinder to these replies by relying upon a recent study according to which only one-quarter of citizen science projects eventually result in a peer-reviewed paper (Davis *et al*., 2023). The authors inferred from this that the "science" in citizen science is "largely irrelevant and meaningless" (*ibid*., p. 8). Notwithstanding, the same and only criteria used by the authors would also imply that other fields have those features, as, for example, almost half of clinical studies are never published as well (Bowers *et al*., 2023; Chan *et al*., 2014). Reasons for non-publication are diverse and may not involve issues with reliability (Song *et al*., 2014). Although both amounts of non-publication are worrisome and have important social consequences, we argue that the rate of publication by itself - instead of the potential to be published as our criteria commands – is not an adequate indication of citizen science reliability nor an exclusive problem of citizen science if it is to be applied.

In summary, even though concerns about reliability may stem from various factors and manifest in numerous forms, we maintain that the four responses outlined above adequately demonstrate that the standard of reliability is met in the case of citizen science.

Power

As we saw, the power of a practice is "measured by its ability to help cognizers find results that answer the questions that interest them" (Thagard, 1997, p. 247). In the case of citizen science, we believe that this standard can be broadly evaluated by the wide spectrum of scientific fields in which citizen science has been applied and generating results. A recent study concluded that the fields most recurrent are, in decreasing order, Ecology, Environmental Sciences, Biodiversity Conservation, Multidisciplinary Sciences, and Astronomy and Astrophysics (Pelacho *et al*., 2021). A previous study found a similar result: Ecology, Environmental Sciences, Geography, Environmental Studies, and Biodiversity Conservation – in sixth place, History and Philosophy of Science (Kullenberg; Kasperowsski, 2016). Although there is a concentration in the environmental sciences, citizen science in the humanities has been increasing as well (Heinisch *et al.*, 2021). Another indication of citizen science power is the recurrent affirmation according to which citizen science allows to get or analyze great amounts of data/samples and address questions that would be impossible otherwise (Macphail; Colla, 2020).

Despite the number of fields that have been impacted by citizen science, one can argue that the results generated by it have important limitations regarding power. In the context of biodiversity research, for example, citizen science data may be prone to taxonomic and spatial biases that may hinder its ability to answer some questions of interest and adequately support conservation policies. Notwithstanding, for identifying species abundance and distribution range, citizen science data may be even more accurate than data from research institutions (Forti *et al.*, 2024). This echoes the reply given in the last section about the importance of considering the specific aim of each citizen science project.

Even so, one could present another limitation regarding power by affirming that the results generated by citizen science projects tend to be more empirical-oriented and provide fewer theoretical contributions, as Thagard (1997, p. 252) understands to be the case in the employer/employee or teacher/apprentice relationships in contrast with the peer-similar one. This concern can be formulated through Parris et al. (2023) distinction between data-first and question-first citizen science projects: while the first kind engages citizen scientists in the collection of data without a research question presupposed (although there may be one in an eventual post-hoc analysis), the second kind is designed to address one or more questions. Data-first citizen science projects may, therefore, have a lower power than question-first ones. If true, this would imply that the theoretical contribution of a part of citizen science projects might be lower than that of traditional forms of scientific research. Although no research, as far as we know, has definitively confirmed or investigated this matter, we contend that even if it were the case, citizen science effectively counterbalances it in the following ways.

It is important to note that the power standard refers to giving results that answer questions of interest to the members of the practice. Thanks to the participation of people interested in science and not only academic scientists in the research, we believe that it enhances the range of the questions posed by science. How different people investigate different questions has been theoretically and empirically demonstrated in various fields, especially within the feminist philosophy of science tradition. Although there are important differences within this field, Anke Bueter (2024, p. 23) notes that its various strands share a common starting point: knowledge and knowers are socially situated, as proposed in Donna Haraway's seminal paper (1988). Building on this, the literature has shown both how a lack of diversity can have detrimental effects on science and how diversity can foster a more socially and epistemically robust scientific enterprise. An illustrative example of this dynamic can be found in research on female birdsong. Historically, birdsong was studied almost exclusively as a male trait, reflecting gender bias within the field. As Haines et al. (2020) demonstrate, this was not merely a social oversight but an empirical inaccuracy; female song is actually widespread and likely ancestral in songbirds. Their research also revealed that as the field diversified, women scientists became the primary drivers of this corrective research – comprising 68% of first authors on female birdsong papers, compared to only 44% on general birdsong papers.

