Scientific Literacy Research in the Context of Citizen Science: Global Developments and Implications for China (Postprint)

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Abstract

[Purpose/Significance] This study analyzes and summarizes existing international research, aiming to clarify the connotations, theories, methodological tools, and influencing factors of scientific literacy within the citizen science context, thereby providing guidance for the development of related research in China. [Method/Process] Based on thematic content analysis, this paper explores current theoretical achievements concerning scientific literacy in the citizen science context. [Results/Conclusion] The research reveals that: the connotation of scientific literacy in citizen science can be divided into a "broad literacy perspective" and a "narrow literacy perspective"; measurement indicators primarily concentrate on the dimensions of knowledge, understanding, and attitude, with methodologies encompassing qualitative, quantitative, and mixed-methods approaches; to enhance measurement sensitivity, some scholars have introduced theories from education, behavioral science, informatics, and other fields to develop customized measurement tools; the balance between scientific goals and educational goals is a dynamic developmental process; and the influence pathways of scientific literacy have not yet formed a relatively complete model system. Through a summary and review of the aforementioned research, it is recommended that future research on scientific literacy in China's citizen science context could proceed from aspects such as research objects, tools, factors, and external environment dimensions.

Full Text

Preamble

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Scientific Literacy Research in the Context of Citizen Science: Global Progress and Implications for China

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Abstract:
This paper analyzes and summarizes existing foreign research to clarify the concepts, theories, measurement tools and methods, and influencing factors of scientific literacy in the citizen science context, providing guidance for related research in China. Based on thematic content analysis, we explore current theoretical achievements regarding scientific literacy in citizen science. The study finds that concepts of scientific literacy in citizen science can be divided into a "broad literacy view" and a "narrow literacy view"; measurement indicators primarily focus on knowledge, understanding, and attitude dimensions, employing qualitative, quantitative, and mixed methods, with some scholars introducing theories from pedagogy, behavioral science, and information science to develop measurement tools; the balance between scientific and educational goals is a dynamic development process, and a relatively complete model system for the influence pathways of scientific literacy has not yet been formed. Based on these findings, we recommend that future research on scientific literacy in China's citizen science context should focus on participants, measurement tools, influencing factors, and external environmental dimensions.

Keywords: Citizen Science; Scientific Literacy; Educational Goals; Scientific Goals; Informal Education
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Introduction

Advances in science and technology have profoundly transformed contemporary social life and will continue to do so. The public faces increasing amounts of scientific content and scientific issues. Meanwhile, in the digital age, the spread of erroneous and false information poses significant threats to information resource allocation, public health, environmental protection, social security, and social cohesion. Addressing these challenges requires scientifically literate citizens who can critically deconstruct false and pseudoscientific information and make sound scientific judgments. For instance, the public's rush to purchase Shuanghuanglian products during the sudden COVID-19 outbreak exemplifies a lack of scientific literacy.

Although science and technology play such important roles in our lives, the general public often feels distant from science because their understanding primarily comes from "scientific theories" and "technological products" rather than participation in scientific and technological projects. The European Parliament's March 2019 report, *Science and Scientific Literacy as an Educational Challenge*, states that cultivating citizens' scientific literacy must address core aspects such as "countering widely disseminated misinformation, supporting innovation and lifelong learning in science education, adopting multiple methods and multidisciplinary approaches, and participatory research and open science" [1]. This demonstrates that continuous technological development presents new challenges and goals for public scientific literacy cultivation.

Currently, China's scientific literacy cultivation mainly relies on school science education. Scholars such as Wang Chunli and Gu Xiaoqing, Y. Wang, and Yan Xiaomei have conducted in-depth explorations of the connotation, indicators, measurement, influencing factors, cultivation approaches, and science curriculum design of scientific literacy in school education [2-4]. However, current research and application primarily target adolescents, with effective science popularization measures still lacking for children and adults. Meanwhile, although Chinese adolescents demonstrate good mastery of scientific knowledge, they lack scientific participation and understanding of science-related careers.

