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SURVEY ARTICLE

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Participatory soil citizen science: An unexploited resource for European soil research

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Abstract

Soils are key components of our ecosystems and provide 95%–99% of our food. This importance is reflected by an increase in participatory citizen science projects on soils. Citizen science is a participatory research method that actively involves and engages the public in scientific enquiry to generate new knowledge or understanding. Here, we review past and current citizen science projects on agricultural soils across Europe. We conducted a web-based survey and described 24 reviewed European citizen science projects in the light of the 10 principles of citizen science and identified success factors for citizen science. Over 66% of the projects generated soil biodiversity data; 54% and 42% of the projects generated data on vegetation cover and soil organic carbon, respectively. Our findings show that soil citizen science projects aligned with the 10 principles of citizen science offer an unexploited resource for European soil health research. We conclude that promoting co-creation, fostering knowledge-sharing networks and enabling long-term communication and commitment with citizens are success factors for further development of citizen science on soils.

KEYWORDS

EJPSOIL, European agroecosystems, participatory research, soil biodiversity, soil health, web-based survey

1 | INTRODUCTION

Soil is a major foundation of health and wealth (FAO & ITPS, 2015). It is a finite and nonrenewable natural resource that stores, filters and transforms many substances including water, nutrients and carbon. Soil is crucial for climate change mitigation and adaptation, agricultural production and food security, preserving nature and biodiversity (Helming et al., 2018; Schirpke et al., 2017). Maintaining soil health—defined by the Soil Mission 'A Soil Deal for Europe' as 'the continued capacity of soils to support ecosystem services'—is vital (Veerman et al., 2020). Nonetheless, soils are in a threatened state across Europe and globally as well (FAO & ITPS, 2015; Popp et al., 2014; Veerman et al., 2020). Accordingly, numerous policies have been implemented by the European Commission in recent years to promote soil health in Europe. In this framework, the EU Soil Strategy was introduced based on the European Green Deal, and it is expected to help fulfil goals outlined in both the EU Biodiversity Strategy and Farm to Fork Strategy. The European Joint Programme SOIL '*Towards climate-smart and sustainable agricultural soil management*' (EJP SOIL, 2020–2025) launched by the European Union is a major initiative to develop an integrated European research community on agricultural soils. Soil science research is essential for understanding and enhancing the contribution of agricultural soils to key societal challenges. Soil health needs to be measurable (Van der Putten et al., 2023). Effectively bridging the gap between our current state of knowledge and societal needs requires a joint effort involving a diverse set of stakeholders, including the public (Mol & Keesstra, 2012). However, approximately half of the world's population is estimated to live disconnected from the natural environment (MacEwan et al., 2017). This suggests that a large portion of the global population may also be disconnected from the soil.

Citizen science is a participatory research method that actively involves the public in scientific enquiry to generate new knowledge or understanding. Although there is no official definition of its methodologies and the discussion on what kind of activities and practices are part of it (Haklay et al., 2021), citizen science projects involve engaging with communities and seeking their participation in data classification, collection and/or co-creation (Pino et al., 2022; Reynolds et al., 2021). This approach improves our ability to capture information from the field. This paper distinguishes between scientists, who are trained professionals conducting scientific research or solving scientific problems, and citizen scientists, who are members of the general public who collect and analyse data related to the natural world, typically as part of a collaborative project with professional scientists. A citizen scientist can also be a person who co-builds projects with scientists that consider different type of knowledge (scientific and empirical ones) taken into account for emerging research questions, new issues around data or new integrated knowledge. In 2015, the European Citizen Science Association (ECSA) developed best practice guidelines for good citizen science, summarized as the 10 principles of citizen science (ECSA, 2015; Table 1).

Highlights

- We review past and current citizen science projects on agricultural soils in Europe.
- Approximately 66% of the reported projects generated soil biodiversity data.
- Projects aligned with the 10 principles of citizen science offer an unexploited resource for soil research.
- Co-creation, knowledge-sharing networks and long-term communication are success factors.

These 10 principles of citizen science provide a benchmark against which to examine existing citizen science projects and support the development of new high-quality projects (Robinson et al., 2018). The number of such projects is increasing rapidly (Pocock et al., 2017), including projects on soils (Ranjard, 2020; Ranjard et al., 2022). Nonetheless, results from these projects are still little published in academic journals, as evidenced by the small scientific corpus when crossing the keywords 'soil' and 'citizen science*'. The Web of Science (consulted on 7 March 2023) provides 191 publications, two-thirds of which have been published in the past 2 years. By comparison, crossing 'biodiversity' and 'citizen science*' yields 1184 papers. Does this mean that it is more difficult to implement these approaches on soils versus other components of the environment? Which successes and/or difficulties are there for such projects? To answer these questions, we conducted a participatory consultation over European countries, with a focus on agricultural soils. Agricultural soils can be defined in a broad sense as soils that are cultivated and produce biomass, for food, feed, fibre or bioenergy.

The main objective of this review was to synthesize the current understanding and use of citizen science approaches for knowledge building regarding soils across Europe. This synthesis reviews soil citizen science based on collected examples of past and current citizen science projects on soil health across Europe. The 10 principles of citizen science provide a framework against which we examine the collected citizen science projects.

2 | MATERIALS AND METHODS

To review soil citizen science in Europe with the focus on agricultural soils, we conducted a web-based survey. We invited experts and national contact points of the EJP SOIL programme, as well as any relevant contacts identified by them, to fill in our online questionnaire. Beyond experienced

TABLE 1 Ten principles of citizen science (ECSA, 2015).

1. Citizen science projects actively involve citizens in scientific endeavour that generates new knowledge or understanding. Citizens may act as contributors, collaborators or as project leaders and have a meaningful role in the project.
2. Citizen science projects have a genuine science outcome. For example, answering a research question or informing conservation action, management decisions or environmental policy.
3. Both the professional scientists and the citizen scientists benefit from taking part. Benefits may include the publication of research outputs, learning opportunities, personal enjoyment, social benefits, satisfaction through contributing to scientific evidence, for example, to address local, national and international issues, and through that, the potential to influence policy.
4. Citizen scientists may, if they wish, participate in multiple stages of the scientific process. This may include developing the research question, designing the method, gathering and analysing data and communicating the results.
5. Citizen scientists receive feedback from the project. For example, how their data are being used and what the research, policy or societal outcomes are.
6. Citizen science is considered a research approach like any other, with limitations and biases that should be considered and controlled for. However, unlike traditional research approaches, citizen science provides opportunity for greater public engagement and democratization of science.
7. Citizen science project data and meta-data are made publicly available and where possible, results are published in an open access format. Data sharing may occur during or after the project, unless there are security or privacy concerns that prevent this.
8. Citizen scientists are acknowledged in project results and publications.
9. Citizen science programmes are evaluated for their scientific output, data quality, participant experience and wider societal or policy impact.
10. 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.

citizen science project managers, we also surveyed those not yet engaged in citizen science to survey the potential for such future projects. Depending on their self-reported experience with managing citizen science projects, we refer to respondents either as 'citizen science coordinators' when already having (co-)organized a citizen science project, or as 'citizen science novices' when not yet having applied citizen science approaches in their work.