In the case of citizen science, the aforementioned phenomenon of amplifying the range of questions can be clearly seen in the case discussed by Ottinger (2010), where citizen scientists were interested in investigating peaks in air pollution and its consequences for human health instead of its average values as the regulatory framework in the case and previous research did. Without their participation, this issue would likely remain unexplored. Similarly, the movement of women with endometriosis in Mexico, as analyzed by Piña-Romero (2023), fundamentally shifted the focus from simply producing knowledge about the disease to critically investigating the systemic production of ignorance surrounding it. Their citizen science "from the margins" questions why the disease is systematically misdiagnosed, why its true incidence remains unknown, and why research into a cure is neglected, issues that were overlooked by traditional biomedical research.

Thus, citizen science has the potential to amplify the questions of interest to the scientific community, correcting not only data gaps but also ignorance about people's experiences (Ottinger, 2022)[2]. This potential, nonetheless, will be severely restrained if there is low diversity in the participants of citizen science projects, as recent papers have been highlighting to be the case in some countries (cf. Pateman *et al*., 2021). Furthermore, even if diversity is present, but people's claims are constantly downplayed, power will be restricted too. Fostering more diversity in citizen science alongside with meaningful inclusion is, therefore, crucial to better attain its power.

Fecundity

Fecundity, we remember, is the ability of a practice to foster a large number of results for many practitioners and not only an elite group. One can relate fecundity to the aim of democratizing science, which is explicitly present in one of the two main traditions in citizen science (Irwin, 1995; cf. also Ottinger, 2017). We argue that citizen science attains fecundity for two main reasons.

First, the very nature of citizen science makes it unlikely that results generated by it will be restricted to a scientific elite thanks to the public participation in research and to the principles of citizen science proposed by its very community. More specifically, two out of the ten principles proposed by the European Citizen Science Association (ECSA) in 2015 – which are also adopted by other associations, such as the Brazilian one mentioned before – are tied to fecundity: principle 5 states that citizen scientists must receive feedback from the project in which they participated, and principle 7 refers to the dissemination of results in an open-access format (Robinson *et al*., 2018). Second, as there is also evidence showing that some of the participants in citizen science projects want to become professional scientists as well (e.g., Hiller; Kitsantas, 2015; Musavi *et al*., 2018), there will be more people fostering results in the future. The formation of new scientists was one of the ways to measure fecundity mentioned by Thagard (1997, p. 249), so it is another important indication of citizen science's fecundity.

Because of the two reasons presented above, we believe that is justified to state that citizen science scores highly at fecundity. Nonetheless, it is worth mentioning an ethical concern with its fecundity: the potential to create problems associated with its transparency, such as violating citizen's privacy in the dissemination of results. This worry is acknowledged by the citizen science community in several ways, such as its presence in principle 10 of the ECSA: "The leaders of citizen science projects take into consideration legal and ethical issues surrounding copyright, intellectual property, data-sharing agreements, confidentiality, attribution and the environmental impact of any activities" (Robinson *et al*., 2018). To preserve the distinctive part of citizen science's fecundity we stated, those concerns must be permanently considered.

Speed

It is not uncommon to read that citizen science accelerates scientific findings or makes data collection and analysis faster (Catlin-Groves, 2012, p. 1; van Vliet; Moore, 2016, p. 14). One of the reasons for so is the

[2] It is important to highlight that Ottinger (2022) uses a different conception of ignorance than the one we have been using here. She understands ignorance as actively constructed in alignment with one of the definitions provided by the agnotology literature, while Thagard's definition here only refers lack of results. Both definitions can be seen as complementary, however: lack of results can be derived from active or passive construction of ignorance. One may argue, nonetheless, that the social construction of ignorance is constitutive of it and not only its causal root. In this way, there would be a potential conflict among both definitions, but it is an innocuous one to the purposes of this paper.

large number of people involved in citizen science projects. How quickly citizen science leads to results, its speed, is often remembered and there is some evidence in favor of it. Cox and collaborators (2015), for example, found that projects on the online platform Zooniverse saved 34 full-time working years on average. Those projects are either contributory or collaborative, however. Co-created projects may be slower in generating results, but they can score higher in other criteria such as power or fecundity.