Furthermore, compared with competition-based, popularization, and science popularization projects, contributory citizen science projects offer advantages such as diverse task attributes, large user scales, absence of competitive pressure, task training, good communication interactivity, and participatory engagement, playing important roles in enhancing public scientific literacy and stimulating innovation. Scientific institutions such as the Royal Society, the Max Planck Society, and the American Association for the Advancement of Science have collaborated with universities and social organizations to develop citizen science series projects like Cornell Lab of Ornithology, Transcribe Bentham, and Galaxy Zoo, covering not only natural sciences but also humanities and social sciences [5-7].

In summary, China urgently needs new approaches to scientific literacy cultivation to address current theoretical and practical deficiencies. Citizen science, as a new research paradigm involving large numbers of science enthusiasts and volunteers in scientific research processes [8], enables participants to master scientific knowledge and methods, establish scientific attitudes, innovate and develop through lifelong learning in scientific practice, and enhance understanding of and participation in scientific processes. This informal learning model can support participatory science for all age groups and represents a feasible and effective approach to improving public scientific literacy.

In China, citizen science projects are continuously advancing, with practical projects such as public supernova searches, Shanghai Library's historical document crowdsourcing, Bring Leopards home, and Bainiaohu wetland protection. Literature on citizen science primarily focuses on project framework design, participation behavior, and task evaluation [9-12], with limited research on scientific literacy within citizen science projects. Although Zhao Yuxiang [13] and Jin

Ying et al. [14] have highlighted the importance of scientific literacy cultivation in citizen science, China still lacks relevant practical and theoretical exploration of scientific literacy development through citizen science projects, constraining the advancement of scientific literacy in China's citizen science context.

Meanwhile, as a supplement to school education, China has implemented informal learning projects such as science lectures, science book exhibitions, technology exhibitions, and interactive experiences. However, further research on influencing factors and measurement of scientific literacy in these contexts is lacking, and no systematic research framework has been formed to effectively guide domestic research on scientific literacy in citizen science contexts. In contrast, foreign scholars have explored the connotation, measurement tools, and influence pathways of scientific literacy in citizen science contexts based on corresponding practical projects [5-7], providing theoretical foundations for advancing citizen science literacy cultivation. As a participatory, open, and lifelong educational paradigm for scientific engagement, the successful implementation of citizen science projects and theoretical achievements abroad can provide references for China's scientific literacy education research and practice.

This study primarily draws on foreign literature, using combinations of search terms including "citizen science," "participant," "citizen" with "scientific literacy," "science literacy," "scientific quality," and secondary indicators of scientific literacy such as "vocabulary of science," "science content," "understanding of scientific inquiry," "nature of science," and "attitudes toward organized science and knowledge," "attitudes toward science." After manual screening, deduplication, and backward citation tracking, 156 representative documents were obtained by October 29, 2020, including 126 journal articles, 17 conference papers, and 13 other documents. We analyze and summarize current research progress from the perspectives of scientific literacy connotation, measurement, and influencing factors to provide references for subsequent work in China and offer clues and insights for domestic scholars to understand this field from a global perspective.

2. Connotation of Scientific Literacy in Citizen Science Context

2.1 Modern Scientific Literacy Connotation

(1) Analysis of Modern Scientific Literacy Connotation. The term "scientific literacy" was distilled by American scholars in 1966 based on a literature survey of the two decades following World War II, specifically including conceptual knowledge, scientific intellect, scientific ethics, science and humanities, science and society, and science and technology. This definition is considered the foundation of modern "scientific literacy" connotation [15]. Currently, international definitions of scientific literacy connotation vary due to differences in research objects, contexts, and levels of focus.

