
Citizen Science and Public Engagement: A Survey of Interconnected Approaches

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Abstract

Citizen science has emerged as a transformative paradigm in scientific research, emphasizing the active involvement of non-professional scientists in data collection, analysis, and dissemination. This survey examines the interconnected approaches of citizen science, public engagement, impact evaluation, participatory research, community-based research, and mixed-methods research. These methodologies foster collaboration between scientists and the public, enhancing data quantity and quality, and addressing complex societal challenges. The survey highlights the integration of technological innovations, such as machine learning and digital platforms like SmartCS and Galaxy Zoo, which have democratized scientific inquiry and improved data accuracy and accessibility. Successful projects, including Galaxy Zoo and Wildbook, demonstrate the potential of citizen science to engage the public in large-scale scientific endeavors, contributing significantly to fields such as environmental monitoring and public health research. Participatory and community-based research methods, such as CBPR, emphasize shared power and leadership, challenging traditional research paradigms and fostering more equitable partnerships between researchers and communities. Mixed-methods research, which integrates qualitative and quantitative methodologies, provides a comprehensive understanding of complex research questions and enhances the robustness of scientific findings. The survey underscores the importance of impact evaluation in citizen science projects, highlighting the need for robust methodologies and ethical considerations to ensure the reliability and sustainability of these initiatives. The integration of advanced computational techniques, such as machine learning, with citizen science projects has significantly enhanced data quality and accessibility, empowering participants to contribute effectively to scientific research. As the field continues to evolve, the development of innovative methodologies and the integration of emerging technologies will be crucial for realizing the full potential of citizen science and its interconnected approaches in advancing scientific research and societal well-being.

1 Introduction

1.1 Concept and Importance of Citizen Science

Citizen science signifies a transformative shift in scientific research, marked by the active involvement of non-professional scientists in the research process. This democratization fosters collaboration between the public and scientists, enhancing public engagement and contributing to knowledge production [1]. Initiatives like Gravity Spy illustrate the essential role of non-experts in fields requiring extensive data analysis [1].

Integrating citizen science into research practices enriches scientific inquiry through diverse perspectives, improving data quality and quantity. While citizen science has gained traction in ecological and environmental research, challenges regarding the accuracy and standardization of volunteer-collected data remain [2]. Factors contributing to uncertainty in tasks like online image classification

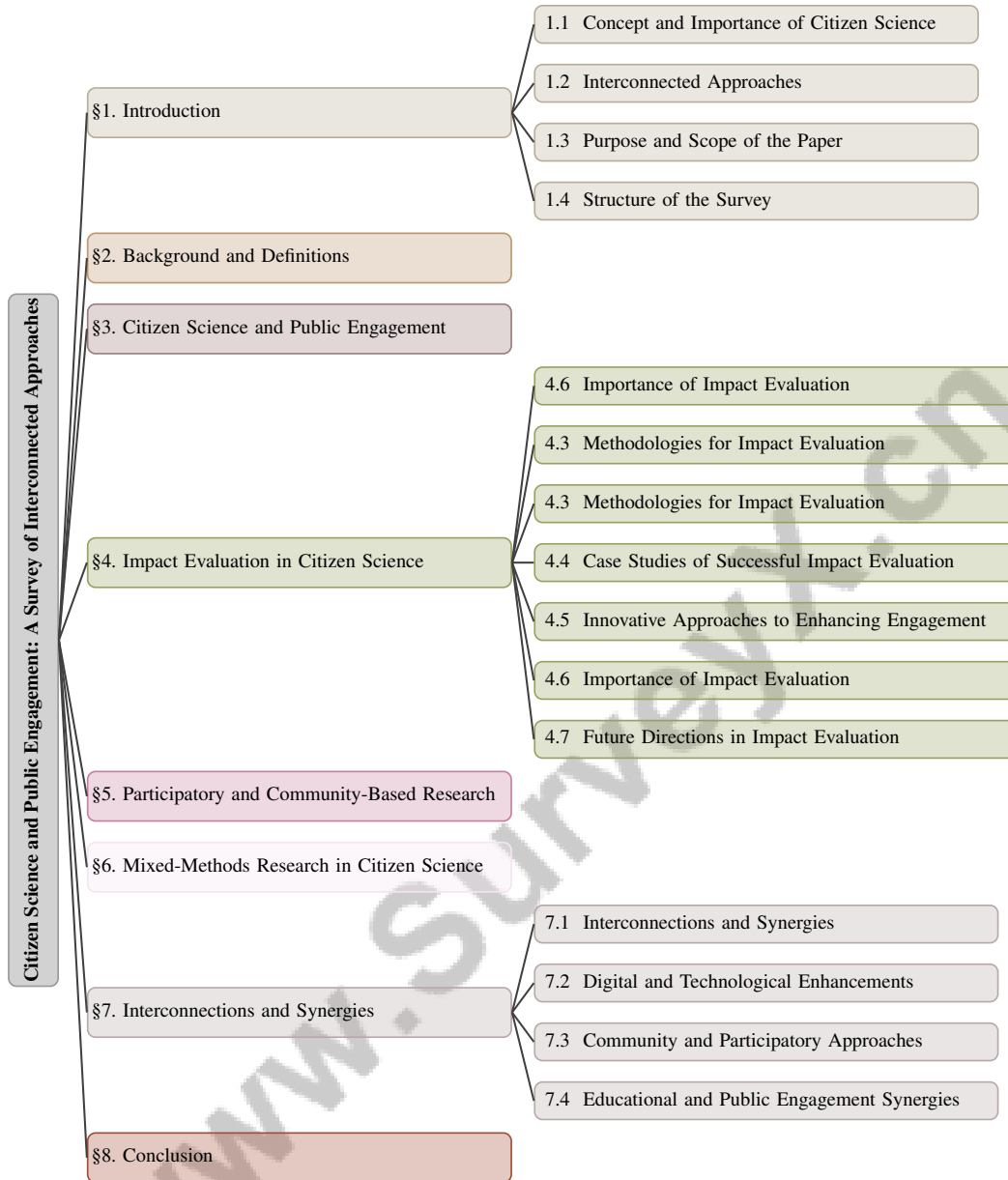


Figure 1: chapter structure

further complicate data reliability [3]. Nevertheless, computational methods utilizing citizen science data, particularly in wildlife conservation, show promise in addressing critical knowledge gaps in population dynamics [4].

Moreover, citizen science addresses societal challenges; for instance, in flood-prone areas, it provides crucial data for accurate flood extent detection, complementing traditional methods [5]. This approach supports scientific advancements and contributes to Sustainable Development Goals by providing essential data for monitoring indicators [6]. The combination of citizen science with machine learning is vital for monitoring coastal and ocean environments, especially in light of climate change threats and limited resources [7].

Ethical considerations in citizen science are critical, particularly regarding informed consent, coercion, and volunteer exploitation [8]. The introduction of Internet of Things devices raises additional ethical concerns surrounding participant autonomy and data privacy [9]. Addressing these dilemmas is essential for maintaining trust and ensuring the sustainability of citizen science initiatives.

Citizen science also has significant implications for science education, particularly through online tools that facilitate crowdsourcing and collaboration, positively impacting the scientific education of school-age children [10]. The rise of video communication platforms like YouTube further enhances research dissemination, creating new avenues for public engagement [11].

As a dynamic and multifaceted approach, citizen science enriches both scientific research and public engagement. The ongoing evolution of citizen science is expected to deepen collaborations between volunteer efforts and scientific inquiry, improving data quality from projects like Galaxy Zoo and enhancing our understanding of volunteer engagement and its impact across various scientific disciplines. By leveraging insights from volunteer interactions and project metrics, citizen science initiatives can better align with participant needs and motivations, ultimately enriching the scientific exploration landscape [12, 13, 14, 15].

1.2 Interconnected Approaches

The citizen science field is enriched by interconnected approaches that enhance public engagement with science, including participatory research, community-based research, and mixed-methods research. Technological innovations, such as mobile applications and real-time machine learning guidance, exemplify the synergy between citizen science and modern technology, enabling more accurate data collection by participants [16]. The SmartCS platform democratizes citizen science by allowing the creation of machine learning-supported applications without coding skills, thereby improving data collection quality and accessibility [16].

Historically, managing large-scale citizen science projects has posed challenges to widespread adoption. However, advancements in online middleware and crowdsourcing platforms are addressing these barriers, facilitating the setup and management of extensive initiatives [17]. These platforms introduce flexible frameworks accommodating new attributes and categories, serving as comprehensive guides for project creators [17]. Additionally, crowd-sourced fuzzy and faceted classification schemes enhance access to prior art, improving concept search and enabling nuanced data interpretation [18].

The dynamic nature of language in citizen science shapes public perception, as evidenced by frameworks categorizing research and terminology based on their roles and contexts [19]. Innovative methodologies combining human and machine classifiers significantly enhance traditional models through broader datasets and advanced computational techniques [18].

In community-based participatory research (CBPR), ethical principles and guidelines are vital for navigating the complexities of partnerships between community members and researchers [20]. These principles ensure that research outcomes align with public needs and that community engagement is meaningful and respectful. Projects like Astro-COLIBRI demonstrate the interconnectedness of citizen science and technological innovation, enhancing collaboration among astronomers and citizen scientists to improve understanding of transient events [21].

Innovative approaches within citizen science, such as utilizing smartphone cameras for environmental monitoring, underscore the potential of everyday technology to contribute to scientific research [22]. These interconnected methods not only enhance citizen science project efficacy but also promote a more inclusive and participatory model of scientific inquiry, bridging the gap between scientists and the public. By emphasizing community engagement and co-design, these approaches represent a shift from traditional top-down methods, fostering a collaborative and dynamic research environment [23]. The integration of traditional astronomical methods with modern citizen science approaches highlights the potential of simple observational techniques to enhance public engagement and scientific understanding [24].

1.3 Purpose and Scope of the Paper

This survey provides a comprehensive exploration of citizen science within open science frameworks, emphasizing its critical role in enhancing data production and accessibility. By examining diverse citizen science projects, the survey highlights the integration of artificial intelligence and machine learning across disciplines such as ecology and astronomy, significantly contributing to scientific research and public engagement [25]. The Galaxy Zoo project serves as a focal point, illustrating insights gained from volunteer participation [15].