For a more comprehensible overview of the 10 principles of citizen science, we grouped the principles into three distinct categories: (i) Participation in citizen science projects; (ii) Citizen science projects' openness; and (iii) Citizen science projects' effectiveness.

2.1 | Online questionnaire

The questionnaire (Appendix SI) was based on a previous initiative by INRAE in France (Gascuel et al., 2023; Ranjard et al., 2022) and was adapted to the diversity of European countries and relative agroecosystems, as well as to our own research objective. The questionnaire included a branching logic, which directed responders to different subsections of the questionnaire depending on their answers. Three general questions were initially asked, after which the questionnaire was divided into questions for coordinators (project basics, 10 principles of citizen science, EJP SOIL-related, project assessment) and for novices. Questions directed at novices were limited to strategies ensuring success in citizen science projects. Questions to citizen science coordinators were aimed at: (i) collecting examples of past and current projects focused on agricultural soil; (ii) describing the projects regarding the above 10 principles of citizen science (ECSA, 2015; Table 1); and (iii) identifying success factors and challenges. The survey for citizen science coordinators and novices contained 34 and eight questions, respectively, including filter questions. The questionnaire also included information boxes on 'What is EJP SOIL', 'Ten principles of citizen science' and 'A Soil Deal for Europe'.

Survey respondents were recruited online through email invitations to people inside and outside of EJP SOIL through EJP SOIL national contact points and through the European Citizen Science Association's (ECSA) email-list, as well as through direct emails to citizen science projects that we could identify through EJP SOIL national contact points but did not get a timely response. The web-based questionnaire was technically implemented with the software 'Askallo GmbH (2022) (Version 2022.6). After a pretest with 11 people and further adaptations, the questionnaire was launched in June 2022 and was active for 4 months, until October 2022.

2.2 | Data processing and analysis

All statistical analyses were performed using R version 4.2.2 (R Core Team, 2022). To create Figure 1, the R package tidyverse (v2.0.0; Wickham et al., 2019) was used. The clusters were calculated with dichotomized data and average linkage method. Figures 2–6 depict the

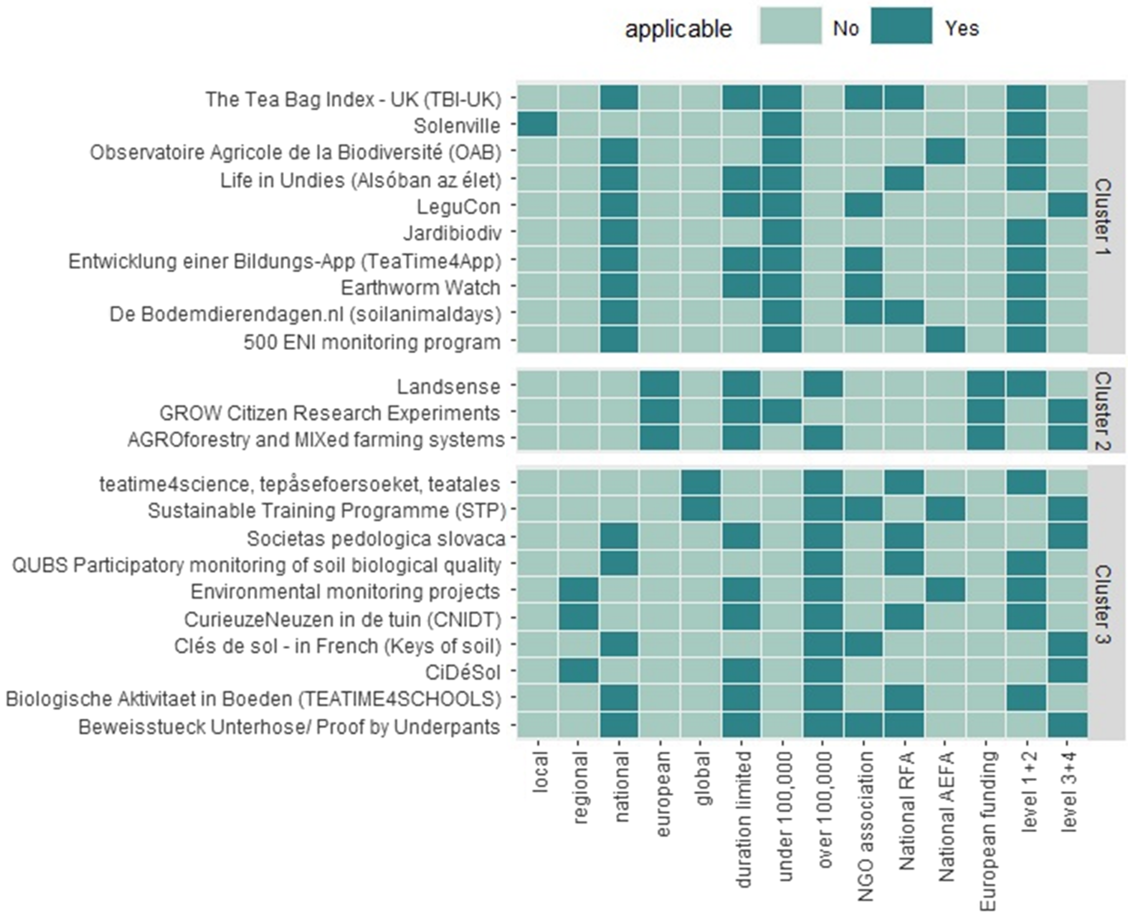

FIGURE 1 Description of the named citizen science project ($n = 23$) as reported by coordinators.

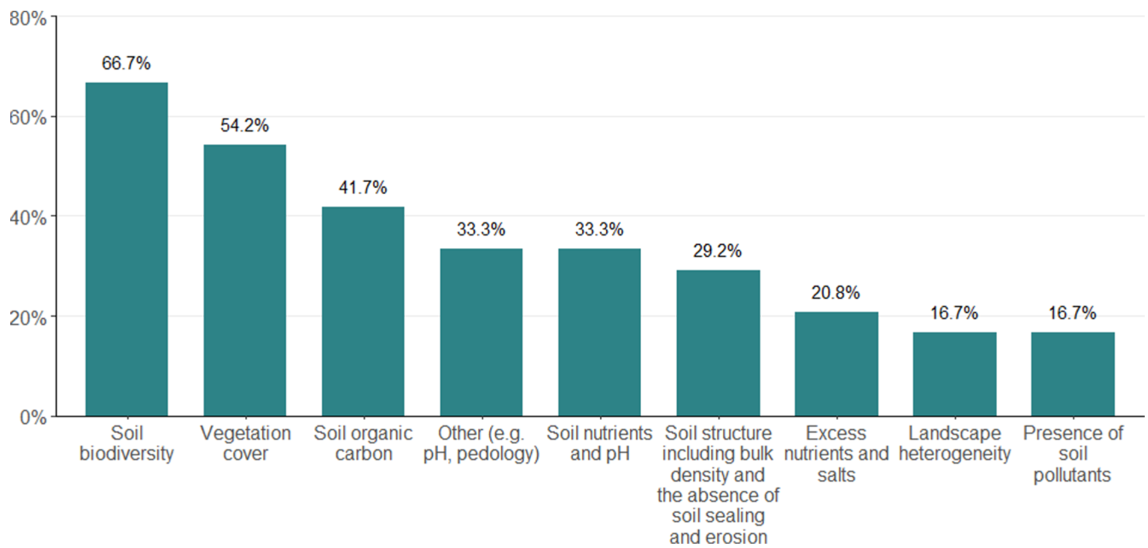

FIGURE 2 Soil health data generated by the citizen science projects ($n = 24$) (EC, 2021).