Representative literature includes: J.D. Miller's three-dimensional model of scientific literacy based on the impact of technological change on society, comprising scientific vocabulary (vocabulary of science, science content), understanding of scientific inquiry (understanding of scientific inquiry, nature of science), and scientific attitudes (attitudes toward organized science and knowledge, attitudes toward science) [16-17]; M. Pella and A. Other's empirical scientific literacy emphasizing human-centeredness, stating that public scientific literacy should encompass understanding of basic scientific concepts, nature of science, relationships between science and humanity, relationships between science and technology, relationships between science and society, and scientists' work ethics [18]; B. Shen's classification of scientific literacy into three categories based on research content: practical scientific literacy, cultural scientific literacy, and civic scientific literacy [19]; and C. Rudiger's focus on four "interest groups": science education groups, social scientists and public opinion researchers, sociologists of science and science educators, and the public participating in science communication, noting that different groups focus on different dimensions of scientific literacy—for instance, social scientists and public opinion researchers focus on science and technology policy issues, while sociologists of science and science educators adopt sociological approaches to scientific literacy research [20].

Although scholars differ in their classifications of scientific literacy, they have reached consensus on its core components: "understanding necessary scientific knowledge, possessing basic understanding of scientific processes, and advocating scientific attitudes."

(2) Terminology Usage. Foreign scholars primarily use three terms: *scientific literacy*, *science literacy*, and *scientific quality*. *Scientific literacy* serves as a more macro-level concept of scientific literacy (J.D. Miller [16]; B. Shen [19]; J. Maienschein [21]), while *science literacy* represents a more specific or knowledge-level concept. For example, B. Shen uses *scientific literacy* as a higher-level concept than *science literacy*, employing *scientific literacy* when proposing the connotation of scientific literacy, and using *science literacy* for the three subdimensions—practical science literacy, cultural science literacy, and civic science literacy [19]. J. Maienschein defines *scientific literacy* as understanding scientific reasoning processes and procedures, and *science literacy* as knowledge of isolated scientific facts [21].

Using CNKI Translation Assistant, we found that Chinese academia translates all three terms, with *scientific literacy* being most common, followed by *science literacy*, and *scientific quality* being least common. Examination of domestic literature reveals that the three terms share essentially the same connotation. Compared with the first two terms, *scientific quality* appears less frequently in literature. Based on literature searches, this term has low relevance to scientific literacy in citizen science contexts, so it is not considered in this paper.

2.2 Scientific Literacy Connotation in Citizen Science Context

Scientific literacy in the citizen science context represents another important outcome of public participation in scientific projects and completion of scientific task objectives. Citizen science was initially science-goal-oriented, aiming to use participants' discoveries for scientific activities. As citizen science projects have developed, participants can master relevant disciplinary knowledge and understand the latest developments in the field while completing scientific tasks, thereby achieving educational goals. As one of the most important manifestations of educational goal effectiveness, the improvement of scientific literacy can effectively enhance the quality of participants' completion of citizen science projects and the educational effectiveness of citizen science literacy, balancing the scientific and educational goals of citizen science projects [22-23]. On the other hand, it can promote participants' sustained involvement in projects, forming a virtuous cycle and supporting innovation and lifelong learning in scientific practice.

Through analysis of literature on scientific literacy in citizen science contexts and considering the characteristics of scientific literacy presented in citizen science projects, we categorize current research on scientific literacy into two types based on scope: generalized scientific literacy connotation (broad literacy view) and specific scientific literacy (narrow literacy view). These two views share similarities but also exhibit differences.

(1) Similarities. First, in terms of goals, both involve balancing scientific and educational goals. The public completes scientific tasks while participating in citizen science projects, accompanied by personal creative processes and interactions with others, closely connected with concepts such as "citizen participation," "open science," "contextualization," and "interactivity." Second, in terminology usage, the secondary indicator terms are basically consistent, mainly including: understanding of science content, understanding of science process, attitudes toward science, skills for conducting science, interest in science, attitudes toward science and epistemological beliefs, science vocabulary knowledge, and science process understanding. The core terminology for both broad and narrow literacy views in citizen science contexts revolves around knowledge, understanding, and attitude, with some literature involving scientific interest, awareness, and experience.