The survey encompasses foundational concepts, methodologies, and challenges inherent in participatory action research (PAR), deliberately excluding non-participatory methods and frameworks that do not prioritize community engagement [26]. It explores the intersection of peer production, citizen science, and Big Data, specifically within projects like Galaxy Zoo, while excluding unrelated scientific projects and traditional proprietary knowledge governance models [27]. Additionally, participatory research methods applicable across various research stages, including engagement, exploration, mobilization, and evaluation, are examined [28].

In wildlife conservation, the survey includes crowdsourced photographs and computational analysis for monitoring wildlife, excluding traditional methods that do not utilize modern technology or citizen science [4]. The role of citizen science in flood extent detection is also investigated, leveraging machine learning to enhance existing methodologies [5].

The survey further delves into community engagement and transdisciplinary research methodologies, focusing on integrating community knowledge to address health disparities among AI/AN populations [29]. It includes participatory research approaches like CBPR and CEnR, while excluding non-participatory methods, particularly in health-related research [30]. The survey also encompasses participatory approaches in epidemiology, which enhance traditional epidemiologic research through various methodologies and frameworks [31].

Moreover, the survey examines the educational implications of online citizen science, particularly in primary school settings in New Zealand, while excluding broader discussions unrelated to education or involving adult participants [10]. Innovative participatory initiatives, such as collaborative bird call recognition games that enhance user interaction with urban biodiversity, are also considered [32]. The survey includes recommendations for developing mobile applications and web platforms for citizen science projects, while excluding unrelated technological developments [33].

By clearly defining the objectives and parameters of this survey, we aim to provide a comprehensive overview of the current landscape and future trajectories of citizen science and its related methodologies. This approach not only enhances our understanding of citizen science as a pivotal area within the broader context of open science and user-generated content but also emphasizes its role in fostering inclusivity and participatory engagement in scientific research. By leveraging digital tools and collaborative efforts, this survey seeks to address critical environmental challenges and promote high-quality data contributions from diverse audiences, ultimately enriching the scientific inquiry process across various disciplines [34, 35, 36].

1.4 Structure of the Survey

The survey is meticulously structured to provide a comprehensive examination of citizen science and its interconnected approaches, aligning with the overarching themes of open science and the democratization of scientific inquiry [37]. The paper is organized into several key sections, each addressing a specific facet of citizen science and its role in modern research and public engagement.

The initial section introduces the fundamental concepts and significance of citizen science, setting the stage for a deeper exploration of its interconnected approaches. This is followed by a detailed background section defining core concepts and tracing their historical development, highlighting the relevance of citizen science in contemporary research contexts [38].

Subsequent sections delve into themes such as public engagement, impact evaluation, and participatory research. The survey examines various models and case studies of citizen science projects that effectively engage the public, analyzing both the benefits and challenges of citizen participation in scientific research. Innovative approaches to enhancing engagement are also explored, showcasing the integration of modern technology and participatory methods [39].

A comprehensive examination of the critical role of impact evaluation in citizen science projects outlines various methodologies and presents diverse case studies exemplifying effective evaluation practices, particularly in enhancing data quality and educational outcomes [34, 35, 40]. Future directions in impact evaluation are discussed, providing insights into potential advancements in the field.

A dedicated section on participatory and community-based research examines the principles and practices facilitating collaboration between researchers and communities. The survey includes applications and case studies from various regions, such as participatory transport planning experiences in

European metropolitan areas [41]. Challenges and solutions in these research approaches are also addressed, offering practical insights for effective implementation.

The role of mixed-methods research in citizen science is explored in a separate section, highlighting frameworks and methodologies that combine qualitative and quantitative approaches to address complex research questions. Examples of projects benefiting from mixed-methods research are provided, along with a discussion on emerging trends and future directions in this area [42].

The survey culminates in an analysis of the interconnections and synergies between citizen science, public engagement, and related research methodologies. This section emphasizes the interdisciplinary and cross-sectoral applications of these approaches, as well as the enhancements brought about by digital and technological advancements [43].

The conclusion synthesizes key findings related to citizen science and public engagement, emphasizing the critical role of information quality in these initiatives. It outlines future research directions and potential advancements in the field, highlighting how citizen science enhances scientific inquiry and fosters greater public involvement and understanding across various disciplines, including the natural and social sciences [34, 35, 40, 15]. The importance of continued collaboration between scientists and the public is underscored, showcasing the transformative potential of citizen science in advancing both scientific knowledge and societal well-being. The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Definitions and Core Concepts

Citizen science is a participatory research model that engages non-professional scientists, or volunteers, in various stages of the scientific process, including data collection, analysis, and classification. This democratization of science fosters diverse perspectives, which are vital for tackling complex societal challenges [11]. Volunteer involvement significantly enhances data collection, particularly in environmental monitoring and biodiversity studies, where large-scale data is essential [7].

Central to citizen science is a framework of participatory and community-based research that emphasizes collaborative knowledge generation between researchers and community stakeholders. This collaboration enables citizens to contribute meaningfully across research aspects, from data collection to project design, thereby improving the quality and applicability of scientific outcomes in disciplines such as ecology and environmental science [34, 13, 44, 40, 35]. Such approaches are particularly effective in addressing intricate societal issues, including health disparities, by promoting shared power and leadership. Participatory research methods challenge conventional research paradigms by involving community members, ensuring that outcomes are relevant and applicable to the communities involved.

Despite its promise, citizen science faces challenges related to data accuracy and reliability. Geospatial sampling bias, arising from uneven spatial coverage of observations, can skew research outcomes. The rapid proliferation of user-generated content underscores the urgent need for strategies to enhance data quality and standardization. Citizen science projects, which invite diverse participation, compel contributors to produce high-quality data essential for scientific inquiry. This context emphasizes the importance of innovative information quality management approaches, as organizations strive to ensure the reliability and usability of the vast data generated to address pressing environmental and societal issues [34, 35, 1]. Additionally, the incorporation of technologies such as mobile apps in citizen science projects presents challenges related to user engagement and data management.

Ethical considerations are paramount in citizen science, particularly regarding informed consent, the risk of coercion in volunteer participation, and the potential exploitation of volunteers unaware of how their contributions are utilized. Many modern citizen science projects allow minimal engagement, which can lead to a lack of understanding among volunteers about their involvement's implications. Issues like the absence of login requirements can compromise informed consent, while mandatory data submission in educational contexts raises coercion concerns. Furthermore, using volunteers merely as instruments for scientific advancement without providing tangible benefits highlights ethical dilemmas inherent in these initiatives. Researchers must establish data privacy protocols, address data quality issues, and clarify intellectual property rights to maintain ethical integrity in

citizen science efforts [45, 9, 8, 15]. The integration of Internet of Things devices further complicates these ethical concerns, introducing issues related to participant autonomy and data privacy.

2.2 Historical Development

The historical evolution of citizen science is closely linked to broader movements advocating for knowledge democratization and the inclusion of diverse perspectives in scientific research. Emerging as an extension of participatory research methods, citizen science arose in response to conventional scientific approaches that often marginalized local knowledge and community involvement. This evolution gained momentum with the recognition of the need for shared leadership and community-driven approaches, as emphasized in frameworks categorizing participatory research into Northern and Southern traditions [30].

The trajectory of citizen science has been characterized by the development of diverse software solutions that enhance the accessibility and applicability of citizen science initiatives. These tools have been pivotal in differentiating between open-source and subscription-based platforms, thereby facilitating efficient data collection and management [18]. However, the expansion of citizen science across various fields has introduced challenges, such as managing diverse perspectives, power dynamics, and ensuring equitable participation among stakeholders, complicating the research process [28].

As citizen science has progressed, so have the challenges associated with its practice. Key issues include ensuring data quality, addressing cybersecurity threats, and developing robust frameworks for managing citizen contributions and integrating artificial intelligence [25]. Evaluating non-experts' ability to engage in critical scientific practices, such as reasoning and consensus-building, remains a significant challenge [1].

The historical trajectory of citizen science underscores the need for comprehensive theoretical frameworks to categorize its attributes and understand its deployment scenarios [28]. This includes organizing participatory research into frameworks emphasizing shared leadership and community-driven approaches, as seen in the Northern and Southern traditions [30]. Such frameworks highlight the importance of community involvement at every stage of the research process, ensuring that the knowledge produced is relevant and accessible to all stakeholders [28].

As citizen science continues to evolve, it confronts ongoing challenges, including ensuring equitable participation and addressing varying levels of experience and institutional arrangements for participatory processes across different regions [46]. Despite these challenges, the field remains a dynamic and multifaceted approach with the potential to significantly enhance scientific research and contribute to the democratization of scientific knowledge.

2.3 Relevance in Contemporary Research

In contemporary scientific inquiry, the integration of citizen science, public engagement, and participatory research is increasingly recognized for its potential to democratize knowledge production and address complex societal challenges. These approaches align with the principles of Post-Normal Science, which emphasizes the inclusion of diverse perspectives and stakeholders to enhance the legitimacy and effectiveness of science-related policy-making [47]. By involving non-professional scientists in the research process, citizen science fosters public engagement and facilitates the collection of valuable data on urban perceptions and other societal issues.

Citizen science has proven significant in ecological research, augmenting data quality and improving the accuracy of scientific findings. Comparative analyses reveal unique information quality challenges faced by citizen science projects, distinct from those encountered in traditional data collection methods [35]. Despite these challenges, benchmarks assessing the accuracy of citizen science data against professional data in various ecological studies underscore its potential contributions [2].

The role of technology in enhancing citizen science is noteworthy. Innovative toolkits designed to actively involve the public in data collection regarding urban perceptions illustrate technology's transformative potential in citizen science initiatives. A recent project utilizing open street view imagery gathered over 22,000 ratings from 331 participants on their perceptions of urban environments, demonstrating the effectiveness of citizen engagement in generating high-quality scientific data. This project also highlights how digital tools can facilitate the management and analysis of

diverse user-generated content, ultimately contributing to a deeper understanding of environmental issues and urban landscapes [34, 35, 48]. Furthermore, the experiences of speleologists exemplify how technology can support exploration and documentation, enhancing citizen scientists' capabilities.