frequencies of the calculated responses and were created using the R package 'ggplot2' (v3.4.2; Wickham, 2016). Figure 7 illustrates the medians of the ratings of prerequisites provided by coordinators and novices. The Friedman test was used to assess differences in the perceived importance of various

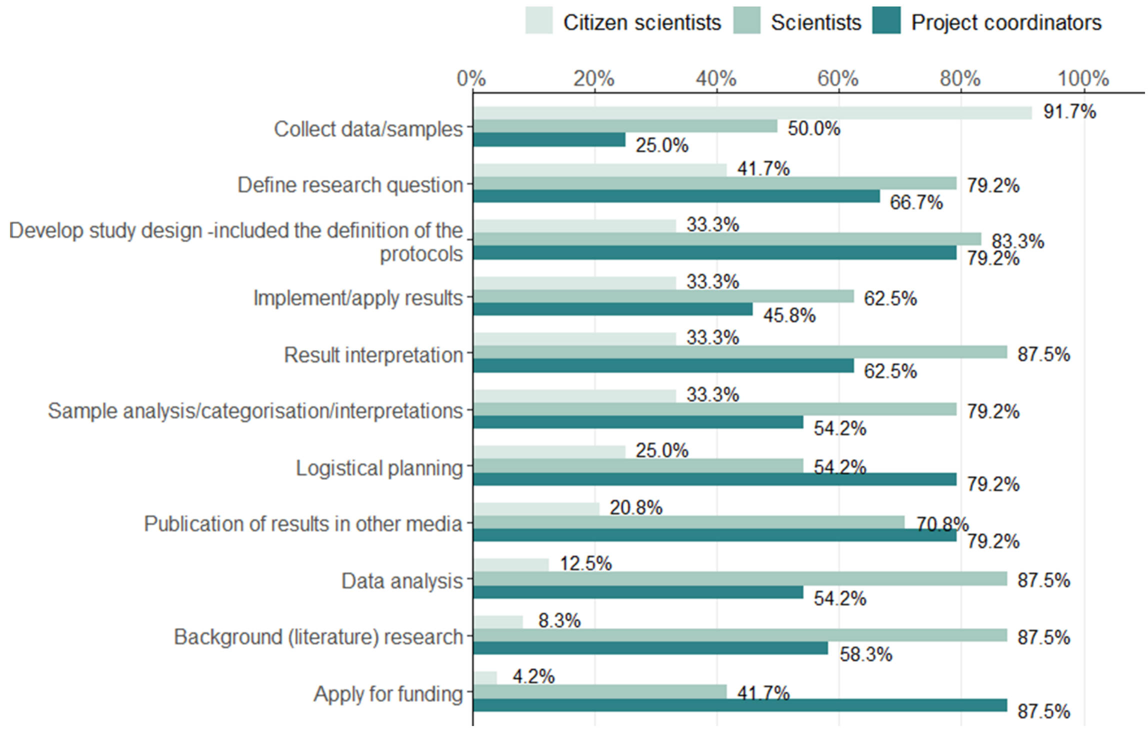

FIGURE 3 The tasks of citizen scientists, project coordinators and scientists in the citizen science projects ($n = 24$).

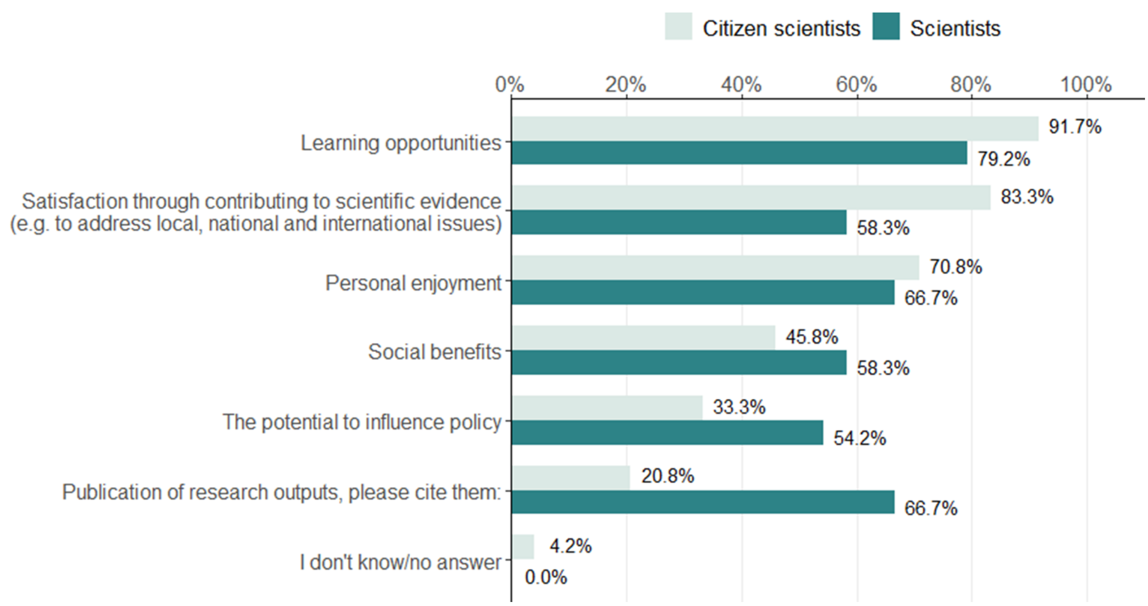

FIGURE 4 Benefits for scientists and citizen scientists in taking part in citizen science projects ($n = 24$).

prerequisites within their projects by coordinators and novices. Further pairwise comparisons using the 'pgirmess' package (v2.0.2, Giraudoux, 2023) revealed statistically significant distinctions. The Mann–Whitney *U* test was used to analyse whether there were significant differences in the perceptions of coordinators and novices regarding the importance of various prerequisites.

3 | RESULTS

3.1 | Survey respondents

A total of 106 views of our survey were registered, of which 58 were complete and 48 incomplete surveys. Two projects were filtered out because they did not focus on soil, leaving 56 questionnaires in the analysis.