(2) Differences. First, in terms of goals, the broad literacy view represents more generalized scientific literacy cultivation, while the narrow literacy view represents more specific literacy cultivation. Second, in terminology usage, the main differences appear in primary indicator terms. The broad literacy view, as in R. Bonney et al.'s research, continues to use "scientific/science literacy" [24], whereas the narrow literacy view employs more specific concepts in literature research, such as ecological literacy [25], biodiversity literacy [26], environmental literacy [23], conservation literacy [22], computing & internet literacy [27], and digital literacy [28], with more specific contexts and fields. Third, in measurement, the two views differ significantly in scale content design. The former emphasizes macro-level, general scientific literacy, with measurement indicators tending toward general, broad scientific knowledge, understanding, and attitude changes, while the latter focuses on specific scientific fields in context, such as ecological literacy, with measurement indicators addressing knowledge, ability, and understanding changes in ecological contexts, making them more concrete. Notably, these two concepts are not completely separate in literature research; some studies use scientific/science literacy while developing measurement tools based on specific citizen science platforms.

In summary, we can derive the interrelationships among scientific literacy, citizen science tasks, and scientific and educational goals, as shown in Figure 1 [Figure 1: see original paper].

Figure 1. Analysis of Scientific Literacy Connotation in Citizen Science Context

First, scientific literacy → educational goals: As one of the most important manifestations of educational goal effectiveness in citizen science projects, scientific literacy connotation inherits "modern scientific literacy connotation" while featuring participatory, open scientific research, interactive, contextualized scientific understanding, and lifelong education characteristics. Based on this, it can be divided into generalized scientific literacy connotation (broad literacy view) and specific scientific literacy (narrow literacy view), with similarities and differences mainly reflected in goals, terminology, and measurement. Second, scientific literacy → tasks: The improvement of scientific literacy can promote the entire scientific research process and ensure task completion quality. Third, tasks → scientific goals: Citizen science aims to use volunteers' discoveries for meaningful scientific purposes; task completion was the original purpose of citizen science, namely scientific goals. Fourth, the combination of scientific and educational goals can break through existing design models of "task-driven, goal-oriented," ensure the balance between scientific and educational goals in citizen science projects, more granularly address issues such as citizen science task decomposition, citizen science project database construction classification, and project recommendation, and more accurately explore the development of scientific literacy measurement tools and influencing factors of scientific literacy pathways.

3. Measurement Analysis of Scientific Literacy in Citizen Science Context

Scientific literacy measurement is crucial for evaluating the educational performance output of citizen science projects, obtaining funding support from enterprises and government agencies, and designing frameworks for scientific literacy cultivation. Scholars have explored theoretical borrowing, construction, and application for measuring scientific literacy in citizen science contexts, with project initiators involving universities, hospitals, research institutes, governments, and social media platforms. Research is primarily led by European and American institutions, with some involvement from Taiwan, China; participation from mainland Chinese scholars and institutions remains to be strengthened.

Literature is mainly distributed in education (e.g., *Science Education*, *International Journal of Science Education*), science communication (e.g., *Public Understanding of Science*, *Journal of Science Communication*), environmental protection and ecology (e.g., *Conservation Biology*, *BioScience*), and information computing (e.g., *Human Computation*, *Information Technology*). Authors' disciplinary backgrounds include natural science experts in astronomy, biology, ornithology, healthcare, and natural resource management, as well as scholars in educational information humanities such as social media research, science education, information science, psychology and education, and pedagogy. The distribution of literature journals and scholars' disciplinary backgrounds indicates that scholars have explored citizen science from both scientific and educational goal perspectives.

From the perspective of diversified citizen science projects, including both natural sciences and humanities and social sciences, we selected nine representative studies closely related to the topic and analyzed their projects, theories, tools, methods, scientific literacy measurement indicators, and conclusions. Representative literature is shown in Table 1 .