Despite its promise, citizen science faces significant challenges in contemporary research. Ensuring the quality and reliability of data collected by volunteers is a major concern, as citizen science projects often encounter different information quality challenges than traditional data collection [35]. Current studies may lack generalizability due to small sample sizes and limited dataset diversity, impacting the robustness of findings [49]. Additionally, the complexities involved in classifying ambiguous or low-quality data, as highlighted in studies like [3], further complicate the integration of citizen science into mainstream research.

3 Citizen Science and Public Engagement

The intricate relationship between citizen science and public engagement is shaped by various participation models, which define frameworks for public involvement and highlight diverse methodologies facilitating engagement in scientific research. As illustrated in Figure 2, the hierarchical structure of citizen science and public engagement encompasses various models of engagement, successful case studies, benefits, and innovative approaches. This figure categorizes contributory and collaborative projects, emphasizes the role of digital platforms and university collaborations, and underscores the significant impact of public engagement on research and society. Furthermore, it explores technological integration and crowdsourced strategies as innovative methods to enhance participation. The subsequent subsection explores specific models of citizen science engagement, detailing their characteristics, applications, and contributions to the democratization of science and research outcomes.

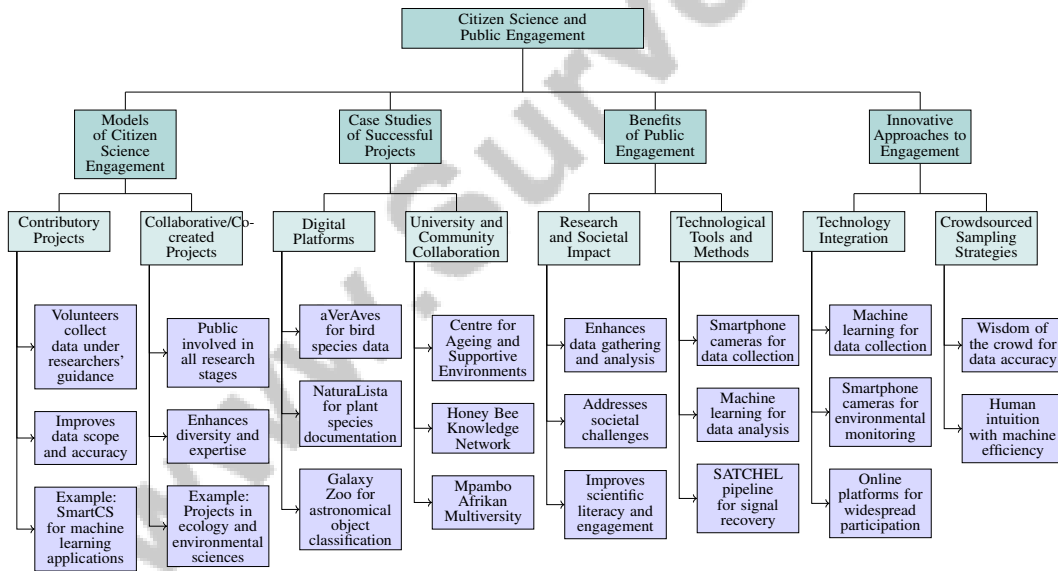


Figure 2: This figure illustrates the hierarchical structure of citizen science and public engagement, detailing models of engagement, successful case studies, benefits, and innovative approaches. It categorizes contributory and collaborative projects, highlights digital platforms and university collaborations, and emphasizes the impact of public engagement on research and society. The figure also explores technological integration and crowdsourced strategies as innovative methods to enhance participation.

3.1 Models of Citizen Science Engagement

Citizen science comprises a range of models enabling public involvement in scientific research, primarily categorized into contributory and collaborative projects. Contributory projects focus on data collection tasks performed by volunteers under researchers' guidance, whereas collaborative or co-created projects engage the public across multiple research stages, including design, data analysis, and

dissemination. This engagement enhances research quality and fosters a deeper connection between volunteers and the scientific community, as demonstrated by platforms like Galaxy Zoo, which emphasize understanding volunteer motivations and improving recruitment strategies [12, 28, 15, 50].

Contributory projects empower volunteers to collect data using technological tools, significantly improving data scope and accuracy. For instance, SmartCS enables users to create machine learning-supported applications without programming skills, democratizing data collection and analysis [16]. Co-created citizen science involves public participation throughout the entire research process, enhancing diversity of perspectives and expertise. This model aims to improve scientific data quality, as seen in various projects across disciplines like ecology and environmental sciences [44, 34, 35, 40]. It emphasizes collaboration between scientists and community members, ensuring research outcomes are relevant and beneficial.

Citizen science's integration of crowdsourced data enhances the quality and diversity of scientific information. By encouraging public participation, it addresses pressing environmental issues and improves data quality through diverse contributions, showcasing non-experts' potential in knowledge production [34, 35, 13, 1]. Projects like Galaxy Zoo exemplify the potential of online platforms to engage the public in large-scale scientific efforts, utilizing machine learning for enhanced classification of astronomical objects and operational efficiency [15].

3.2 Case Studies of Successful Citizen Science Projects

Numerous citizen science projects exemplify successful public engagement and collaborative research. 'aVerAves' is a digital platform dedicated to recording bird species, facilitating extensive ornithological data collection and fostering a community of bird enthusiasts [37]. 'Ciencia que se respira' has established a comprehensive database of diseases in Mexico, showcasing citizen science's potential in public health research and policy-making [37]. 'NaturaLista', focusing on plant species, engages the public in biodiversity documentation, enhancing scientific knowledge and conservation efforts [37].

University involvement in citizen science projects has been crucial for their success. The Centre for Ageing and Supportive Environments illustrates how academic institutions collaborate with community members to address issues related to ageing and accessibility, ensuring research is informed by community needs [51]. This participatory approach ensures research relevance and benefits stakeholders. Initiatives like the Honey Bee Knowledge Network and the Mpambo Afrikan Multiversity highlight participatory research's potential in fostering community empowerment and knowledge exchange, emphasizing the importance of equitable partnerships between researchers and communities [51].

The Galaxy Zoo project stands out as a successful citizen science example, where volunteers classify astronomical objects. This platform utilizes machine learning to enhance data accuracy and operational efficiency, demonstrating citizen science's significant contributions to research. Its success underscores the value of public engagement in scientific endeavors, leading to numerous discoveries and publications [15].

Figure 3 illustrates the categorization of successful citizen science projects, highlighting key initiatives, university collaborations, and the Galaxy Zoo project's contributions to scientific research. This visual representation complements the discussion by providing a clear overview of the interconnectedness of these projects and their impact on both academic and community spheres.

3.3 Benefits of Public Engagement in Citizen Science

Citizen science, as a participatory research model, plays a transformative role in modern scientific inquiry by enhancing public engagement and democratizing the scientific process. Integrating diverse perspectives from non-professional scientists enriches research, leading to nuanced understanding of complex societal challenges. This engagement facilitates incidental learning among participants and improves research outputs through varied contributions that reflect a wide range of experiences and knowledge. In digital humanities projects, for example, citizen involvement has contributed to corpus enrichment and comprehension of classical literature, empowering individuals to engage with scientific discourse [52, 19].

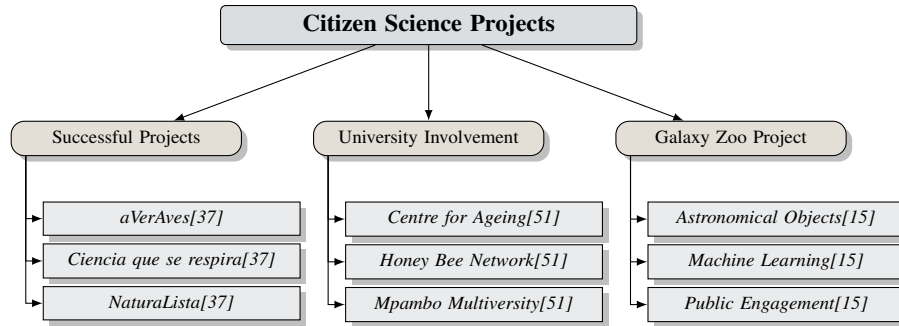


Figure 3: This figure illustrates the categorization of successful citizen science projects, highlighting key initiatives, university collaborations, and the Galaxy Zoo project's contributions to scientific research.

A notable advantage of citizen science is its ability to leverage volunteers' collective efforts for extensive data gathering, particularly valuable in environmental monitoring and biodiversity studies. Technological tools, including smartphone cameras and real-time machine learning guidance, have enabled more accurate and efficient data collection. For instance, the SATCHEL pipeline exemplifies citizen science's potential by combining human volunteers' strengths with machine learning to enhance data analysis and signal recovery rates [53].

Citizen science initiatives also play a pivotal role in addressing societal challenges, especially through community-based participatory research (CBPR) and other participatory methods. These approaches facilitate collaboration between researchers and community members, ensuring research outcomes are relevant and beneficial. By promoting shared power and leadership, participatory research methods challenge traditional paradigms, contributing to equitable and inclusive scientific inquiry [30]. Citizen science initiatives address pressing societal issues, such as environmental monitoring, utilizing machine learning for enhanced data classification and operational efficiency [7].

In education, citizen science initiatives significantly impact scientific literacy and engagement among school-age children. Online tools facilitating crowdsourcing and collaboration positively influence science education, providing platforms for students to engage with research and develop critical thinking skills [10]. The rise of online platforms facilitates public engagement and education [11].

Citizen science initiatives exemplify public engagement's potential to enhance scientific research and societal well-being. They serve as vital platforms for knowledge generation, promoting a more inclusive and participatory model of inquiry. These initiatives encompass diverse activities, from data collection to involvement in research design, allowing citizens to contribute at various levels. Despite the potential for democratizing science, studies indicate many citizen science projects experience low participation levels, particularly in roles classified as "citizens as sensors." However, citizen science enriches scientific knowledge while cultivating a scientifically literate and engaged public, underscoring its importance in the contemporary scientific landscape [44, 54, 55, 35].

