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Citizen science and the nexus approach: unlocking synergies for sustainable development

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Abstract

This article explores how citizen science can contribute to achieving the United Nations (UN) sustainable development goals (SDGs) by focusing on the complex and sometimes interrelated nature of sustainability challenges. Citizen science presents a unique opportunity to ethically engage communities in research by actively involving them in defining sustainability targets, gathering data, and analysing results, thereby generating actionable insights that directly inform both local and global sustainability efforts. The authors advocate for integrating citizen science with the nexus approach to environmental resources management, which examines the interrelatedness and interdependencies that are inherent within complex systems, emphasising the relationships among water, energy, and food systems. The nexus approach proposes strategies to enhance the role of citizen science in addressing sustainability challenges. These include strengthening collective interaction and knowledge exchange between the five subsystems described by the quintuple helix innovation model, namely policy, science, industry, society and environment. The article also highlights the importance of inclusive participation, co-defining localised sustainability indicators, and co-creating citizen-led actions. By empowering communities to engage in participatory knowledge production and promoting multi-actor collaboration, citizen science not only has the potential to contribute valuable data to monitoring progress on the SDGs but also to help deliver on the UN's pledge to 'leave no one behind.' Ultimately, creating an inclusive environment for the participation of diverse societal actors in nexus-oriented research and innovation can unlock the full potential of citizen science in advancing the SDGs and ensuring a sustainable future.

Keywords Citizen science · Sustainability · SDGs · Nexus

1 Introduction

The *sustainable development goals* (SDGs) set forth by the United Nations represent an ambitious roadmap for a sustainable and equitable future. The SDGs are interconnected because they address complex, global challenges. Actions taken to achieve one sustainability goal may influence progress on other social, economic, political, and environmental dimensions, either positively or negatively. Therefore, addressing the SDGs in isolation is neither suitable, nor recommended (Davies et al. 2024; Fronza et al. 2023; Pradhan et al. 2024). Understanding and achieving these interconnected goals often requires a thorough understanding of the context (Gharesifard et al. 2019; Pham-Truffert et al. 2020), and an appreciation of the role of interested parties and actors in the quintuple helix model, which involves the collaborative interaction of science, policy, industry, society, and the environment in driving sustainable innovation (König et al. 2020).

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For example, clean water and sanitation (SDG 6) are essential for food security (SDG 2), good health (SDG 3), and decent living conditions (SDG 11). Therefore, water quality is related to the competing goals of improving the environment, human health and food production. Agriculture remains the primary consumer of freshwater globally, accounting for approximately 70% of total water use (UN 2024b). As countries strive to increase food production, they often expand irrigation and other water-intensive agricultural practices, potentially leading to heightened water consumption, strain on water resources, depletion of aquifers, and pollution of water bodies through the use of fertilisers and pesticides, thus undermining the aims of SDG 6.

Another example is clean air, which is essential for good health (SDG 3) and sustainable cities (SDG 11), as well as climate action (SDG 13). Poor air quality can significantly impact human health and well-being, while also affecting productivity and economic stability. Urbanisation and increased vehicle emissions are significant contributors to air pollution, and as cities expand, the demand for transportation intensifies, potentially leading to greater emissions and health risks, thereby undermining the objectives of SDG 3.

According to the Sustainable Development Goals Report 2024 (UN 2024a), data challenges pose a significant obstacle to effective monitoring and achievement of the SDGs. While data coverage has improved significantly, with 68% of indicators now having good coverage and all 231 indicators using internationally agreed methodologies, some areas like gender equality, climate action, and peace still suffer from major shortfalls. Additionally, about one-third of the indicators lack recent data from the past three years, limiting timely decision-making (U, 2024a). The primary sources of data for identifying SDG interlinkages are official databases, and sometimes scientific literature (Bennich et al. 2020; Fronza et al. 2023). These data sources don't always fully capture local nuances and context-specific challenges. Local issues such as community-specific access to services or health disparities are sometimes not well-reflected in these broad indicators, leading to gaps in understanding and misaligned policy responses.

Irwin (1995) highlights that sustainable development depends on informed public support, strengthened roles for key stakeholders, and a balance of local, global, citizen-driven, and state-led efforts. Citizen science, understood as various forms of public participation and collaboration in scientific research (Haklay et al. 2021), presents a pivotal opportunity for addressing these data challenges, understanding local contextual realities, and mobilising communities and other interested parties and actors in the achievement of the SDGs. Involving citizens in various stages of scientific research, including identifying problems, collecting and analysing data, and collaboratively interpreting results, allows for a better understanding of complex societal and environmental challenges, and promotes more effective and inclusive solutions.