Table 1. Representative Literature on Scientific Literacy in Citizen Science Context

Study	Project	Main Theory/Tools	Measurement Method	Scientific Literacy Measurement	Conclusions
D. Brossard et al. [29]	New England Plant Conservation Project	ATOSS; MATOSS; Context-specific measures; D. Brossard et al. [29] framework	Pre-post survey; closed questions; open questions	Scientific literacy: attitudes, knowledge, understanding of scientific process	Bird biology knowledge (significant), attitudes (not significant), scientific process understanding (not significant); Need more sensitive tools
R. Jordan et al. [22]	Invasive Plant Species Monitoring	Elaboration Likelihood Model, Experiential Education Theory; ATOSS; MATOSS; NEP	Training pre-post assessment; open questions	Conservation literacy: knowledge, understanding, identification ability and awareness	Knowledge: significant; Understanding: not significant; Identification ability and awareness: significant

Study	Project	Main Theory/Tools	Measurement Method	Scientific Literacy Measurement	Conclusions
R. Cronje et al. [30]	Invasive Species Science Research	NSKS framework; Scientific attitude tool (self-developed)	Pre-post test	Scientific literacy [21]	Knowledge: significant; Understanding: not significant; Identification ability and awareness: significant
A. Cral et al. [31]	National Invasive Species Science Research	SEI; Multi-item context-specific instruments	Pre-post test; closed questions; open questions; science and topic tests	Science literacy: knowledge, attitudes	Multi-item contextual instrument: scientific literacy significant; SEI not significant; Context-specific measurement tools

Study	Project	Main Theory/Tools	Measurement Method	Scientific Literacy Measurement	Conclusions
C. Price and H. Lee [32]	ATOSS; MATOSS; Context-specific measures	Qualitative	Open-ended content	Scientific literacy: attitudes, cognition	D. Brossard et al. [29] results not significant; Knowledge, attitudes moderately significant; Need alternative survey tools
D. Cronin and J. Messmer [33]	RRBSA Project	Experiential Learning Theory	Repeated measures design; self-report survey	Civic Science Literacy: scientific vocabulary knowledge, scientific process understanding	Attitudes, cognition: significant; Knowledge assumed increased, not measured
C. Jennett et al. [6]	Old Weather, Transcription	Self-report; semi-structured concepts and probes	Scientific literacy: knowledge, understanding	Knowledge: significant; Understanding: significant	

Study	Project	Main Theory/Tools	Measurement Method	Scientific Literacy Measurement	Conclusions
C. Hsu et al. [23]	Taiwan Land Crab Project	PMM Mapping	Pre-post survey test	Knowledge, attitudes (only 2 dimensions studied: Environmental literacy)	General evaluation method: short-term training not significant; PPM: knowledge, attitudes significant
J. Westland [34]	Netherlands Zoëmt	MATS questionnaire framework	Quasi-experimental study	Attitudes (only one dimension studied: scientific literacy)	Not significant; Attitude measurement is complex, needs more sensitive tools

Note: To facilitate scholars' understanding of terminology differences in scientific literacy literature, items in Column 5 are presented in English without translation.

3.1 Main Theories, Tools, and Methods

(1) Theories and Tools. Theories primarily derive from information science, pedagogy, and behavioral science, mainly used for developing measurement tools. Measurement tools have undergone an iterative exploration process from standardized to self-developed and back to standardized tools. Volunteer scientific literacy measurement tools can be divided into two categories:

First, standardized measurement tools. Examples include the National Science Foundation's (NSF) ATOSS (Attitude Toward Organized Science Scale);

Modified ATOSS (MATOSS, Modified Version of Attitude Toward Organized Science Scale); NEP (New Environmental Paradigm); MATS (My Attitudes Toward Science); NSKS (Nature of Scientific Knowledge Scale); and SEI (Science and Engineering Indicator). Standardized assessment tools target general scientific literacy rather than being designed for citizen science contexts. In application, these tools measure citizen science literacy knowledge effectively, capturing pre-post differences. However, they yield unsatisfactory results for complex attitudes and scientific process understanding indicators.