3.4 Innovative Approaches to Enhancing Engagement

Innovative approaches to public engagement in citizen science are driven by technological advancements and the recognition of public participation's value in research. One approach is integrating cutting-edge technologies, such as machine learning, to facilitate effective data collection and analysis. SmartCS, for instance, empowers participants to create machine learning-supported applications without advanced coding skills, democratizing the scientific process and enhancing data quality and accessibility [16].

Sampling strategies based on the wisdom of the crowd have emerged as another innovative method to augment public engagement in citizen science projects. By leveraging diverse participants' collective knowledge and experiences, these strategies achieve accurate and comprehensive data collection [56]. Moreover, modern technology integration into citizen science projects has opened new avenues for public engagement. For example, smartphone cameras are utilized for environmental monitoring, demonstrating everyday technology's potential to contribute to scientific research [22]. This approach

broadens data collection scope and encourages greater public participation by making scientific inquiry accessible and interactive.

The emergence of online platforms has transformed public engagement in citizen science, facilitating widespread participation in research and enabling individuals to contribute to various scientific fields [44, 34, 35, 54]. Projects like Galaxy Zoo have successfully harnessed online platforms to involve the public in large-scale scientific endeavors, utilizing machine learning for improved data classification and operational efficiency. These platforms facilitate collaboration between scientists and volunteers, allowing for the collection and analysis of vast amounts of data that would otherwise be unattainable.

Furthermore, integrating human intuition with machine efficiency, as seen in methodologies like the SATCHEL pipeline, underscores the potential of merging human intuition with machine efficiency to improve citizen science project outcomes [53]. By incorporating these innovative approaches, citizen science can evolve as a dynamic and inclusive model of scientific inquiry.

4 Impact Evaluation in Citizen Science

The importance of impact evaluation in citizen science transcends simple assessment; it is a critical component that shapes the design, execution, and long-term viability of projects, ensuring that they not only engage diverse participants but also produce high-quality data that can effectively contribute to scientific research across various disciplines. [34, 57, 35, 40]. As we delve into the importance of impact evaluation, it is essential to recognize how systematic assessment can enhance the quality of citizen science initiatives. This evaluation process not only measures the outcomes of these projects but also provides insights into the methodologies employed, the engagement of participants, and the ethical considerations that underpin citizen science. Understanding these dimensions is crucial for fostering effective collaboration between professional scientists and the public, thereby maximizing the benefits of citizen science for both research and community engagement.

4.1 Importance of Impact Evaluation

Evaluating the impact of citizen science projects is a fundamental aspect of ensuring their success and sustainability. The active engagement of non-professional scientists in the research process, including data collection, analysis, and interpretation, necessitates a robust framework for assessing the quality and impact of the data generated. This participatory research model democratizes science by integrating diverse perspectives, which is essential for addressing complex societal challenges [11].

Citizen science projects, particularly in fields like environmental monitoring and biodiversity studies, significantly benefit from the collective efforts of volunteers, which allow for extensive data collection. However, these projects often face challenges related to data accuracy and potential biases due to the varied expertise of participants [2]. To address these challenges, innovative methodologies such as crowd-sourced fuzzy and faceted classification schemes have been developed, which enhance data interpretation and access to prior art [18].

The integration of technological advancements, such as machine learning, has also been instrumental in improving the quality and accessibility of data collected through citizen science initiatives. Platforms like SmartCS facilitate the creation of machine learning-supported applications without requiring coding skills, thus democratizing the process of data collection and analysis [16]. In the context of environmental monitoring, the combination of citizen science and machine learning has proven essential for addressing the scale of threats posed by climate change and filling critical knowledge gaps [7].

The development of robust methodologies for impact evaluation is crucial for assessing the outcomes and effectiveness of citizen science projects. This includes the use of crowd-sourced fuzzy and faceted classification schemes to improve data quality and standardization, as well as the integration of machine learning to enhance data accuracy and operational efficiency [18]. The Galaxy Zoo project serves as a prime example of a citizen science initiative that has successfully utilized machine learning to enhance data classification and engage the public in large-scale scientific endeavors.

To further illustrate the interconnectedness of these elements, Figure 5 depicts the hierarchical structure of key concepts related to the importance of impact evaluation in citizen science projects.

The figure categorizes the challenges of data quality and biases, the integration of technological advancements such as machine learning, and ethical considerations, highlighting their relationships and significance in ensuring the success and sustainability of these initiatives.

Ethical considerations are also critical in impact evaluation, particularly concerning informed consent, coercion, and the potential exploitation of volunteers. The use of Internet of Things devices in citizen science projects introduces additional ethical concerns related to participant autonomy and data privacy. Effectively addressing the ethical dilemmas inherent in citizen science initiatives—such as data privacy, data quality, and intellectual property rights—is essential for fostering public trust and ensuring the sustainable success of these projects, particularly as they increasingly rely on technology and user-generated content [34, 9, 35, 58].

In contemporary research contexts, citizen science has demonstrated its potential to enhance data quality and improve the accuracy of scientific findings. By involving non-professional scientists in the research process, citizen science projects can access a broader range of data sources, particularly in fields such as environmental monitoring and biodiversity studies. The integration of machine learning (ML) and other technological advancements in citizen science projects has significantly improved their effectiveness by facilitating the processing of large datasets across various fields, such as astronomy, ecology, and natural language processing. This synergy between human and machine capabilities allows for more efficient data classification and analysis, as citizen scientists collaborate with algorithms to enhance data accuracy and address challenges that arise during classification tasks. Furthermore, the involvement of experts throughout the project lifecycle ensures that the knowledge shaping the data collection and validation process is robust and reliable, ultimately leading to higher-quality scientific outcomes [34, 13, 59, 60]. However, addressing challenges related to data quality, ethical considerations, and meaningful volunteer engagement is crucial for realizing the full potential of citizen science initiatives.

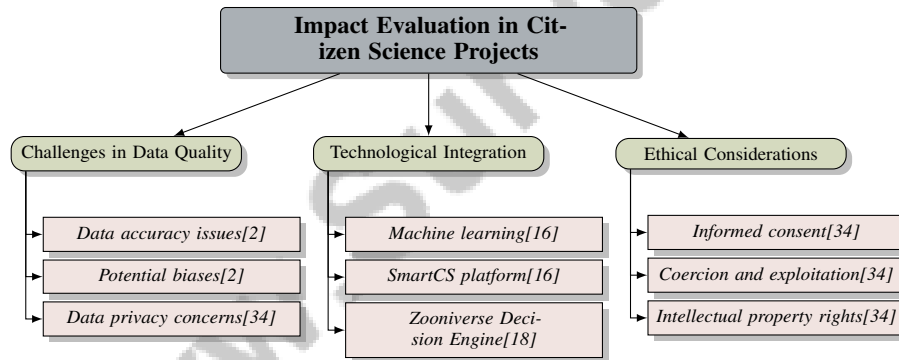


Figure 4: This figure illustrates the hierarchical structure of key concepts related to the importance of impact evaluation in citizen science projects. The primary categories include the challenges of data quality and biases, the integration of technological advancements such as machine learning, and ethical considerations. The figure highlights the relationships between these categories and their significance in ensuring the success and sustainability of citizen science projects.

4.2 Methodologies for Impact Evaluation

Table 2 provides an in-depth examination of representative benchmarks across multiple domains, highlighting their significance in the methodologies for impact evaluation.

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Evaluating the impact of citizen science projects is a critical component in understanding their effectiveness and value in scientific research and public engagement. A diverse array of methodologies has been developed to comprehensively assess the impacts of social marketing campaigns on conservation, utilizing both qualitative and quantitative approaches. This includes well-established

Benchmark	Size	Domain	Task Format	Metric
mEPA[61]	68	Physical Activity	Mvpa Frequency Measurement	Wilcoxon signed rank test, Poisson regression
MAPS[62]	26	Public Health	Partnership Evaluation	Qualitative Indicators, Quantitative Measures
CS-TBD[63]	4,261	Epidemiology	Tick Exposure Assessment	AIC, MAE
QLB[64]	5,000,000	Citizen Science	Game Performance Measurement	Replay Rate, Fidelity
JWST-CAMP[65]	145	Astronomy	Photometry	Magnitude, Lightcurve Variation
FE[66]	86,000	Deforestation Monitoring	Image Classification	Homogeneity Ratio
ED[67]	130,000	Seismology	Classification	F1-Score
SatBird[68]	122,593	Ecology	Multi-output Regression	MAE, MSE

Table 1: This table presents a comprehensive overview of various benchmarks utilized in different scientific domains for impact evaluation. It details the size, domain, task format, and evaluation metrics for each benchmark, providing insights into their application and measurement techniques.

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mixed methods techniques, such as sequential explanatory and exploratory designs, which facilitate a structured analysis of data collected from various stakeholder groups. For instance, the General Elimination Methodology has been effectively employed to evaluate the long-term effects of the Rare Pride Campaign on the lora parrot population in Bonaire, revealing that changes in population dynamics were significantly influenced by reductions in illegal poaching and local demand, driven by a combination of law enforcement efforts, social marketing initiatives, and educational programs. By triangulating qualitative insights with quantitative data from government reports and literature, these methodologies provide a robust framework for understanding the multifaceted outcomes of conservation efforts. [69, 70]

One prevalent methodology in impact evaluation is the integration of crowd-sourced data, which involves the aggregation of data collected by non-professional scientists with standardized datasets. This approach is particularly valuable in fields such as environmental monitoring and biodiversity studies, where large-scale data collection is essential. However, citizen science projects often face unique information quality challenges, such as geospatial sampling bias, which can affect the reliability of the data [35]. Addressing these challenges requires the development of strategies to improve data quality and standardization.

The integration of technological innovations into citizen science projects has significantly enhanced the potential for accurate data collection and analysis. Platforms like SmartCS enable participants to create machine learning-supported applications without requiring advanced coding skills, thereby democratizing data collection and improving its quality and accessibility [16]. Additionally, the use of crowd-sourced fuzzy and faceted classification schemes has enhanced the precision of data interpretation in projects such as Zooniverse, where human and machine classifiers are combined to improve traditional models [18].