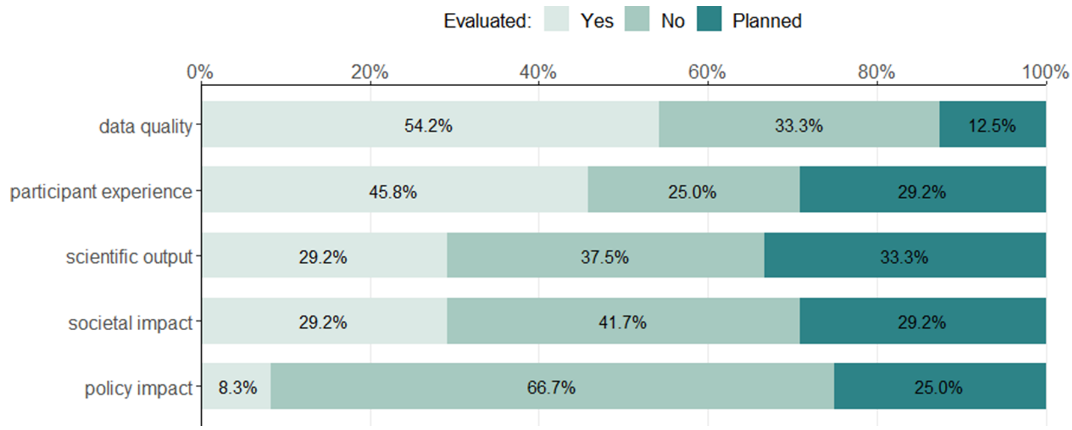

FIGURE 5 Reported evaluation of the citizen science projects by the coordinators ($n = 24$).

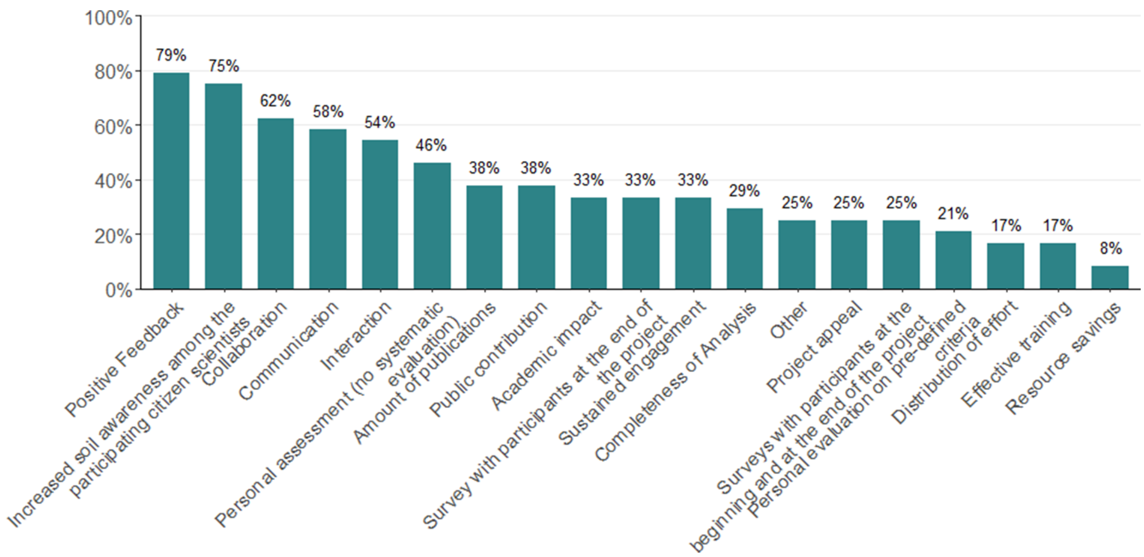

FIGURE 6 Reported ways to indicate the success of a project ($n = 24$).

Most of the respondents ($n = 56$) were members of a research institute (59%) or university/college (21%). Some were from business companies (4%), NGOs (4%) or governmental administrative offices (5%). Nearly all of the respondents reported being familiar with the concept of citizen science; only one respondent had never heard of the concept before. Less than half of the respondents (43%) reported having already participated in or (co-) organized a citizen science project: these are defined as citizen science coordinators. The other proportion, denoted as novices, had never participated in or (co-) organized such a project (57%).

3.2 | Description of the citizen science projects

The reported citizen science projects (Appendix SII) presented diverse characteristics. Approximately 90% of them involved Western European countries (France, United Kingdom, Belgium, the Netherlands and Ireland) ($n = 24$). National-scale projects represented 63%, local or regional-scale projects 17% and only 13% of the projects covered the whole of Europe. The budget for projects ($n = 24$) varied; 25% had a budget below 50,000 €, 45% had a budget between 50,000 € and 500,000 € and 30% had a budget exceeding 500,000 €. The projects were mainly funded by national research funding agencies (42%), followed by a foundation/NGO/association (33%) and national agricultural or environmental funding agencies (17%). Most of the projects were short, around 60% of them less than 3 years. The shortest project duration was 6 months and the longest 140 months (=11.5 years). The mean project duration was 46 months and the median 29 months ($n = 20$). The claimed reason for project completion was the end of the funding (87%) or the achievement of the scientific goals (27%). According to project coordinators ($n = 24$), most (58%) of the citizen science

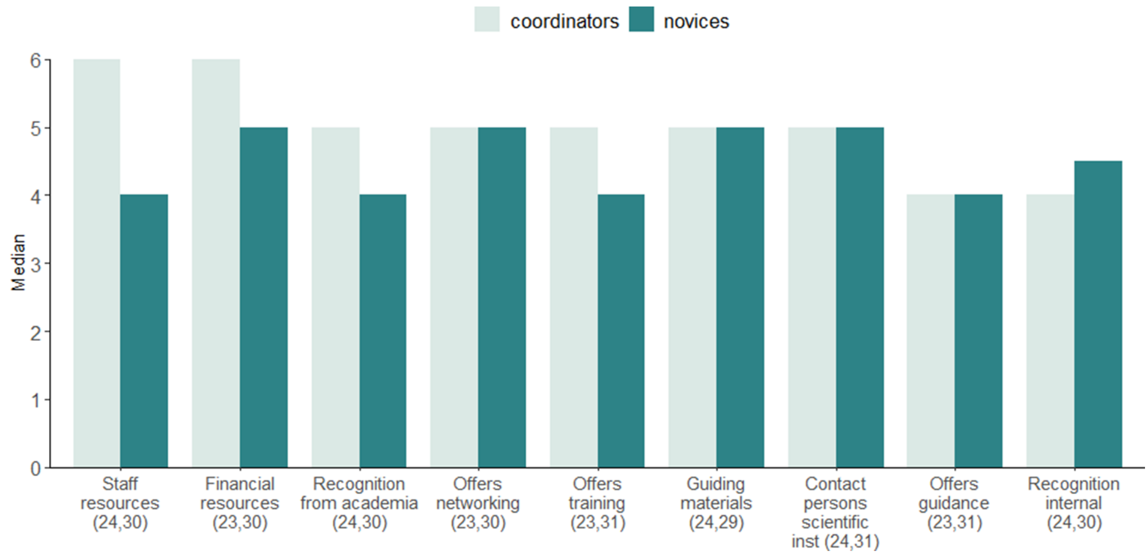

FIGURE 7 Important prerequisites (median score on a scale 1–6) reported for coordinators' citizen science work and for citizen science novices to conduct a citizen science project in the future (n indicates the number of respondents).

projects used a crowdsourcing approach, for which citizen scientists contributed only to the collection of soil data. Nearly 30% of the projects' participatory activities went further, that is, the citizen scientists contributed not only to data collection but also to defining research questions. The citizen scientists involved in these projects were farmers, students, teachers, citizens and gardeners.