Second, self-developed measurement tools. Theories from information science, education, and behavioral science are introduced to develop measurement tools for scientific literacy attitudes, knowledge, abilities, cognition, and awareness in citizen science contexts, such as the Elaboration Likelihood Model, Theory of Experiential Education, Learning Theory, Multi-item Contextual Instruments, Context-Specific Measures, Experiential Learning Theory, and PMM Mapping (Personal Meaning Mapping). Self-developed tools include: (a) those based on standard scales with introduced theories—for example, A. Cral et al. [31] built upon the MATOSS standardized tool by introducing context-specific measures theory, finding that MATOSS yielded non-significant results for scientific literacy indicators, while the improved model showed moderate significance in knowledge and attitudes, emphasizing the importance of developing sensitive tools; (b) those based entirely on relevant theories—for example, C. Hsu et al. [23] directly used PMM mapping, which, compared to general evaluation methods that showed non-significant results for short-term training, demonstrated significant improvements in knowledge and attitudes, again highlighting the significance of self-developed, sensitive tools.

Although self-developed measurement tools are more sensitive, they are difficult to apply to other citizen science projects, preventing the generalization of research findings across different projects. Scholars [30, 34] generally agree that how to evolve from self-developed measurement tools back to standardized measurement tool framework design remains an important future research direction.

(2) Measurement Methods. Measurement methods present a triad of qualitative, quantitative, and mixed approaches. Common quantitative methods include self-report surveys, content analysis, pre-post project comparisons, and closed/open questions. Common qualitative methods include experimental tests, quasi-experiments, comparative tests, science and topic tests, pre-post training assessments, and repeated measures designs. These methods are generally used in combination, integrating quantitative and qualitative approaches.

3.2 Scientific Literacy Measurement Indicators and Conclusions

As shown in Table 1, the content settings of scientific literacy measurement are closely related to literature's definitions of scientific literacy connotation, yet secondary measurement indicators show high consistency, primarily focusing on three indicators: scientific knowledge, scientific understanding, and scientific attitude. We focus our analysis on these three indicators. Current research has reached consensus that citizen science projects promote scientific literacy, but conclusions on scientific literacy measurement require further exploration.

First, scientific knowledge includes general scientific knowledge and project-specific scientific knowledge. Citizen science projects can enhance volunteers' scientific knowledge, particularly project-specific knowledge. For example, R. Bonney's summary of scientific literacy in citizen science projects concluded that volunteers' scientific knowledge improved after participation [24]. C. Evans' study on scientific literacy in a community bird nest observation project found that 90% of volunteers reported learning new things, with even the most experienced participants gaining new bird knowledge [35]. Subsequent researchers continue exploring this issue, such as Kevin et al., who used machine learning in a working science project to guide user image classification tasks and found that users' scientific knowledge improved, consistent with previous conclusions [36].

Second, scientific understanding, as the interpretation of scientific norms and methods, shows increasingly consistent research findings. For example, D. Trumbull's qualitative analysis of volunteer letters in Cornell Lab of Ornithology's seed preference test project found that volunteers interested in the project, who carefully formulated and wrote hypotheses and suggested modifications to experimental design, improved their understanding of biology and scientific processes. However, since the project could not determine whether less educated, less motivated, or less knowledgeable participants would join, qualitative conclusions could not be entirely attributed to the citizen science project. The seed preference test project hoped that younger, less educated individuals could also participate and benefit [37]. Subsequently, D. Brossard conducted further research for more convincing results but obtained opposite findings [29]. R. Jordan et al. also found no change in volunteers' understanding of scientific processes [22]. However, recent studies such as R. Bonney's summary of multiple projects concluded that citizen science promotes volunteers' scientific understanding [38], and S. Mahajan's study on a citizen science environmental pollution project with informal education as its primary goal found that volunteers' scientific understanding indeed improved [39]. Research findings are gradually converging.