Impact evaluation in citizen science also necessitates a focus on ethical considerations, particularly concerning participant rights and data quality management. The use of Internet of Things devices introduces additional ethical challenges, such as ensuring participant autonomy and data privacy [9]. Addressing these ethical dilemmas is crucial for maintaining participant trust and ensuring the long-term viability of citizen science initiatives [8].

The development of comprehensive theoretical frameworks is essential for categorizing the various attributes of citizen science and understanding its deployment scenarios [28]. These frameworks provide a structured approach to managing citizen contributions and integrating artificial intelligence, which is increasingly viewed as a critical component in enhancing the accuracy and efficiency of data collection and analysis in citizen science projects [25].

Case studies of successful impact evaluation in citizen science projects illustrate the potential of these methodologies to enhance scientific research and public engagement. For instance, the Galaxy Zoo project has effectively utilized machine learning to improve data classification and operational efficiency, demonstrating the potential of citizen science to contribute significantly to scientific research. The integration of crowd-sourced data in environmental monitoring and biodiversity research has underscored the significant role of citizen science in tackling intricate societal challenges, as it not only democratizes data collection by engaging a diverse array of volunteers but also enhances the quality and accessibility of scientific information, thereby addressing urgent environmental issues and promoting effective resource management. [34, 35, 13]

4.4 Case Studies of Successful Impact Evaluation

Impact evaluation is a critical component of citizen science projects, providing insights into their effectiveness and guiding future improvements. Numerous case studies across various fields, including health research and community-based participatory approaches, demonstrate the effective application of impact evaluation methodologies, emphasizing the importance of stakeholder engagement and the articulation of research impact in addressing social justice issues and improving practices. [71, 28, 40, 72]. For instance, the Galaxy Zoo project is a notable example where citizen science has been leveraged to enhance the classification of astronomical objects. By integrating machine learning with human input, this project has demonstrated the potential of citizen science to improve data accuracy and operational efficiency.

In the realm of environmental monitoring, the integration of citizen science with machine learning has been pivotal in addressing large-scale ecological challenges. The combination of crowdsourced data and computational analysis, as demonstrated in projects like Wildbook, has significantly contributed to monitoring wildlife populations and addressing critical knowledge gaps in population dynamics [4]. Such initiatives highlight the potential of citizen science to support the achievement of Sustainable Development Goals by providing essential data for monitoring environmental indicators [6].

In the domain of public health, the 'Ciencia que se respira' project exemplifies the value of citizen science in generating comprehensive databases of diseases, which can inform public health policies and interventions [37]. This project underscores the potential of citizen science to contribute to public health research by leveraging the collective efforts of volunteers to gather extensive data on health-related issues.

The integration of remote sensing data with citizen science has also been shown to enhance the accuracy and reliability of scientific findings. For example, the combination of remote sensing data with crowdsourced observations has been used to improve the detection of flood extents, providing valuable data for disaster management and response [5]. This approach not only enhances the accuracy of scientific findings but also fosters public engagement by providing volunteers with the tools and knowledge necessary to contribute effectively.

The effectiveness of citizen science projects across diverse fields underscores the significant role of public engagement in advancing scientific research and tackling intricate societal challenges. Despite the involvement of citizens in various capacities—ranging from data collection to research design—many projects exhibit low levels of participation, particularly in ecological and environmental sciences. This limited engagement often correlates with reduced scientific output, as evidenced by the analysis of over 2,300 projects, where only a small percentage foster high-quality contributions. Nonetheless, citizen science remains a promising frontier for enhancing information quality and fostering interdisciplinary collaboration, ultimately contributing to a more informed and responsive approach to pressing environmental issues. [44, 34]. By incorporating diverse perspectives and fostering collaboration between scientists and the public, citizen science initiatives can contribute significantly to the advancement of scientific knowledge and the achievement of societal goals.

4.5 Innovative Approaches to Enhancing Engagement

In the evolving landscape of citizen science, innovative approaches are being developed to enhance public engagement and participation. These approaches leverage technological advancements, such as mobile applications, real-time data collection, and machine learning, to facilitate more effective and inclusive citizen science initiatives [16].

One innovative approach to enhancing public engagement in citizen science is the development of platforms that enable participants to create and use machine learning-supported applications without requiring advanced coding skills. The SmartCS platform, for instance, empowers citizen scientists to collect and analyze data more accurately and efficiently, thereby enhancing the quality of the data collected and the overall impact of the project [16].

Another innovative approach is the use of smartphone cameras for environmental monitoring, which allows participants to collect and analyze images of their surroundings. This approach leverages the widespread availability of smartphones to engage a broader audience in citizen science projects, facilitating the collection of large-scale data for environmental research [22].

The integration of modern technology with citizen science has also led to the development of new methodologies that combine human and machine classifiers, significantly improving traditional models by utilizing broader datasets and advanced computational techniques [18]. These methodologies, exemplified by projects like Galaxy Zoo, have successfully harnessed the power of online platforms and machine learning to enhance data classification and operational efficiency, demonstrating the potential of citizen science to contribute significantly to scientific research.

Furthermore, innovative participatory initiatives, such as a collaborative bird call recognition game, have been developed to enhance user interaction with urban biodiversity [32]. These initiatives leverage technology to create engaging and interactive experiences for participants, fostering greater public engagement and contributing to the advancement of scientific knowledge.

The use of smartphone cameras to collect and analyze images for environmental monitoring represents another innovative approach to enhancing public engagement in citizen science [22]. By utilizing everyday technology, citizen scientists can contribute to scientific research with greater ease and accessibility, making scientific inquiry more interactive and inclusive.

The emergence and growth of online platforms have significantly transformed public engagement in citizen science by facilitating widespread participation in scientific research, allowing individuals from diverse backgrounds to contribute high-quality data, and enhancing opportunities for collaborative knowledge production across various scientific disciplines. [44, 34, 35, 54]. Projects such as Galaxy Zoo have successfully harnessed the power of online platforms to involve the public in large-scale scientific endeavors, utilizing machine learning to improve data classification and operational efficiency. These platforms facilitate collaboration between scientists and volunteers, allowing for the collection and analysis of vast amounts of data that would be otherwise unattainable.

The integration of modern technology, such as machine learning and digital tools, into citizen science projects, along with the development of innovative methodologies for data collection and analysis, has the potential to significantly enhance public engagement in scientific research by enabling diverse participation and improving the quality of scientific data produced. This evolution not only democratizes the research process but also allows for a more collaborative approach between citizen scientists and experts, ultimately advancing knowledge across various scientific disciplines. [44, 34, 35, 59]. By making scientific inquiry more accessible and interactive, these approaches foster a more inclusive and participatory model of scientific inquiry, bridging the gap between scientists and the public.

4.6 Importance of Impact Evaluation

Impact evaluation plays a crucial role in assessing the effectiveness and sustainability of citizen science projects. Understanding the various factors that influence these projects is essential for their success. Figure 5 illustrates the hierarchical structure of key concepts related to the importance of impact evaluation in citizen science projects. This figure categorizes the challenges of data quality and biases, the integration of technological advancements such as machine learning, and ethical considerations. By highlighting the relationships between these categories, the figure underscores their significance in ensuring the success and sustainability of citizen science initiatives. Such a

comprehensive evaluation framework not only aids in identifying potential pitfalls but also fosters the development of strategies that enhance the overall impact of these projects.

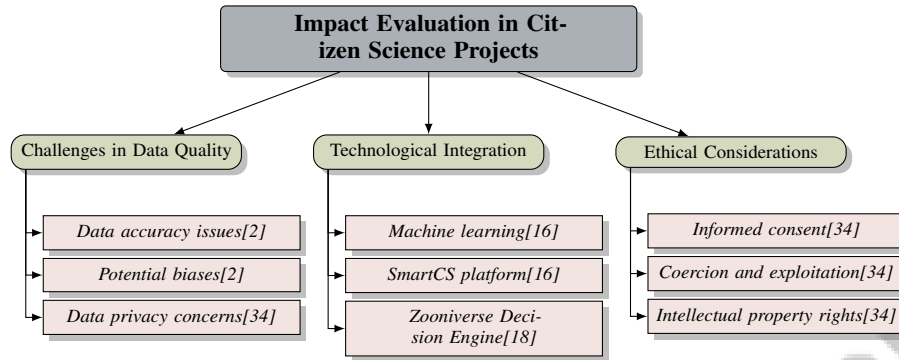


Figure 5: This figure illustrates the hierarchical structure of key concepts related to the importance of impact evaluation in citizen science projects. The primary categories include the challenges of data quality and biases, the integration of technological advancements such as machine learning, and ethical considerations. The figure highlights the relationships between these categories and their significance in ensuring the success and sustainability of citizen science projects.

4.7 Future Directions in Impact Evaluation

The future trajectory of impact evaluation in citizen science is poised to be shaped by the integration of advanced technologies and the development of standardized methodologies. As citizen science continues to evolve, it is imperative to explore the long-term impacts of artificial intelligence (AI) on the roles of citizen scientists and the overall research process. Leveraging AI can significantly enhance data accuracy, streamline processes, and support the evolving roles of citizen scientists in research initiatives [11].

One promising area for future research is the development of robust frameworks for data sharing and management in citizen science projects. These frameworks are essential for ensuring the reliability and comparability of data collected by volunteers, particularly in fields like environmental monitoring and biodiversity studies, where large-scale data is crucial [35]. Addressing the unique information quality challenges faced by citizen science projects, such as geospatial sampling bias, is essential for improving data quality and standardization [35].

The integration of AI and machine learning in citizen science projects is anticipated to play a pivotal role in advancing impact evaluation methodologies. For example, the ASAS-SN variable stars database project has successfully utilized machine learning to enhance data classification and operational efficiency, demonstrating the potential of AI to improve the accuracy and reliability of citizen science data. Future research should focus on further developing these methodologies, particularly in terms of their long-term impacts on citizen science roles and the broader scientific community [11].

Moreover, the development of best practices for citizen science is crucial for ensuring the success and sustainability of projects. Establishing comprehensive guidelines for data collection, management, and analysis will help address challenges related to data quality and standardization, ensuring that citizen science data is reliable and comparable [35]. This includes the development of best practices for citizen science projects, as well as the integration of privacy-preserving techniques to reduce data lag and enhance user engagement.