Among all reported citizen science projects, 23 were named by the coordinators (Appendix SIII). The named projects formed three different clusters (represented in Figure 1) according to their attributes regarding the (i) geographic scope of the project, ranging from local to regional, national, European and global scale; (ii) project duration, that is, a limited duration or not; (iii) project budget, categorized as either 'under 100,000 € 'or 'over 100,000 € '; (iv) funding source for the project, including categories such as 'foundation/NGO/association', 'national research funding agency (RFA)', 'national agricultural or environmental funding agency (AEFA)', or 'European funding'; (v) level of citizen science: the level of citizen science activities envisioned by the project coordinators, categorized into two levels (level 1 + 2, which includes 'crowdsourcing' and 'distributed intelligence', and level 3 + 4, which includes 'participatory science' and 'extreme citizen science').

Cluster 1 consisted of 'National low-budget projects with a crowdsourcing approach'. Most of the projects here were at a national level (only one was local). There were no projects with a regional, European or global focus within this cluster. All projects had a budget under 100,000 €. No projects received funding from European sources. NGO associations or national funding sources were involved. Most of the projects were in the 'crowdsourcing' category. Cluster 2, 'European limited-term projects', consisted solely of European-scale projects. All projects had a limited duration, with budgets both under and over 100,000 €. All received funding from European sources. One project fell into Level 1 'crowdsourcing', while two projects fell into Level 3 'participatory science'. Cluster 3, 'Regional and national high-budget projects', did not include any local or European projects. Six projects had a limited duration, while four had an unspecified duration, suggesting potentially unlimited-term projects. All budgets exceeded 100,000 €. No European funding was involved, the primary funding sources consisted of NGO associations and national research funding agencies. Cluster 3 demonstrated an equal distribution of projects across different levels. Half of the projects were categorized as level 1 + 2, which includes 'crowdsourcing' and 'distributed intelligence', whereas the other half were categorized as level 3 + 4, which includes 'participatory science' and 'extreme citizen science'.

Over 66% of the projects ($n = 24$) generated soil biodiversity data (Appendix SIII). These projects included, for example, Earthworm Watch, Teatime4schools and Proof by Underpants, which used earthworm surveys, teabag decomposition and microorganisms entering the teabags, as well as pants decomposition to measure biodiversity, respectively. Approximately 54% and 42% generated vegetation cover and soil organic carbon data, respectively (Figure 2 and Appendix SIII). More than half of the projects studied urban gardening (58%), 42% croplands, 33% fruit and vegetables or grassland, 21% arboriculture and vineyards (Appendix SIV).

3.3 | Application of the 10 principles of citizen science

This analysis was performed based on the responses from citizen science coordinators and based on the 10 principles of citizen science (Table 1).

3.3.1 | Participation in citizen science projects

The first principle of citizen science as outlined by the ECSA (ECSA, 2015) is the citizens' involvement in scientific endeavour that generates new knowledge or understanding for them. In this review ($n = 24$), citizen scientists were mainly involved in the projects as data contributors (88%), collaborators (50%) or project (co-) leaders (13%). Regarding the project tasks, citizen scientists participated in different stages of the scientific process (fourth principle of citizen science) (Figure 3, $n = 24$). They mainly dealt with the collection of data and samples (92%), whereas the main tasks of project coordinators were applying for funding (88%), developing study design, publishing results and planning the logistics (all three 79%). Interpretation of the results (88%), analysis of data (88%) and background literature research (88%) along with study design (83%) concerned mainly scientists. Thus, the different tasks of the projects were generally not equally distributed (Figure 3).

The third principle of citizen science (Figure 4) ($n = 24$) illustrates the benefits for the citizen scientists taking part in the projects, which in our review was reported by the coordinators and ranged from learning opportunities (91%) and satisfaction through contributing to scientific evidence (83%), to publication of research outputs (21%). The reported benefits for the scientists ranged from learning opportunities (79%), personal enjoyment and publication of research outputs (both 67%), to the potential to influence policy (54%).

The fifth citizen science principle is citizen scientists receiving feedback from the project (ECSA, 2015). Over 75% of the citizen scientists ($n = 24$) received feedback through the project webpage, and over 58% through newsletters. Personal support, workshops and Facebook were mentioned at 54%, 50%, 50%, respectively.

In most projects (83%, $n = 24$), citizen scientists were acknowledged in the project results and publications (eighth citizen science principle; ECSA, 2015). The acknowledgements were carried out by several means such as sending emails to citizen scientists, organizing workshops, acknowledging in papers, websites and publications. One respondent also mentioned having the selected students as co-authors in papers. The reason stated for not acknowledging citizen scientists was that the results were not published yet. The acknowledgement was planned when results would become available.

3.3.2 | Citizen science projects' openness

The seventh citizen science principle states that citizen science project data and meta-data are made publicly available and, where possible, results are published in an open access format (ECSA, 2015). Most of the projects (58%, $n = 12$) had their results and meta-data published in an open access format; the remaining projects that had not been published yet in an open access format reported a plan to do so. Most of the projects' results ($n = 24$) were published on websites (79%), in reports (75%), social media (58%) and scientific peer-reviewed journals (38%). Flyer, radio and TV were not used as often for results dissemination (33%, 29% and 25%, respectively). Coordinators reported the intention to publish in scientific peer-reviewed journals for 58% of the projects. Some of the projects' research data and meta-data were entered into other databases (national or research infrastructure). The most reported databases were the Tea Bag Index Database (www.teatime4science.org), the SoilTemp database (www.soiltempproject.com), Jardibiodiv and INDORES.

The tenth citizen science principle states that 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 (ECSA, 2015). Most of the reported projects ($n = 24$) took into consideration confidentiality (92%), intellectual property (83%), data sharing agreements (79%) and environmental impact (79%).

3.3.3 | Citizen science projects' effectiveness

The second principle of citizen science is a genuine science outcome (ECSA, 2015). Examples of scientific outcomes of the reported projects were answering research questions such as the impact of soil sealing on soil functioning, or soil mapping of degraded soil and soil quality for management decisions or policymaking.

Citizen science is considered a research approach like any other, with limitations and biasesthat should be considered and controlled for (sixth citizen science principle; ECSA, 2015). In our review, coordinators identified 'project very time consuming' and 'funding temporary' as the main research challenges for the projects ($n = 24$).

The ninth citizen science principle states that projects are evaluated for their scientific output, data quality, participant experience and wider societal or policy impact (ECSA, 2015). In our review, around half of the projects were assessed in terms of their data quality (54%, $n = 24$; Figure 5), but less for participant experience (46%), scientific output and societal impact (both 29%). Less than 8% had evaluated their project for policy impact. Citizen science coordinators noted that data quality was strictly controlled by experts (scientists, thematic teams or specialized technicians).

3.4 | How to tap into citizen science potential?