Despite these common claims about speed, Davis et al. (2023) found that the average time from the launch of a citizen science project to its first publication in a peer-reviewed journal was 9.15 years. Their analysis relied upon data from projects that vary widely in their origin date, such as the Cooperative Observer Program (which started in 1890 and got its first paper in 2005) and more recent ones. In our view, this is an important limitation of their study. Indeed, although it is historically legitimate to see "proto" citizen science projects in previous centuries, it is only in the last few decades that this form of public participation in science has been institutionalized, with its international and national associations, specific academic journals, principles, and conferences. In other words, one should not equate previous citizen science projects with the ones that emerged out of the recent process of institutionalization of the field. When taking this into account, the force of their potential objection to speed decreases: the authors also found that newer projects publish more quickly (three months in the quickest one).

Efficiency

Citizen science's cost-effectiveness is often remembered as well. Participants in citizen science projects are usually volunteers who are not expected to get financial rewards but scientific ones, so there are a lot of unpaid hours of contribution. Sauermann and Franzoni (2015), for example, estimate 129,540 unpaid hours at seven Zooniverse projects using data only from 180 days in 2010. Another study estimates that the contributions of volunteers in France to deliver data related to one of the indicators of the Convention on Biological Diversity ranged from 678,523 to 4,415,251 euros per year (Levrel *et al*., 2010). Gardiner et al. (2012) estimates the cost of "collecting lady beetles from one location using a sticky card trap at US$126.62 per trap for traditional science, US$40.29 for verified citizen science [with expert verification], and US$31.44 for direct citizen science [without expert verification]". In a context where scientific funding is scarce and highly competitive, it is not surprising that this standard is frequently mentioned by the citizen science community. On the other hand, it may make citizen science and citizens an instrument of neoliberalism and its emphasis on minimal government interventions (Vohland *et al*., 2019) or subject to exploitation (Resnik *et al*., 2015).

Implications

The application of Goldman's standards to citizen science has important implications. For example, it calls attention to several epistemic criteria that have been discussed by the citizen science community than reliability. It also combines previous discussions (e.g., about speed and cost) in a unified way by showing possible trade-offs among the standards. As we saw, by doing a comparative analysis with traditional scientific research, common criticisms can also be responded to. Furthermore, these standards can be used as a tool for citizen science project proponents by allowing them to visualize which standard of their project is most distinctive and to visualize potential trade-offs among them. In Table 1, we synthetize these findings before drawing other implications of the last section, focusing on the standards of power and fecundity:

Table 1 – Summary of Goldman's standard application to citizen science.

Criteria	Analysis	Potential conflict with other standards
Reliability	Met. Concerns are addressed via contextual adequacy, empirical evidence, and robust quality-control protocols.	Can reduce Speed and Efficiency due to the time and resources required for training and validation protocols.
Power	Met. Its power lies in diversifying research questions and addressing "undone science."	High power in co-created projects often comes at the cost of Speed, as participatory problem definition and analysis take more time.
Fecundity	Met. Built-in mechanisms ensure results are public and foster new scientists.	Ensuring broad access (fecundity) can sometimes conflict with Reliability if rapid, open data release precedes rigorous quality control.
Speed	Context-dependent. Contributory projects are fast; co-created ones are slower but with more power.	Maximizing Speed (e.g., in data-first projects) can limit the Power to address complex, co-created questions and may compromise Reliability.
Efficiency	Met. It is highly cost-effective due to volunteer labor, but this is a key ethical challenge.	Pursuing maximum Efficiency through unpaid labor can undermine Fecundity if it leads to exploitation, reducing long-term participation and trust.