Future research should also explore design interventions to improve classification processes and assess the impact of content complexity on volunteer engagement [3]. This involves investigating the potential of design interventions to enhance the accuracy and engagement of citizen scientists, particularly in projects that involve complex content and classification tasks [3].

The integration of AI and machine learning in citizen science projects is anticipated to play a pivotal role in advancing impact evaluation methodologies. By leveraging these technologies, citizen science initiatives can achieve a more comprehensive understanding of their impacts and contribute

significantly to scientific research and public engagement [4]. Future research should focus on exploring the integration of AI with emerging technologies like the Internet of Things (IoT) and blockchain, which have the potential to enhance data collection and management, address ethical concerns, and improve the overall effectiveness of citizen science initiatives [49].

5 Participatory and Community-Based Research

5.1 Principles and Practices

Participatory and community-based research are pivotal to citizen science, emphasizing active community involvement in the research process. These methodologies foster collaborative knowledge creation, ensuring research is conducted with communities, promoting inclusivity in scientific inquiry [26]. The Aristarchus Campaign illustrates this by engaging the public in lunar distance measurements, demonstrating meaningful public participation in scientific research [24].

Shared leadership is integral to these methodologies, promoting collaboration between researchers and community members. Theoretical frameworks categorize participatory research into stages—engagement, exploration, mobilization, and evaluation—ensuring inclusivity and responsiveness to community needs [28]. Community-based participatory research (CBPR) enhances research relevance by fostering shared power and leadership, challenging paradigms that marginalize local knowledge [30].

Technological innovations enhance citizen science efficacy, particularly in data collection and analysis. Platforms like SmartCS enable citizen scientists to create machine learning-supported applications without advanced coding skills, democratizing the scientific process and improving data quality [16]. Crowd-sourced fuzzy classification schemes improve access to prior art, enhancing concept search and nuanced data interpretation [18]. Ethical considerations are crucial, requiring adherence to principles that respect participant rights and autonomy [20].

5.2 Facilitation of Collaboration

Participatory and community-based research frameworks enhance collaboration between researchers and communities, increasing societal relevance. By involving community members, these approaches foster shared ownership and co-creation of knowledge, ensuring research outcomes align with community needs [20]. Platforms like SmartCS demonstrate technology's potential to democratize science, allowing citizen scientists to create machine learning applications without advanced coding skills [16]. This democratization enhances data quality and accessibility, empowering participants with tools for effective contributions.

CBPR emphasizes shared power and leadership, ensuring research outcomes are relevant and beneficial to communities, addressing societal challenges such as health disparities and environmental sustainability [20]. These projects leverage local expertise and traditional knowledge, promoting equitable partnerships and a more inclusive scientific model [30]. Technological advancements further facilitate public engagement in citizen science. Toolkits for urban data collection exemplify technology's role in enhancing citizen science capabilities. Projects like Galaxy Zoo mobilize large-scale public participation, with over 200,000 volunteers contributing to 100 million galaxy classifications. By crediting volunteer contributions and employing advanced analytics, Galaxy Zoo sets a precedent for best practices in citizen science, optimizing volunteer engagement and data management [18, 73, 74, 49, 75].

E2 tools promote collaboration between community and academic partners, facilitating collective reflection and data-driven insights, enabling meaningful scientific inquiry while fostering community ownership [76].

5.3 Applications and Case Studies

Participatory and community-based research methods are effectively applied across sectors like health, education, and environmental sciences to address societal challenges. These approaches emphasize collaboration at every research stage, empowering communities and ensuring their voices shape the research process. As institutions recognize community engagement's value, the adoption of these methods is expected to grow, enhancing their impact on real-world issues [77, 28, 30, 26]. Projects

illustrate citizen science’s potential to enhance scientific research and public engagement through active non-professional involvement.

The ‘aVerAves’ project uses a digital platform for bird species recording, engaging the public and enhancing ornithological data collection [37]. The ‘Ciencia que se respira’ project in Mexico creates a comprehensive disease database, leveraging volunteer efforts for public health research and policy-making [37]. In environmental monitoring, citizen science combined with machine learning addresses large-scale ecological challenges. Projects like Wildbook use crowdsourced data and computational analysis for wildlife population monitoring, significantly contributing to population dynamics understanding and supporting Sustainable Development Goals by providing essential data for environmental monitoring [6].

The Astro-COLIBRI project enhances collaboration between astronomers and citizen scientists, improving understanding of transient events and demonstrating citizen science’s significant contributions to scientific research through volunteer efforts and technological innovation [21].

As illustrated in Figure 6, the diverse applications of participatory research span health, education, environmental sciences, and astronomical studies. This figure highlights specific projects and frameworks that emphasize community collaboration and citizen engagement in scientific endeavors. These case studies highlight the transformative potential of participatory action research (PAR) and CBPR in addressing societal challenges by involving marginalized communities. Projects empowering local stakeholders to identify concerns and develop solutions align with inclusion, equity, and empowerment principles central to social justice movements [77, 72, 28, 26, 30].

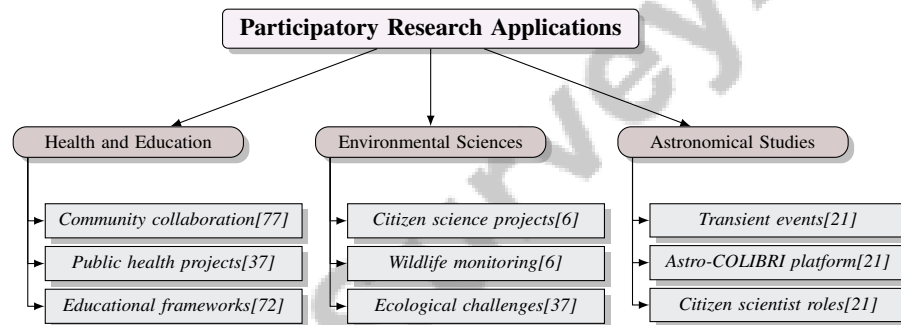


Figure 6: This figure illustrates the diverse applications of participatory research across health, education, environmental sciences, and astronomical studies. It highlights specific projects and frameworks that emphasize community collaboration and citizen engagement in scientific endeavors.

5.4 Challenges and Solutions

Despite the benefits of participatory and community-based research, challenges persist. Designing effective human-infrastructure (HI) systems that adapt to diverse participant needs and project requirements is a primary challenge, hindering inclusive and effective citizen science initiatives [78]. Methodological weaknesses, such as low internal validity and limited generalizability due to narrow participant samples, complicate participatory research [40]. Robust frameworks are necessary to accommodate diverse citizen scientist perspectives for reliable and broadly applicable research outcomes.

Unequal access to technology and digital literacy disparities pose significant challenges, particularly for projects reliant on technological tools for data collection and analysis [79]. Biases towards easily classifiable data sources and missed detections of complex light curves necessitate sophisticated data filtering methods and expanded datasets. Integrating advanced computational techniques, such as machine learning and Association Rule Mining, can enhance data accuracy and operational efficiency, allowing for a deeper understanding of collaborative knowledge production processes. Innovative measurement algorithms, like the Mann-Kendall Trend Test, can enhance data accuracy and operational efficiency, allowing for a deeper understanding of collaborative knowledge production processes [19, 1].

The underrepresentation of non-Western projects and biases in databases like SciStarter challenge accurate classification of citizen involvement levels and inclusivity in citizen science initiatives [44].

Addressing these limitations requires efforts to engage diverse communities and recognize their contributions. Significant gaps remain in understanding how to effectively engage marginalized communities and ensure citizen science initiatives are inclusive and representative [44]. Ethical considerations emphasize mutual respect and recognition of diverse contributions throughout the research process [20]. The complexity of some E2 tools can challenge effective implementation, particularly for partnerships at different development stages [76]. Addressing these challenges necessitates developing user-friendly tools that facilitate meaningful engagement and collaboration between researchers and community members.

Current studies often overlook seniors’ specific needs regarding motivation and engagement with technology, highlighting gaps in understanding their unique challenges [46]. Addressing these challenges requires developing user-friendly tools that facilitate meaningful engagement and collaboration between researchers and community members. Additionally, current studies often overlook seniors’ specific needs regarding motivation and engagement with technology, highlighting gaps in understanding their unique challenges [46]. Addressing these challenges necessitates developing user-friendly tools that facilitate meaningful engagement and collaboration between researchers and community members.

6 Mixed-Methods Research in Citizen Science

Category	Feature	Method
Frameworks and Methodologies	Research Approaches	CSLDM[24]
	AI Integration	DNN-EP[7], SC[16], ZDE[18]
Examples of Mixed-Methods Approaches	Mixed-Methods Integration	ET[80]

Table 3: This table provides a comprehensive overview of key frameworks and methodologies employed in mixed-methods research within citizen science. It delineates specific features and methods, highlighting the integration of artificial intelligence and mixed-methods approaches to enhance data collection and analysis. The references cited illustrate the diverse applications and advancements in this field.

The complexities of mixed-methods research in citizen science necessitate a clear understanding of the frameworks and methodologies that guide this approach. By integrating diverse data collection and analytical strategies, mixed-methods research enriches the research process and enhances the validity and reliability of findings. Table 3 presents an organized summary of the primary frameworks and methodologies utilized in mixed-methods research in citizen science, underscoring their significance in addressing complex scientific inquiries. Additionally, Table 4 offers a comparative overview of the primary methodologies employed in mixed-methods research within citizen science, elucidating their respective integration methods, data contributions, and technological enhancements. This section delves into the frameworks and methodologies that exemplify mixed-methods research in citizen science, highlighting their importance in addressing intricate scientific inquiries.