Our research revealed how citizen science project coordinators indicated the success of their project ($n = 24$; Figure 6). Positive feedback from participants (79%), increased soil awareness among the participating citizen scientists (75%) and collaboration (63%) were the main key points of project success.

Citizen science coordinators and novices rated the given key factors for citizen science projects on a scale 1–6 with 1 as 'not important' and 6 as 'very important' (Figure 7). Coordinators ($n = 24$) reported 'more staff resources' as the most important key factor (median = 6) for citizen science work followed by 'more financial resources' (median = 6) and 'more recognition from academia for citizen science' (median = 5). Novices ($n = 31$) identified 'more financial resources' as the most important key factor to lead a citizen science project in the future (median = 5). 'Guiding materials for citizen science' was also reported as an important key factor (median = 5). All key factors listed in our survey were mentioned as required (or wished). Among coordinators, there was an overall significant difference in the perception of the importance of various prerequisites ($p < 0.0001$). Additional pairwise comparisons unveiled statistically significant differences, specifically between staff resources and guidance ($p = 0.017$), staff resources and internal recognition ($p = 0.001$), financial resources and guidance ($p = 0.023$), as well as between financial resources and internal recognition ($p = 0.002$). Among novices, there were no significant differences detected among the prerequisites. In the analysis of prerequisites, it was found that coordinators and novices exhibited significant differences in their perceptions of the importance of staff resources ($p < 0.001$) and financial resources ($p = 0.015$) using the Mann–Whitney *U* test.

Citizen science novices also shared their suggestions for improving citizen science in Europe. In general, novices noted that having a European mapping of soil citizen science would be helpful and interesting as a starting point for sharing experiences and best practices. Accessible open data and good cooperation were requested as well. Regarding networks on soil citizen science, novices highlighted their great interest in seeing collaboration improved between countries. They expressed the need to harmonize methods and to share approaches and outcomes. They wished for a long-lasting and self-supporting network.

4 | DISCUSSION

4.1 | European citizen science in a soil health perspective

Soil science projects carried out collaboratively with citizens can contribute to protecting and improving soil health (Head et al., 2020). The development of citizen science has been accompanied by an increase of citizen science projects on soils (Ranjard, 2020; Ranjard et al., 2022), as is evident in the 24 citizen science projects reviewed here. We dedicated our review to projects within Europe as the programme EJP SOIL is European. Among the 24 citizen science projects reported, 63% were national-scale projects and 13% covered the whole of Europe. To disseminate our survey widely outside of EJP SOIL, we used focal points of each countries from EJP SOIL consortium. They spread the survey within their countries. Furthermore, our review focused on agricultural soils, and citizen science projects on other types of soils such as forestry were not collected—limiting the number of projects treated. Citizen science projects addressing agricultural soils are scarce compared with those in the broader citizen science community (Ryan et al., 2018). From the 23 named citizen science projects we identified, three clusters emerged: (i) national low-budget projects with a crowdsourcing approach, (ii) European limited-term projects and (iii) regional and national high-budget projects. Pino et al. (2022) also recently reviewed soil citizen science projects. They identified three main trends: (i) projects that link soil to human health, such as those focused on lead or healthy soil for food; (ii) projects focused on awareness raising and education; (iii) projects focused on soil health and productivity, such as those designed to combat soil degradation and increase agricultural productivity. For agricultural soils, the projects we reviewed mainly focused on the latter two categories. All met these two trends, that is, educate and improve soil health.

Soil, compared to water and air, is still poorly monitored by citizen scientists mainly due to a lack of funding for soil monitoring (Fraisl et al., 2020; Head et al., 2020). Nonetheless, citizen science has a clear role to play in soil health monitoring (Head et al., 2020). Most of the projects reviewed here generated soil biodiversity data (Figure 2). Head et al. (2020) and Ranjard et al. (2022) observed a similar trend. It is relatively easy for citizen scientists to connect with organisms such as earthworms, which are relatively large and simple to find and observe without special equipment, making earthworms an ideal subject for projects (Burton & Cameron, 2021; Pocock et al., 2018). Our analysis revealed the availability of citizen science methods and toolkits appropriate for monitoring different aspects of soil biodiversity. Other generated soil health data in our review were vegetation cover and soil organic carbon, which are also related to biodiversity issues but go further towards soil conservation or climate change mitigation. The European Soil Observatory (EUSO) established a comprehensive dashboard containing indicators that present data on soil-related issues such as soil erosion, soil biodiversity, soil carbon, pollutant, soil nutrients, etc. (Panagos et al., 2022). Citizen science has an enormous potential to gather a wide range of site-specific data to contribute to the EUSO (Schillaci et al., 2022).

4.2 | Fulfilment of principles of citizen science

4.2.1 | Participation in citizen science projects

Our analysis of the answers given by the coordinators showed that the reported citizen science projects largely follow the 10 principles of citizen science. Citizen scientists were reported to participate in different stages of the scientific process, but to be mainly involved as data contributors (88%) in projects (1st and 4th principles; ECSA, 2015), as similarly observed by Turrini et al. (2018). To date, the dominant method for engaging citizens in scientific research has been the 'contributory' method, where citizens mostly collect and submit observational data (Phillips et al., 2019). In our review, 13% of the projects involved citizen scientists as project (co-) leaders. The citizen science community is beginning to explore and adopt 'collaborative' and 'co-creating' methods, where the public are not only involved in collecting data, but also in designing projects, analysing data and developing research questions (Robinson et al., 2018). Multiple benefits emerge with deeper involvement of citizens in scientific research, such as learning opportunities for citizens, increased public trust in research and more effective research outcomes (Bonney et al., 2016; Trimble & Berkes, 2013). This calls for an increased participation of citizens throughout the research process.

Learning opportunities was the main reported benefit for both citizen scientists (91%) and scientists (79%) (3rd principle; ECSA, 2015) in our review. Various studies have highlighted learning outcomes, including behaviour, motivation and self-efficacy, which result from citizen scientists' engagement in citizen science (Phillips et al., 2018; Schuttler et al., 2018). Being involved in such projects can contribute to gaining new knowledge and skills as well as increase scientific and environmental literacy (Forrester et al., 2017; Turrini et al., 2018). This is particularly important given that, until now, soil has been largely invisible to much of the population (Frelih-Larsen et al., 2018). To further foster learning opportunities, Roche et al. (2020) suggested that, prior to launching a citizen science project, coordinators and citizen science activity planners should take the time to align educational learning outcomes and the project's goals through a co-creational approach. Giving feedback from the project to citizen scientists (5th principle; ECSA, 2015) could also be a way to contribute to citizen scientists' learning opportunities. Good feedback brings multiple benefits, such as encouraging more participation (Robinson et al., 2018). Another way to show citizen scientists that their contribution is recognized is to acknowledge them in the results and publications (8th principle; ECSA, 2015). In most projects reported here (83%), they were acknowledged in the project results and publications. For example, Daebeler et al. (2022) included high school students as co-authors in a scientific publication for their active involvement and scientific input.