Community members can play an instrumental role in uncovering local interlinkages by highlighting how social, ecological, and environmental factors interact. For instance, in urban areas, citizen-led air quality monitoring can reveal how traffic emissions (an environmental factor) disproportionately impact lower-income neighbourhoods, leading to health issues like asthma while also limiting outdoor activities and potentially affecting local economies. This grassroots data collection sheds light on the trade-offs between urban development and public health, which may not be visible at broader scales. By engaging local communities in identifying both the interlinkages and potential actionable approaches, citizen science helps bridge gaps between local realities and broader sustainability efforts, empowering communities to contribute to the achievement of the SDGs—particularly Goal 3 (Good Health and Well-being), Goal 11 (Sustainable Cities and Communities), and Goal 13 (Climate Action)—in a way that reflects their lived experiences.

Despite the growing recognition of the impacts of participatory research practices, research at the intersection of citizen science and the SDGs is still in its early stages (Fritz et al. 2019), and the potential for citizen science contributions to the underlying target indicators was first fully analysed in 2020 (Fraisl et al. 2020). Existing studies primarily highlight how citizen science contributes to tracking individual goals and indicators, and measuring direct progress toward their achievement (Fraisl et al. 2020; Parkinson et al. 2022), but often overlook the interconnections between sustainability goals.

This article explores how citizen science addresses the complex interconnections between SDGs using the nexus approach, emphasising its role in filling data gaps and uncovering synergies and trade-offs. It also provides recommendations for enhancing the impact of citizen science through local engagement, policy integration, and the development of context-specific sustainability knowledge.

2 Pathways of impact of citizen science on sustainability research

Citizen science is commonly recognized for its impact on the SDGs through **two main pathways**, namely enhancing the official monitoring of the goals and directly contributing to the achievement of the goals (Fraisl et al. 2023b; Parkinson et al. 2022). Citizen science can play a critical role in addressing the data gaps present within the resources nexus in particular, where the interconnectedness of systems such as water, energy, and food can cause actions in one area to influence outcomes in others (Estoque 2023; Kurian 2017; Liu et al. 2018). These interdependencies are frequently

overlooked due to a lack of localised, fine-scale data, presenting an opportunity for citizen science to fill this gap and provide insights into these interconnections by enabling communities to monitor and collect data on, for instance, resource usage at the local level. Engaging citizens in monitoring agricultural water usage not only supports SDG 6 (Clean Water and Sanitation) but also contributes to SDG 2 (Zero Hunger) by helping farmers manage water resources more efficiently. These local insights are indispensable for designing policies that consider the trade-offs and synergies between water, energy, and food systems.

There is also a **third pathway** that has received far less attention in current research, namely helping define SDG targets and indicators at a more local level. As highlighted by The Stockholm Environment Institute in 2017, citizen science can help make the goals more relevant to people's lived experiences, and contextualise the targets, such as defining what "affordable" and "reliable" mean in access to energy services, by connecting global goals with local realities (West and Pateman 2017). Engaging the public in this process not only refines national targets to better reflect diverse needs but also encourages accountability, helping governments to develop and implement more effective strategies, and encouraging citizens to co-create innovative local solutions.

2.1 Fostering a more democratic and inclusive approach to policy-making

Citizen-generated data is not only crucial for addressing contemporary data challenges, particularly where geographic and temporal gaps remain (Alfonso et al. 2022), but it also fosters a more democratic approach to policy making (Fraisl et al. 2023a; Irwin 1995). Encouraging a more inclusive process of data collection promotes fairness, openness, accountability, and transparency in public policy and resource management, all of which are crucial for living up to the pledge to 'leave no one behind' (Long 2018). Additionally, citizen engagement in other aspects of environmental resource management and policy-making processes can bring about broader societal changes alongside the produced data (Oudheusden et al. 2024). Nevertheless, to maximise the impact of citizen science in addressing global challenges such as achieving the SDGs, additional work is needed to enable and support citizen science and to better align data and policy-making (Sherbinin et al. 2021).