Third, due to the ambiguity and complexity of volunteers' scientific attitudes, measuring scientific attitudes is more challenging than the previous two indicators, and research progress has been slower [16, 40]. D. Brossard, based on the Cornell Birdhouse Network (TBN) project and using the Elaboration Likelihood Model and experiential education theory framework, found that the project affected participants' bird biology knowledge but showed no statistically significant changes in scientific or environmental attitudes or scientific process understanding, suggesting the need to design more sensitive measurement tools to assess attitude changes in citizen science. Subsequently, new measurement tools have repeatedly measured volunteers' scientific attitudes with some progress. For example, J. Westland, based on the Netherlands Zoëmt project using the MATS questionnaire framework, found non-significant scientific attitudes, requiring more sensitive tools [34]. C. Hsu et al., based on the Taiwan land crab project, verified the impact of short-term training on knowledge and attitude indicators of scientific literacy, finding that general evaluation methods yielded non-significant results for knowledge and attitudes, while their self-developed PMM mapping tool, integrating quantitative and qualitative dimensions, showed significant improvements in knowledge and attitude indicators [23].

In summary, current research has reached consensus on measuring scientific knowledge, findings on scientific understanding are gradually converging, but conclusions on scientific attitudes vary significantly. This variation relates to indicator connotation, participants' existing scientific literacy, and measurement tool development. On one hand, scientific knowledge is easier to quantify, while changes in scientific understanding and attitudes are more ambiguous and complex, and participants' response accuracy to measurement tools needs improvement. On the other hand, the sensitivity of currently developed measurement tools remains insufficient.

4. Influencing Factors of Scientific Literacy in Citizen Science Projects

Current research has identified influencing factors including task design, platform role assignment, platform training, participation duration, social behavior, and participation motivation, primarily from platform, task, and volunteer dimensions. We explore a framework model of scientific literacy influencing factors from three dimensions—platform, task, and participant—offering a more open classification that can accommodate additional influencing factors and categorize currently explored factors.

4.1 Platform Level

At the platform level, factors include platform training and platform role assignment. R. Cronje, C. Price and H. Lee, and M. Aristeidou and H. Christothea found that scientists' training of volunteers on platforms can improve volunteers' scientific knowledge, attitudes, and understanding [30, 32, 41]. Platform role refers to volunteers' roles in citizen science projects, which vary by task, such as data collectors, analysis assistants, or project leaders. R. Bonney categorized platform roles into three types—contributory, collaborative, and co-creative—based on the importance of volunteers' roles in citizen science projects. Research shows that platform role assignment significantly affects scientific knowledge and methods, though its impact on scientific attitudes remains unknown [24]. Additionally, if volunteers find their roles replaceable, their participation has limited impact on scientific literacy improvement [38].

4.2 Task Level

At the task level, factors include task design. Task design refers to the design and planning of project frameworks relevant to and influencing volunteer behavior, specifically including incentive mechanisms for volunteers and the balance between educational and scientific goals. Project design must consider the balance between educational and scientific goals; overemphasizing scientific goals sacrifices educational goals, reducing participation among less professional volunteers and hindering public scientific literacy improvement [22]. In specific task development, such as the Netherlands' ISPEX (Innovative Way to the Spectropolarimeter for Planetary Exploration) project, incorporating incentive mechanisms can improve volunteers' self-efficacy, thereby enhancing scientific literacy [42].

4.3 Volunteer Level

At the volunteer level, factors include demographic characteristics, participation duration, social behavior, and participation motivation. **Demographic characteristics** (such as age, occupation, education level, and family income) correlate with scientific literacy improvement. For example, A. Cral and O. Sagy et al. note that education level, gender, age, and religious belief correlate with scientific literacy improvement, with participants from middle- to upper-income families and higher education levels showing stronger learning abilities and more significant scientific literacy improvement [31, 43]. **Participation duration**: A. Cral and R. Jordan indicate that brief participation in a single citizen science project may only improve volunteers' scientific knowledge, while changes in scientific understanding and attitudes require long-term processes [22, 31]. **Social behavior** refers to communication and interaction with scientists and other volunteers during participation, including virtual social network interactions via blogs, Twitter, and Talk, as well as explanations to the public outside the project. C. Price and H. Lee et al. and C. Llorente et al. experimentally confirmed that volunteer participation in exchanges improves scientific attitudes [32, 44]. **Participation motivation** includes learning-oriented and interest-oriented motivations and is an important factor affecting volunteers' scientific literacy. Notably, some scholars point out that repetitive mechanical participation does not change scientific literacy [6, 31].