4.2.2 | Citizen science projects' openness

The seventh and tenth citizen science principles relate to data sharing (ECSA, 2015). In our review, all reported projects had either their results and meta-data published in an open access format or reported planning to do so. Projects with data open to the public allow participants to use the data collected in the project for their own benefit, as well as make the findings from the project available to the interested public and scientific community. This increases the power to benefit society through use and reuse of the collected data in another research project (Cooper et al., 2021). Therefore, openness is key when it comes to citizen science projects (Albert et al., 2021; Heigl et al., 2019). Public authorities have implemented open data policies to make extensive amounts of information available to all who wish to search through, process and analyse it (Mazumdar et al., 2018). Most of the projects reported here considered data sharing agreements (79%). At the European level, open access publishing is already a requirement under Horizon 2020 and Horizon Europe, the EU research and innovation funding programmes from 2014 to 2020 and from 2021 to 2027, respectively (European Commission, 2016, 2017; European Commission, 2021). However, open access is not always a systematic requirement for nationally or regionally founded projects. Indeed, many such projects are not EU projects and are not yet required to publish open access. Even so, citizen science supports open science and many resources are available for project coordinators on this topic from the wider citizen science community. This includes the working group on citizen science and open science from the European Citizen Science Association (www.ecsa.ngo/working-groups/citizen-science-and-open-science). Towards this end, Fantappiè et al. (2021) recently elaborated an improved draft agreement for soil data sharing among EJP SOIL partners and the European Soil Data Centre that could also be used in citizen science projects. That agreement consisted of a list of the best suggested practices.

A few challenges remain towards open science. First, citizen science projects must protect the privacy of participants by informing them about potential threats and implementing safeguards (Bowser et al., 2014). Careful attention to data protection is essential. Complying with data protection laws is a legal requirement, such as the GDPR (Pierce & Evram, 2022). Secondly, making data open to the public implies additional costs such as the costs of publishing in an open access journal, or the costs of maintaining a webpage presenting the results and meta-data of a project. Finally, it is still being debated whether data that are open to the public should be reused without obtaining explicit consent from the citizen scientists. There is a clear contradiction between the ideals of openness and accessibility that citizen science encourages and participants' data protection (Suman & Pierce, 2018).

4.2.3 | Citizen science projects' effectiveness

Citizen science projects are an important tool for engaging the public in scientific research and for increasing scientific literacy (Bonney et al., 2009). Such projects have been shown to have a positive effect on science, society, economy, environment and individual participants (Heigl et al., 2019; Somerwill & Wehn, 2022). Science outcomes from these projects were reported in our review (2nd principle; ECSA, 2015): 58% of the newly generated knowledge was planned to be published in scientific peer-reviewed journals. The number of peer-reviewed publications stemming from citizen science projects is growing rapidly year by year (Follett & Strezov, 2015; Pocock et al., 2017). The same trend is observable for soil citizen science projects. When crossing the keywords 'soil' and 'citizen science*' in the Web of Science (consulted on 7 March 2023), two-thirds of the 191 listed publications have been published in the past 2 years. The success of citizen science projects depends heavily on the ability to achieve and maximize the science outcomes. Without significant scientific outcomes, the trust of citizens in the project and the motivation to participate can erode (Robinson et al., 2018).

Despite the potential of citizen science projects, their impact is often difficult to measure and evaluate. In many cases, such evaluation fails to capture the full extent of the positive impact of citizen science due to limited resources for evaluation. To ensure that projects are effective, they must be evaluated for their scientific output, data quality, participant experience and wider societal or policy impact (9th principle; ECSA, 2015). Recently, the number of scientific articles and requests for assessing the impact of citizen science projects has increased (Schaefer, Kieslinger, Brandt, & Van den Bogaert, 2021). For example, the MICS project developed a state-of-the-art tool for assessing impact in five areas: society, the environment, the economy, governance and science and technology (Wehn et al., 2021). In our review, 29% and 8% of the reported projects here were evaluated for their societal and policy impact, respectively, whilst there is a high demand for proof of societal and policy impact of citizen science practices in certain countries, for example, in Germany (Perelló et al., 2021). Those authors expected the demand to expand to other countries in the future. Societal and policy impacts are equally crucial as scientific output and participant experience because citizen science projects could make a noteworthy contribution to establishing and implementing policies (Nascimento et al., 2018). For example, the citizen science project on insect biomass trends in Germany (Hallmann et al., 2017) has led to the adoption of the new German Insect Protection Law (BMUV, 2019). In another example, in Ghana, data on beach litter from citizen science project have been integrated into the official monitoring of an SDG indicator (Fraisl et al., 2022). According to Von Gönner et al. (2023), citizen science project coordinators should strive to make an impact on society and politics by getting involved with decision-makers early on and ensuring that their plans are aligned with ongoing policy processes. Data quality impact, however, was more often and more easily measured. Around half of the reported projects were assessed in terms of their data quality, which shows there is still room for improvement before the inclusion of citizen science data can be easily incorporated into existing databases (INSPIRE, 2013). Soils are still often unknown, which makes high-quality measures difficult. This makes expertise particularly important. In our review, data quality was reported to be strictly controlled by experts (scientific, thematic team or specialized technicians). Ensuring data quality in a citizen science project enhances the reputation of the project (Balázs et al., 2021). Data sets produced by citizen scientists can be of very high quality (Kosmala et al., 2016). To ensure such quality, more resources are required such as time, skills, investing in technology and gathering participants who can help with the process (Balázs et al., 2021). Engaging with authorities, namely with policymakers and scientists, is used to strengthen the creditability of data quality (Ekström, 2023). CS data benefit from the application of the FAIR principles—Findability, Accessibility, Interoperability and Reusability (Wilkinson et al., 2016). The application of the principles guides citizen scientists and CS coordinators when using CS data. When these principles are applied, in addition to respecting the 10 principles of citizen science, the chance is highest of not misusing data. For example, at the Austrian Citizen Science Platform, Österreich forscht, all presented projects need to fill in a questionnaire about their project, including questions about data quality, before being accepted to the platform.

In our review, some of the reported projects' research data and meta-data were entered into other databases (national or research infrastructure), such as the Tea Bag Index Database or the SoilTemp database. It is easier to integrate CS data into already existing databases (Sandén et al., 2021). CS data could be, for example, integrated into the EUSO, or into national soil monitoring databases. In 2023, the EC published the proposal for a 'Directive of Soil Monitoring and Resilience' referred to as the 'Soil Monitoring Law' (EC, 2021). The framework would create a common database integrating data from EU-level and member states. The 'Soil Monitoring Law' could be an opportunity to also integrate CS data to the common database. There could be a national CS representative responsible to integrate CS data to the common database, like there are national contacts to ensure that data is fulfilling INSPIRE guidelines (INSPIRE, 2013). One or more persons like this could, for example, be chosen from the national soil mission action groups or national citizen science networks that already exist in many European countries (as described in Section 4.3). By incorporating citizen science data into existing databases, the data automatically needs to go through the same rigorous data quality checks as any data entering that particular database. Standards also need to be implemented, that is, rules (format and meaning) by which data are described, recorded and exchanged. Throughout the entire data collection process, it is crucial to exert diligent endeavours to ensure standardized data such that they can be incorporated into long-term databases (Smith et al., 2022), such as for LTER research infrastructures (Holzer & Orenstein, 2023). Depending on which database the citizen science data would be incorporated, would indicate the requirements for the process. In addition, new technologies, such as artificial intelligence, are an opportunity to integrate data from multiple information sources in a common analytical framework (Ceccaroni et al., 2023).