According to the recent Copenhagen Framework on Citizen Data (UNSD 2024), the three main considerations in defining citizen(-generated) data are: (1) levels of citizen participation, (2) type of initiative, and (3) stages of the data value chain. They define the level of citizen participation according to Arnstein's ladder of participation (Arnstein 1969), whereby the top three rungs—partnership, delegation of power, and citizen control—are considered to be 'sufficient'. The type of initiative indicates the initiators and the level of collaboration. It can range from initiatives with minimal or tokenistic engagement to civic action initiatives that are fully driven and owned by citizens, communities, or civil society organisations. The data value chain illustrates the journey of data from collection and analysis to dissemination and its final impact on decision making.

2.2 Mapping citizen science contributions to the SDGs

Research on the contribution of citizen science to the SDGs has so far focused on either **mapping the areas of potential contributions**, or has adopted a case-based and often disciplinary perspective to demonstrate **specific contributions of citizen-generated data to sustainability goals or indicators**. However, it is also highly important to think about the broader societal changes that citizen science can bring besides the produced data, while also acknowledging the various ways and levels in which citizens participate (Oudheusden et al. 2024).

Citizen-generated data can fill in gaps in traditional data sources for monitoring and implementing the SDGs, particularly where monitoring is infrequent or lacks spatial coverage. This is especially important for Tier III indicators for which no established monitoring methodology or standard has been identified or agreed upon (Fritz et al. 2019). A study by Fraisl et al. (2020) mapped the data sources underpinning each of the 244 SDG indicators and identified those where citizen science approaches can provide or enhance data for monitoring progress. The study highlights seven goals in particular that benefit directly from citizen-generated data, namely SDG 3 (Good Health and Well-being), SDG 4 (Quality Education), SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land).

By mapping specific citizen science projects to the indicators underpinning these goals, the authors highlighted the versatility and broad applicability of community-driven data collection for filling in critical gaps in official statistics or providing proxy indicators where no data source has yet been agreed on (Tier III). This mapping exercise underscores the essential role of citizen science in advancing the global sustainability agenda. In a similar exercise, Schleicher and Schmidt (2020) examined 127 citizen science projects showcased on the German platform 'Bürger schaffen Wissen'. Through a qualitative content analysis of the project descriptions, they discovered that 12 of the 17 SDGs were addressed by at least one of the projects. A more recent mapping study highlights that citizen science could significantly contribute to monitoring health and well-being-related SDGs and the

WHO's Triple Billion Targets (WHO 2019), with potential applications for 48 out of 58 indicators (Fraisl et al. 2023b).

Various publications provide examples of specific contributions of citizen-generated data to individual sustainability goals or indicators. Some examples include, Quinlivan et al. (2020), which focuses on understanding how citizen science can contribute to monitoring SDG Indicator 6.3.2 "proportion of bodies of water of good ambient water quality". Wuebben et al. (2020) examine how alliances between citizen science and energy communities could contribute to achieving SDGs 7 (Affordable and Clean Energy), 11 (Sustainable Cities and Communities), 13 (Climate Action), and 17 (Partnerships for the Goals). Kral et al. (2020) collaborated with local farmers on an island in the Java Sea to investigate how increased citizen participation could aid in advancing the goal of Zero Hunger (SDG 2). Fraisl et al. (2023a) showed how Ghana became the first country to incorporate citizen science data on marine plastic litter into its official monitoring and reporting for SDG indicator 14.1.1b. In doing so, the country successfully connected local data collection efforts with global monitoring processes and policy frameworks, using the SDG framework to enhance both local and international environmental agendas. Another example is Loghmani-Khouzani et al. (2024), in which a systematic literature review demonstrates that citizen science can support agri-food-related SDGs such as Zero Hunger (Goal 2), Clean Water and Sanitation (Goal 6), and Responsible Consumption and Production (Goal 12).

3 Identifying interdependencies with the help of citizen science

System interdependencies and feedback loops are two key concepts in nexus studies. System interdependencies refer to the interconnectedness between different resources, such as water, energy, and food, where changes in one system often affect the others (Zhang et al. 2018). Feedback loops describe the cyclical relationships where actions in one domain can trigger responses in another, creating reinforcing or balancing effects (Groundstroem and Juhola 2021). The integration of citizen science with the nexus approach offers significant benefits in understanding and addressing both system interdependencies and feedback loops in sustainability challenges.