Column 1 lists the standards. Column 2 states whether each is met and provides the rationale. Column 3 identifies potential conflicts with other standards.

Source: Author (2025).

As presented in section 2.2, citizen science's power can amplify the questions posed by science, filling not only data gaps but also correcting ignorance. It can, therefore, alleviate worries about undone science, i.e., "areas of research that are left unfunded, incomplete, or generally ignored but that social movements or civil society organizations often identify as worthy of more research" (Frickel *et al*., 2010, p. 44), a potentiality already highlighted by Ottinger (2022) and illustrated by the cases we mentioned in the section "power" (Ottinger, 2010; Piña-Romero, 2023).

However, we advance that due to its public character and its fecundity, citizen science can also mitigate forms of unseen science, i.e., research whose results are never shared outside an institution's boundary. Unseen science happens mainly with industry-funded science, since its results may remain restricted thanks to instruments as Confidential Business Information (CBI) or, in some cases, may be actively kept secret to avoid regulations (Richter *et al*., 2018). A case in point is the chemical company 3M, which conducted internal research on the harmful effects of per- and polyfluoroalkyl substances (PFAS) on the immune system as early as 1978 but did not release the findings until 2000, significantly delaying public awareness and further scientific investigation (Grandjean, 2018).

More precisely, citizen science can mitigate forms of unseen science, provided certain conditions are met.[3] It is important that its governance ensures the knowledge produced is public and actionable, that it is strategically directed toward research gaps created by industrial secrecy, and that its design incorporates mechanisms for data sovereignty to prevent downstream privatization. The PFAS-REACH project, a collaboration between Silent Spring, Michigan State University, and Northeastern University exemplifies this

[3] We thank a reviewer for suggesting a more nuanced approach on how citizen science can mitigate unseen science. It was also suggested a dialogue with Zukerfield (2017). For reasons of scope, we could not do it here, but we mention his reference for future work on this topic.

approach. The project was publicly funded and governed, explicitly designed to address the specific research gap on PFAS immunotoxicity — a gap that emerged from 3M's delayed disclosure of study results. Its core output, the PFAS Exchange, is an open-access resource center that ensures the findings remain a public good (Elliott, 2022). A counterfactual scenario underscores the critical importance of these conditions: had PFAS-REACH been privately funded with proprietary rights over the resulting childhood immunotoxicity data, the project could have become yet another instance of unseen science, its findings restricted as CBI to preempt liability or regulation.

Mitigating forms of unseen science is important for at least two reasons. First, because it can reduce publication bias, the selective publication of research only with positive results. The open science elements mentioned in the citizen science principles and the public participation in research that characterizes citizen science make it unlikely. Second, correcting unseen science is relevant for potentially preventing cases of "early warnings, late lessons", i.e., cases where there was initial evidence about a potential threat to the environment or human health but mitigatory actions were taken only decades later (Harremoës *et al*., 2001). In some of them, the problem was not undone science, but unseen science for early evidence existed but remained restricted inside an institution, as the case of per and polyfluoroalkyl substances illustrates (Grandjean, 2018). Citizen science's fecundity, therefore, is a strong antidote to unseen science and its scientific and societal consequences.

Conclusions

In this paper, we applied Goldman's five standards- reliability, power, fecundity, speed, and cost – to epistemically evaluate a practice – citizen science. After presenting a definition of citizen science provided by the RBCC and a common classification of it (contributory, collaborative, and co-created), we not only showed how citizen science met each of the standards, but we also detailed eventual trade-offs, limitations, ethical concerns, and distinctive features. The framework we used, therefore, integrated several aspects of the theoretical reflections about citizen science, providing a broad evaluation of it. Importantly, it also responded to common criticism. Finally, we advanced that citizen science's fecundity counterbalances the problem of unseen science, a contribution that highlights a different potential of this valuable form of public participation in research.

Data availability statement

The main focus of this article is contributions of a theoretical or methodological nature, without the use of empirical data sets. Therefore, in accordance with the journal's editorial guidelines, the article is exempt from being deposited in SciELO Data.

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