4.3 | How to tap into soil citizen science potential?

Our findings show that soil citizen science projects aligned with the 10 principles of citizen science offer an unexploited resource for European soil research. In addition, we raise success factors for further citizen science development on agricultural soils.

First, in our review, citizen scientists were reported to participate in different stages of the scientific process and to be involved in citizen science projects as data contributors (88%), collaborators (50%) and project (co-)leaders (13%). Collaboration (63%) was also indicated by coordinators as a key success factor, and previous research has revealed this to be one of the opportunities for real transformation power at a societal level of citizen science (Turrini et al., 2018). The citizen science community is starting to explore and adopt 'collaborative' and 'co-created' methods (Senabre Hidalgo et al., 2021), where the involvement goes beyond mere data collection. When farmers and researchers join forces and develop and implement research projects over the long-term, they create a winning combination that can lead to sustainable behaviour change (Lobry De Bruyn et al., 2017). There is a need to further promote co-creation to bring together citizens (such as farmers), politicians and scientists throughout the research process (Leino & Puumala, 2021), ultimately leading to policy outcomes (Criscuolo et al., 2023). To bridge this gap, the concept of Living Labs and Lighthouses was put forward by the European Commission through the EU Mission 'A Soil Deal for Europe' (EC, 2021). Living Labs and Lighthouses can be key instruments for stakeholder engagement in participatory science. These approaches can connect researchers, farmers, advisors, citizens and politicians to create solutions with real effects as well as spread existing sustainable practices (Veerman et al., 2020). Research conducted in Living Labs and Lighthouses can contribute to the EU Mission's goal to 'ensure that 75% of soils are healthy by 2030 and are able to provide essential ecosystem services', thus, making a true societal impact.

Secondly, citizen science novices highlighted their great interest in seeing knowledge sharing improve between countries, for example, the need to share citizen science approaches and outcomes, as well as having a long-lasting and self-supporting citizen science network. Platforms for citizen science have been set up to showcase the range of projects available. Platforms offer access to national citizen science networks that seek to promote citizen science in certain countries such as Germany (Bürger schaffen Wissen, n.d.), Australia (Atlas of Living Australia, n.d.), Switzerland (Schweiz forscht, n.d.) and Austria (Österreich forscht, n.d.) (Liu et al., 2021). Some national platforms are tailored to a particular topic, such as the platform in France dedicated to biodiversity (OPEN Sciences Participatives, n.d.). Additionally, there are cross-national platforms such as one with projects from both the Netherlands and Belgium (Iedereen Wetenschapper, n.d.). At a European level, EU-Citizen. Science (n.d.) is an online platform established to share useful resources related to citizen science, such as tools and guidelines, best practices and training modules. Furthermore, some citizen science networks also provide the opportunity to collaborate in working groups on particular issues, such as 'legal aspects of citizen science' or 'citizen science in schools'. These groups involve a variety of stakeholders. Their purpose is to advance the aims of citizen science networks by sharing resources, best practices and relevant information among members and throughout the wider citizen science community. Ensuring that participants remain involved in these working groups brings advantages not only to the network but also to each individual participant (Liu et al., 2021). Fostering knowledge sharing through citizen science networks is therefore a second success factor for citizen science development on soils. The successful implementation of citizen science network at a national level generally requires strong commitment from citizens (Schaefer, Kieslinger, & Fabian, 2021).

Finally, another success factor is enabling long-term communication and commitment with citizens. From recruiting participants, to keeping them engaged and motivated, effective communication between scientists and project participants is essential for any citizen science project (Hecker & Taddicken, 2022; Vattakaven et al., 2022; Veeckman et al., 2019). Rüfenacht et al. (2021), however, described communication as one of the main challenges for citizen science projects. Druschke and Seltzer (2012) highlighted the importance of considering the perspectives and needs of participants, as well as of maintaining active communication between scientists and project participants. De Vries et al. (2019) recommended those creating and leading citizen science projects to be mindful that participants value communication regarding information on their collected data, findings of the project and publications. Successful communication will enhance participants' motivation to engage in the project and ensure their long-term commitment (De Vries et al., 2019). Pino et al. (2022) observed an increase in community engagement in various soil citizen science projects. The TeaComposition project is an example of increased community engagement: the number of schools engaged increased from seven in the first year of the project to 50 after 4 years (Pino et al., 2021). Citizens participating in long-term projects are more likely to develop a sense of responsibility and act towards preserving the environment than those working on shorter-term projects (Hansen & Bonney, 2022). Therefore, future citizen science projects will gain from a deeper understanding of the factors that influence and limit people's motivation for long-term commitment (Phillips et al., 2019). Furthermore, in our review, 'project very time-consuming' and 'funding temporary' were identified as the main challenges for the projects ($n = 24$). The claimed reason for project completion was the end of the funding (87%). More funding is therefore needed. This would enhance the number of involved staffs in the scientific community needed to coordinate and implement projects, create networks and partnerships with citizens.

5 | CONCLUSIONS

Soil is a common good, so is knowledge. Citizen science can contribute to soil knowledge. This review highlights past and current citizen science projects on agricultural soils, relating them to the 10 principles of citizen science. The 23 named citizen science projects focusing on agricultural soils identified here revealed 3 clusters: (i) national low-budget projects with a crowdsourcing approach, (ii) European limited-term projects and (iii) regional and national high-budget projects. Our findings show that soil citizen science projects aligned with the 10 principles of citizen sciences offer an unexploited resource for European soil health research. Promoting co-creation, fostering knowledge-sharing networks and enabling long-term communication and commitment with citizens are success factors that will help tap into this resource and further promote citizen science involvement with soils. Further developing this research approach will require human resources and funding.

AUTHOR CONTRIBUTIONS

Taru Sandén: Conceptualization; formal analysis; investigation; methodology; project administration; resources; supervision; validation; writing – original draft; writing – review and editing. **Eloise Mason:** Investigation; writing – original draft; methodology; validation; writing – review and editing; formal analysis; project administration. **Chantal Gascuel-Odoux:** Conceptualization; formal analysis; investigation; methodology; project administration; supervision; validation;

writing – original draft; writing – review and editing. **Ulrike Aldrian:** Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing – original draft; writing – review and editing. **Hao Sun:** Data curation; formal analysis; validation; visualization; writing – original draft; writing – review and editing. **Julia Miloczki:** Conceptualization; methodology; validation; writing – original draft; writing – review and editing. **Sophia Götzinger:** Conceptualization; investigation; methodology; writing – review and editing. **Victoria Burton:** Formal analysis; validation; writing – original draft; writing – review and editing. **Froukje Rienks:** Formal analysis; validation; writing – original draft; writing – review and editing. **Sara Di Lonardo:** Formal analysis; validation; writing – original draft; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from https://doi.org/10.57745/LZBPTC or from the corresponding author upon reasonable request.

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