Community members can play a crucial role in complementing and validating current SDG monitoring practices by statistical offices and government agencies. They can collect data that highlight the interconnections between systems such as water, energy, and food at the local level. This data collection can be related, for example, to monitoring water usage in agriculture (nexus of water and food), energy consumption patterns (nexus of energy and water), or impacts of agricultural practices on local ecosystems (nexus of food and environment).

Policy makers can use such data to better understand trade-offs and synergies. For example, data on water usage and agricultural practices can help in creating policies that balance water conservation with food production. Citizen science projects can both facilitate learning from the local communities and educate the public about the interconnected nature of sustainability issues. This encourages a broader understanding of how actions in one area affect others, facilitating behaviour change and encouraging sustainable practices.

3.1 Examples from the practice of citizen science

An example is deploying citizen science approaches to encourage public acceptance of refined wastewater reuse in agriculture, as encouraged by the EU Water Reuse Regulation of 2022 (For more details see: Berti Suman et al. 2023; Berti Suman and Toscano 2021). Such community-based approaches can lead to more efficient use of natural resources, benefiting both local ecosystems and agricultural productivity.

In urban contexts, where dense populations exert significant pressure on finite resources, understanding interconnections between different sustainability goals is especially critical. Cities account for the majority of global resource demand, and their concentrated consumption patterns have far-reaching environmental, social, and economic impacts. Approaches such as the urban metabolism framework provides a way to analyse these complex flows by critically examining the interrelated consumption of energy, water, and food within cities (Pincetl et al. 2012).

Nevertheless, such models often struggle to capture the variability of resource use across diverse communities. This is where citizen science becomes invaluable, as it enables residents to track their own resource consumption and environmental impacts. By generating localised data, citizen science enhances the accuracy of urban resource management systems, ensuring that policies are more responsive to the unique needs of different areas within a city.

3.2 Key considerations: inclusivity and institutional support

Inclusivity at all levels is essential for effectively balancing the trade-offs among interconnected natural resource management systems. Montanari et al. (2021) highlight the importance of making citizen science projects accessible to diverse populations and actors, aligning with the UN pledge to "Leave no one behind". The nexus approach aligns well with this as it promotes connectivity across sectors, and interested parties and actors, ensuring they are all included

in critical resource management decisions that cut across water, food, and energy.

Institutional support and infrastructure are essential for the sustainability of citizen science initiatives. Moczek et al. (2021) stress the need for creating interfaces between citizen science projects and official databases, providing adequate funding, and reducing bureaucratic hurdles. Despite efforts to integrate citizen science into official monitoring systems, progress remains slow, with challenges including bureaucratic hurdles and limited funding. In the context of the nexus, this requires robust multi-sectoral data integration frameworks and coordination among water, energy, and food management actors.

3.3 Challenges of integration

Despite its potential, integration of citizen-generated data into the resources nexus faces several challenges. Ensuring the reliability and accuracy of data collected by non-professional scientists remains a key concern. Capdevila et al. (2020) emphasise the importance of rigorous quality control measures, standardised methodologies, and thorough training for participants to enhance the credibility of citizen-generated data. This is especially crucial given the interlinkages between resources such as water, energy, and food systems, where inaccuracies of observations in one domain can create cascading effects in others.

Established practices, limited cross-disciplinary expertise, and a siloed approach to sustainability can impede the development of citizen science projects designed to explore the synergies and trade-offs among SDGs. To address these challenges, it is crucial to promote the creation of interdisciplinary projects that encompass various sectors. Furthermore, equipping project initiators with the resources and training needed to transcend disciplinary boundaries will facilitate a more collaborative and holistic approach to sustainability.

Assessing the impact of citizen science projects is inherently challenging, especially when considering SDGs within a broader, global context (Sprinks et al. 2021; Wehn et al. 2021). Many of the SDGs involve long-term objectives, and contributions from citizen science projects may take years to materialise. The literature also points to the challenges of analysing SDG interlinkages due to data gaps and methodological limitations (Fronza et al. 2023; Ospina-Forero et al. 2022). For instance, qualitative methods such as semantic analysis can offer insights into potential synergies or trade-offs, but they often lack the context-specific details needed to inform decision-making (Fronza et al. 2023). Similarly, statistical correlation analyses may fail to capture the directionality or causality of these interlinkages, limiting their use in policy contexts (Smith et al. 2021).