6.1 Frameworks and Methodologies

Mixed-methods research in citizen science combines qualitative and quantitative approaches, facilitating a comprehensive investigation of complex scientific questions. This integration is particularly advantageous in citizen science, where non-professional scientists contribute diverse perspectives [81]. A notable framework is the Generalized Linear Model for Species Abundance, which merges citizen-collected data with standardized scientific datasets, especially in ecology and biodiversity studies, thereby enhancing research validity. Between 2008 and 2017, approximately 350 studies have demonstrated the increasing popularity of mixed-methods designs, such as sequential explanatory and exploratory frameworks, which enable systematic data collection and analysis across various fields, including education and health research. Participatory methods engaging community stakeholders further ensure diverse perspectives are incorporated into research formulation and dissemination [82, 28, 69, 83].

The integration of artificial intelligence (AI) within citizen science initiatives marks a significant advancement in mixed-methods research. Platforms like SmartCS illustrate AI’s potential to enhance data collection and analysis, enabling participants to create machine learning-supported applications

without advanced coding skills [16]. This democratization of technology improves data quality and accessibility, empowering citizen scientists to contribute more effectively to research.

Crowdsourced data has emerged as a means to integrate opportunistic data with standardized datasets, allowing citizen scientists to significantly impact environmental monitoring and biodiversity studies. This engagement enhances public involvement and the overall quality of scientific data through activities like data collection, analysis, and interpretation [44, 34, 35, 84]. Projects like Galaxy Zoo exemplify how crowdsourced data and machine learning can improve data quality and standardization by leveraging online platforms for large-scale scientific endeavors.

In environmental monitoring, the synergy of citizen science and machine learning is crucial for addressing climate change threats and filling knowledge gaps [7]. Toolkits engaging the public in urban perception data collection highlight technology’s role in enhancing citizen science capabilities [10]. Furthermore, the integration of human and machine classifiers improves traditional models by utilizing broader datasets and advanced computational techniques [18].

The CSLDM method, capturing images to estimate lunar distance, exemplifies mixed-methods research’s potential to enhance scientific findings’ accuracy and reliability [24]. Online citizen science platforms have bolstered public engagement and facilitated data collection and analysis. The binary tree model categorizes existing research based on citizen scientists’ involvement across various scientific stages, providing a structured understanding of citizen science engagement models [10].

To illustrate the hierarchical structure of frameworks and methodologies in citizen science, Figure 7 presents a visual representation highlighting three primary categories: Mixed-Methods Research, AI Integration, and Crowdsourced Data. Each category encompasses key components and examples of their application in enhancing scientific research and public engagement.

The development of online platforms and mobile applications has augmented citizen science capabilities, facilitating accurate data collection and analysis. These tools enhance public engagement, enabling comprehensive and representative large-scale data collection [10]. The anticipated integration of AI and machine learning in citizen science projects is expected to advance mixed-methods research methodologies, improving data accuracy and operational efficiency [7].

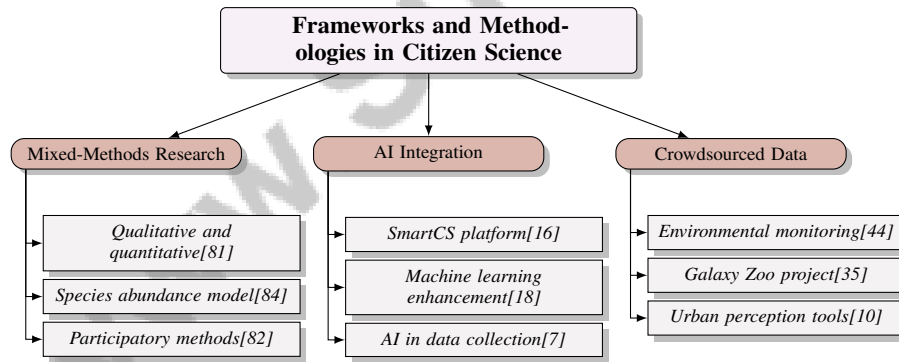


Figure 7: This figure illustrates the hierarchical structure of frameworks and methodologies in citizen science, highlighting three primary categories: Mixed-Methods Research, AI Integration, and Crowdsourced Data. Each category includes key components and examples of their application in enhancing scientific research and public engagement.

6.2 Examples of Mixed-Methods Approaches

Mixed-methods research in citizen science is vital for tackling multifaceted scientific inquiries. By integrating quantitative and qualitative methodologies, these projects leverage community engagement and participatory approaches, enhancing the robustness and relevance of findings [82, 28, 69].

The ExeTera project exemplifies this integration by utilizing key algorithms for accessible data curation and analytics, demonstrating how mixed-methods research can enhance data accuracy and operational efficiency [80]. By facilitating diverse data collection methods, ExeTera underscores mixed-methods research’s potential to improve data quality and advance scientific knowledge.

Another notable example is the 'Muon g-2' project, which combines data analysis with volunteer classification and follow-up investigations based on volunteer findings. This project highlights how mixed-methods approaches can enhance data accuracy and operational efficiency by integrating human intelligence with machine learning. Insights from around 350 studies on mixed methods illustrate how sequential and concurrent designs improve research robustness and significance, showcasing the crucial role of non-experts in collaborative knowledge production through innovative techniques like Association Rule Mining [59, 69, 1].

In urban studies, the 'Quantified Community' initiative in Red Hook, New York, demonstrates mixed-methods research's potential to inform policy-making and urban planning. By combining low-cost urban sensors with citizen science initiatives, this project gathers real-time data on urban metrics, contributing to sustainable urban planning practices [85]. This approach exemplifies the integration of quantitative and qualitative methodologies to address complex urban challenges and enhance research effectiveness.

The integration of crowdsourced data with standardized datasets has emerged as a powerful strategy, enhancing the reliability of collected data, particularly in fields like environmental monitoring and biodiversity studies where extensive data collection is vital [34, 35]. By leveraging collective volunteer efforts and diverse data collection methods, citizen science initiatives can significantly contribute to scientific research and societal well-being.

The incorporation of advanced computational techniques, such as machine learning, further enhances mixed-methods research potential. For instance, machine learning algorithms in projects like Galaxy Zoo have improved data quality and standardization by leveraging online platforms for large-scale scientific endeavors. This human-machine intelligence integration not only enhances data accuracy but also fosters public engagement, allowing volunteers to gain insights into scientific processes and contribute to knowledge advancement [86, 15].

6.3 Future Directions and Emerging Trends

The future of mixed-methods research in citizen science will be shaped by integrating advanced technologies and innovative methodologies. A key area for development is the incorporation of artificial intelligence (AI) and machine learning into citizen science, which will improve data accuracy and operational efficiency. Future research should investigate the balance between automation and engagement in ML-enhanced projects [59].

Exploring online learning to enhance engagement and knowledge generation in citizen science is another promising avenue. Online platforms can equip volunteers with the skills necessary for effective contributions to research, thereby improving citizen science initiatives' quality and impact [59]. Future studies should focus on online learning's potential to enhance public engagement and knowledge generation, particularly in fields requiring extensive data collection, such as environmental monitoring.

The development of sophisticated tools for citizen science, including advanced data collection and analysis platforms, is crucial for future research. These tools can enhance project accuracy and efficiency, facilitating comprehensive data collection and analysis [87]. By leveraging technological advancements, citizen science initiatives can evolve into dynamic and inclusive scientific research models, significantly contributing to both knowledge and societal well-being.

Future research should also focus on the evolving roles of citizen scientists in ML-enhanced projects, examining the balance between automation and engagement. Developing platforms for amateur astronomers to publish findings and create communication channels for knowledge exchange is another important area for future research [88]. By equipping amateur astronomers with necessary tools, these platforms can enhance public engagement and facilitate scientific knowledge dissemination.

The exploration of participatory design trends and innovative crowdsourcing opportunities is vital for sustaining volunteer interest and ensuring the long-term viability of citizen science initiatives. Addressing representation and equity issues in citizen science initiatives is crucial. Investigating the evolving roles of citizen scientists in machine learning-enhanced projects will ensure inclusivity and diversity in scientific practices [57]. This exploration can empower communities and promote equitable representation in scientific inquiry.

Feature	Generalized Linear Model for Species Abundance	SmartCS	Galaxy Zoo
Integration Method	Citizen-scientific Data	AI Platforms	Crowdsourced Data
Data Contribution	Ecology, Biodiversity	Machine Learning Apps	Environmental Monitoring
Technological Enhancement	None	AI Democratization	Machine Learning

Table 4: This table provides a comparative analysis of three distinct methodologies utilized in mixed-methods research within citizen science. It highlights the integration methods, data contributions, and technological enhancements associated with each approach, namely the Generalized Linear Model for Species Abundance, SmartCS, and Galaxy Zoo. The table underscores the diverse applications and technological advancements that facilitate effective citizen science research.

7 Interconnections and Synergies

7.1 Interconnections and Synergies

The fusion of citizen science with public engagement, impact evaluation, participatory research, community-based research, and mixed-methods research forms a comprehensive framework that elevates scientific inquiry and societal participation. These interconnected approaches leverage the strengths of both professional scientists and the public to address complex challenges effectively [11].

In environmental monitoring, the synergy between citizen science and crowdsourced data with standardized datasets has been pivotal in addressing ecological challenges like wildlife population and biodiversity monitoring. Technological innovations such as mobile applications and real-time machine learning empower citizen scientists, improving data accuracy and collection [16].

Advanced computational techniques, notably machine learning, have expanded citizen science’s potential to enhance research and public engagement. Platforms like SmartCS illustrate AI’s transformative impact on data collection, equipping participants with essential tools and knowledge to engage in scientific research effectively [16]. This technological democratization fosters a more inclusive scientific inquiry model [11].

In public health research, citizen science initiatives have significantly influenced policy-making by enabling large-scale data collection [37]. These initiatives highlight the transformative potential of citizen science in advancing research and public engagement, especially in fields like environmental monitoring and biodiversity studies [7].

Mixed-methods research in citizen science offers comprehensive insights into complex scientific and societal issues by integrating quantitative and qualitative methodologies. The ‘Quantified Community’ initiative in Red Hook, New York, exemplifies this by combining low-cost urban sensors with citizen science efforts to inform policy-making and urban planning [85].

Digital platforms have facilitated cross-sectoral applications of citizen science, enhancing collaboration among scientists and volunteers across fields [17]. These platforms allow for large-scale data accumulation, enhancing public engagement and data collection [18]. By leveraging technology and fostering interdisciplinary collaboration, citizen science democratizes knowledge production and addresses issues like environmental management and resource sustainability [44, 34, 58].