Citizen science can help address this need by offering local insights about these interlinkages, complementing top-down, global datasets. Yet, capturing long-term impacts remains difficult, as SDG-related outcomes often manifest over timeframes that exceed the typical lifespan of citizen science projects, particularly in areas such as biodiversity conservation or climate resilience.

4 Recommendations for enhancing citizen science contributions to the SDGs

To maximise the potential of citizen science in advancing the SDGs and studying the interconnections and trade-offs between different sustainability goals, several strategies can be implemented.

(1) **Re-imagine the role of citizen science in relation to SDGs** Citizen science projects should not only focus on their contribution to monitoring progress toward individual SDGs but also explore the synergies and trade-offs between them. For example, local citizen science data on water use can inform the nexus of water, food, and energy, providing a more holistic approach to sustainability. To achieve this, citizen science projects should focus more on identifying local interconnections between goals and how actions in one area affect others, bridging gaps between global targets and local realities. Greater emphasis must also be placed on capturing locally-relevant contextual insights that may help explain the extent of achievement of the SDGs on a global scale.

(2) **Co-create local sustainability targets and indicators** There is a pressing need to concentrate on the less-explored pathway for enhancing the impact of citizen science projects: the development of localised targets and indicators. By co-creating context-specific metrics that resonate with local communities, a robust framework can be created for monitoring progress that ultimately feeds into the broader objectives of the SDGs. This approach not only encourages community engagement and ownership but also allows for more accurate and relevant data collection that reflects the unique challenges and opportunities within specific locales.

(3) **Strengthen partnerships and integration with official data systems** Collaborations between citizen science projects, national statistical offices and government agencies should be prioritised (Fraisl et al. 2023b). These partnerships are essential for ensuring that citizen-generated data are integrated into official monitoring systems and policy-making processes. Ethically engaging key actors from multiple sectors can enhance data sharing, technical support, and the scal-

ability of citizen science efforts, facilitating greater alignment between local data collection and global SDG reporting.

(4) **Integrate citizen science into education and public awareness** Citizen science is a great tool for enhancing education and awareness about complex topics such as trade-offs and synergies across sustainability goals. Integrating citizen science into educational curricula can provide students with hands-on experience and a deeper understanding of such synergies and trade-offs. Schools, universities and other education spaces like vocational training institutes should be encouraged to participate in cross-disciplinary citizen science projects, creating meaningful learning experiences that inspire future generations to contribute to the SDGs.

(5) **Foster academic innovation in citizen science for SDG advancement** Academia can lead in integrating citizen science with the nexus approach by driving interdisciplinary research and fostering innovative approaches to addressing interlinked sustainability challenges. Universities and research institutions should prioritize developing tools and frameworks to analyse synergies and trade-offs across the resources nexus. Additionally, researchers can help ensure that citizen data-gathering efforts are methodologically and scientifically robust, to most effectively address real-world challenges and inform impactful policies. By implementing these strategies, citizen science can contribute not only to individual SDGs but also to the complex interconnections and trade-offs that define global sustainability challenges, enabling a more nuanced, inclusive, and effective approach to achieving sustainable development goals on both local and global scales.

5 Conclusion

This article emphasises the critical role of citizen science in advancing the SDGs by addressing their interconnected nature. It highlights how traditional methods and established practices may fail to capture local contexts, which is essential for monitoring and achieving the sustainability goals. By engaging local communities in data collection and analysis, citizen science uncovers the synergies and trade-offs among the SDGs, for example within the water-energy-food nexus.

The article outlines the potential pathways through which citizen science can contribute to the SDGs, including enhancing official monitoring, filling local data gaps, and co-developing relevant sustainability targets at the local level. It acknowledges existing challenges, such as ensuring data reliability, securing institutional support, and encouraging interdisciplinary collaboration, which are vital for maximising the impact of citizen science initiatives.

The authors call for actionable strategies to enhance the effectiveness of citizen science. These include redefining its role in relation to the SDGs, co-creating localised metrics with communities, strengthening partnerships with official data systems, integrating citizen science into educational curricula, and fostering academic innovation in citizen science for SDG advancement. By implementing these strategies, citizen science can significantly contribute to a more nuanced, inclusive, and effective approach to achieving sustainable development on both local and global scales.

Declarations

Conflict of interest This article serves as the cover article for the collection *Citizen Science and the Resources Nexus for Sustainable Development* in the same journal. The authors declare that there are no financial or non-financial interests that are directly or indirectly related to the work submitted for publication.

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