Initiatives like the ‘IceCube Neutrino Observatory’ illustrate citizen science’s research advancement potential, supported by scientific institutions and funding agencies. Toolkits for urban perception studies highlight the synergy between citizen science and public engagement, underscoring their contributions to scientific and societal advancements [48]. Addressing power dynamics is crucial for achieving health and social justice [30].

As illustrated in Figure 8, the key interconnections and synergies in citizen science highlight the integration of various research frameworks, technological innovations, and their applications and impacts in fields like environmental monitoring and public health.

Interdisciplinary and cross-sectoral applications of citizen science, public engagement, and participatory research methodologies are vital for addressing complex societal challenges and advancing scientific research. By promoting collaboration among diverse stakeholders and incorporating technological innovations, these strategies enhance data collection efforts, improve data quality, and democratize access to scientific knowledge [34, 44]. This process leverages non-expert contributions

for generating valuable insights while addressing data management and bias challenges, fostering a more inclusive and effective scientific research environment [35].

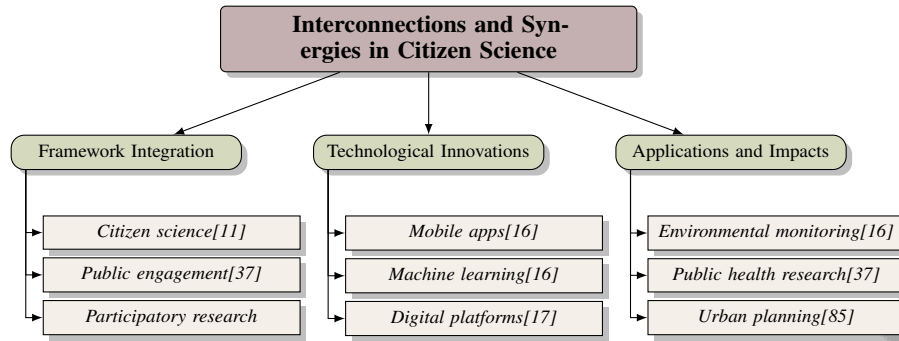


Figure 8: This figure illustrates the key interconnections and synergies in citizen science, highlighting the integration of various research frameworks, technological innovations, and their applications and impacts in fields like environmental monitoring and public health.

7.2 Digital and Technological Enhancements

Digital and technological advancements have revolutionized the synergies between citizen science, public engagement, and research methodologies. Modern technology integration in citizen science projects enhances data collection, collaboration, and knowledge sharing among scientists, community members, and other stakeholders, creating unique opportunities for interdisciplinary engagement across fields [34].

Digital platforms and mobile applications have democratized the scientific process, enabling broader public participation. Tools like SmartCS allow citizen scientists to create machine learning-supported applications without advanced coding skills, enhancing data quality and accessibility [16]. This technological democratization fosters effective engagement in scientific research [11].

The integration of machine learning and AI in citizen science has significantly improved data accuracy and operational efficiency. Projects like Galaxy Zoo demonstrate technology's potential to enhance data classification and analysis, engaging the public in large-scale scientific endeavors [18]. These advancements facilitate collaboration between scientists and volunteers, enabling the collection and analysis of vast datasets.

Technological innovations have addressed data quality challenges in citizen science. The combination of crowdsourced data with advanced computational techniques, such as machine learning, has been pivotal in enhancing data accuracy. Toolkits engaging the public in urban perception data collection highlight technology's transformative potential in citizen science initiatives [34, 89, 40, 48].

The rise of video communication platforms like YouTube facilitates research dissemination and fosters a scientifically literate public [11]. Integrating these platforms with citizen science initiatives enhances public engagement by providing new avenues for knowledge sharing and collaboration.

The future of impact evaluation in citizen science will be shaped by integrating advanced technologies and developing standardized methodologies. Leveraging AI and machine learning can provide a comprehensive understanding of citizen science initiatives' impacts [49]. Developing robust frameworks for data sharing and management ensures the reliability and comparability of volunteer-collected data, especially in fields like environmental monitoring and biodiversity studies [35].

Innovative methodologies, such as crowdsourced fuzzy and faceted classification schemes, have enhanced data interpretation and access to prior art, allowing nuanced data analysis and improved concept searches [18].

In education, citizen science initiatives significantly enhance scientific literacy and engagement among school-age children. Online tools facilitating crowdsourcing and collaboration positively impact science education, providing students with platforms to engage with scientific research and develop critical thinking skills [10]. The increasing prevalence of video communication platforms

like YouTube enhances research dissemination, creating new opportunities for public engagement and education [11].

7.3 Community and Participatory Approaches

Community and participatory approaches are central to citizen science, enhancing collaboration between researchers and communities and increasing scientific inquiry's societal relevance and impact. These approaches emphasize active community involvement, fostering shared ownership and co-creation of knowledge. Engaging communities as equal partners ensures that research outcomes are tailored to their specific needs, enhancing the relevance and applicability of scientific findings [20].

Innovative technologies have enhanced citizen science projects, particularly in data collection and analysis. Platforms like SmartCS democratize the scientific process, enabling participants to create machine learning-supported applications without advanced coding skills, improving data quality and accessibility [16]. Projects such as Wildbook demonstrate citizen science's potential to address large-scale ecological challenges by leveraging crowdsourced data and computational analysis [4].

Community-based participatory research (CBPR) is a crucial component of citizen science, emphasizing shared power and leadership between researchers and community members to ensure research outcomes are tailored to specific needs and priorities [20]. By fostering collaboration and co-design, CBPR projects promote a more inclusive model of scientific inquiry.

Despite their potential, community and participatory approaches face challenges in integrating diverse perspectives and engaging marginalized communities. Addressing these challenges requires developing robust frameworks and strategies ensuring equitable participation and meaningful engagement from all stakeholders, alongside integrating advanced technologies. Future research should prioritize community knowledge and advocacy, fostering collaboration and co-design to address complex societal challenges and advance scientific research [30, 90].

7.4 Educational and Public Engagement Synergies

The intersection of educational initiatives and public engagement in citizen science fosters a scientifically literate and engaged public. Online citizen science projects significantly impact science education by providing students with opportunities to engage with scientific research and develop critical thinking skills [10]. These initiatives allow students to participate in authentic scientific inquiry, fostering a scientifically literate public.

Digital platforms and mobile applications have democratized the scientific process, enabling broader public participation in research initiatives. Tools like SmartCS allow citizen scientists to create machine learning-supported applications without advanced coding skills, enhancing data collection quality and accessibility [16]. These advancements empower participants to engage effectively in scientific research, fostering a more inclusive model of inquiry [11].

The increasing prevalence of video communication platforms like YouTube creates new opportunities for public engagement and education, facilitating research dissemination and fostering a scientifically literate public [11]. Integrating these platforms with citizen science initiatives can enhance public engagement by providing new avenues for knowledge sharing and collaboration.

The synergies between educational initiatives and public engagement in citizen science offer significant potential for advancing scientific research and addressing complex societal challenges. These initiatives promote collaboration among diverse stakeholders, including citizen scientists, researchers, and technology developers, enhancing data collection efforts, improving data quality, and democratizing access to scientific knowledge [44, 34, 91, 92, 1, 35]. However, many initiatives exhibit limited citizen participation, with 91% of projects classified at lower engagement levels, highlighting the need for more effective strategies to elevate citizen involvement and bridge the gap between academia and community-driven research efforts.

The development of online toolkits that engage the public and facilitate data collection on urban perceptions exemplifies the potential of technology to augment citizen science capabilities [48]. These toolkits equip volunteers with essential skills and knowledge, enabling them to engage effectively in scientific research, thereby improving data quality and significantly enhancing the overall impact and

success of citizen science initiatives. Addressing power dynamics throughout the research process is crucial for achieving health and social justice [30].

In education, online citizen science platforms have demonstrated significant potential to impact science education positively, particularly in primary school settings in New Zealand [10]. By providing students with opportunities to engage with scientific research and develop critical thinking skills, online citizen science initiatives contribute to developing a scientifically literate and engaged public.

8 Conclusion

Citizen science represents a paradigm shift in scientific research, marked by the active participation of non-professional scientists in various research stages. This survey underscores the synergy between citizen science and public engagement, impact evaluation, participatory research, community-based research, and mixed-methods approaches, highlighting its significant contributions to scientific advancement and societal welfare. Central to this paradigm is the incorporation of diverse perspectives and the democratization of science, essential for tackling complex societal issues.

Projects like Galaxy Zoo and Wildbook demonstrate the transformative potential of online platforms and machine learning in enhancing data classification and operational efficacy, particularly in environmental monitoring and biodiversity research. These initiatives exemplify citizen science's capacity to involve the public in extensive scientific projects, thereby significantly contributing to both scientific research and public engagement.

Participatory and community-based research methods promote collaboration between researchers and community members, ensuring research outcomes are relevant and beneficial. By emphasizing shared power and leadership, these methods challenge conventional research paradigms, fostering a more inclusive model of scientific inquiry. The development of validated tools for measuring success indicators in community-based participatory research (CBPR) partnerships is crucial for evaluating progress toward health equity and addressing societal challenges.

The integration of advanced computational techniques, like machine learning, with citizen science initiatives has been instrumental in enhancing data quality and standardization. Digital tools and platforms have broadened public participation and improved data collection efforts, highlighting the importance of sustained collaboration between scientists and the public. Innovative methodologies, including crowdsourced fuzzy and faceted classification schemes, have significantly enhanced data interpretation, enabling more nuanced analyses.

Looking forward, the evolution of citizen science will be driven by the integration of advanced technologies and innovative methodologies. Future research should focus on establishing equitable partnerships, enhancing community engagement, and exploring solutions that prioritize human welfare. By fostering deeper collaborations between practitioners and researchers, exploring new communication models, and promoting citizen science initiatives to increase public participation, the field can continue to develop as a dynamic framework for advancing scientific research and societal well-being. The continued growth of these initiatives will rely on successfully integrating diverse perspectives and developing robust methodologies to address the unique challenges associated with citizen science.

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