In summary, this paper frameworkally categorizes influencing factors of scientific literacy in citizen science contexts. Current foreign research does not directly explore influencing factors of scientific literacy but rather examines factors affecting secondary indicators such as scientific knowledge, attitudes, and understanding, with more granular research variables. The aforementioned research on platform, task, and user-level factors remains exploratory, with no systematic and comprehensive influencing factor pathway model formed yet, leaving considerable research space. Second, although existing research has confirmed the positive significance of secondary factors at platform, task, and user levels on scientific literacy, how to organize and implement them in practice requires further exploration. For example, platform training, as an important factor influencing scientific literacy, is primarily undertaken by scientists as initiators. Scientists' training and participation in exchanges positively affect scientific literacy improvement, but scientists themselves are not necessarily skilled at training. Therefore, questions such as who should train volunteers, who should train scientists, or whether third-party training institutions should be introduced remain to be verified.

5. Implications for Scientific Literacy in China's Citizen Science Context

China attaches great importance to the development of universal scientific literacy. In 2006, the State Council promulgated the *Outline of the National Action Plan for Scientific Literacy (2006-2010-2020)*, with 2020 marking the final year. The 13th Five-Year Plan affirmed the phased achievements of the universal scientific literacy initiative; however, China's scientific literacy level still lags behind that of innovative countries. The European Parliament's Committee on Culture and Education March 2019 report, *Science and Scientific Literacy as an Educational Challenge*, indicates that future scientific literacy should focus on "basic literacy, scientific knowledge and ability, contextualized scientific understanding, critical thinking, subjectivity and participation," emphasizing core keywords such as "active participation, critical thinking, spanning natural sciences and humanities, lifelong education, and supporting innovation." Based on the above discussions, scientific literacy development in citizen science contexts aligns with these descriptions. Therefore, as China formulates a new round of citizen scientific literacy improvement plans for 2035, discussions on scientific literacy in citizen science contexts have guiding significance for China.

As an important and effective approach to improving scientific literacy with strong contemporary characteristics, citizen science projects reflect current technological innovation and digital transformation that make the connection between the public and science closer, while public knowledge surplus and participation unrestricted by time and space have led to flourishing citizen science projects. Currently, foreign academia has achieved phased research results on scientific literacy in citizen science contexts, providing references for China's theoretical development and practical exploration. In view of this, we summarize international experience and propose that future research on volunteers' scientific literacy in China's citizen science projects can be conducted from the following four aspects:

5.1 Target Participants

At the participant level, expand research targets to include adolescents and economically disadvantaged groups. As analyzed above, citizen science project participants are primarily adult volunteers and relatively affluent groups, effectively filling gaps in adult scientific literacy education but also resulting in relatively homogeneous participant demographics. Citizen science projects should expand research targets to include adolescents and economically disadvantaged groups. Compared with adults, adolescents' scientific cognition is still developing, making their scientific literacy more malleable. Currently receiving formal education, adolescents can benefit from citizen science projects' engaging nature and incentive mechanisms as effective educational strategies complementary to the rigor of formal education [45]. Moreover, citizen science projects can cultivate adolescents' interest and positive attitudes toward science, not only producing scientific outcomes but also improving adolescents' scientific literacy and stimulating their interest in scientific careers. On the other hand, economically disadvantaged groups are easily marginalized. As China promotes universal scientific literacy improvement, we should emphasize research on scientific literacy among economically weaker groups, exploring whether economic disparities affect volunteers' scientific literacy to help improve their scientific literacy.

5.2 Measurement Tools

At the tool level, strengthen the development, validation, and promotion of scientific literacy assessment tools. Foreign measurement tools mainly include standardized and self-developed tools. Standardized tools are not designed for citizen science contexts, emphasizing measurement of students' scientific knowledge and ability levels but lacking sensitivity for indicators such as critical thinking, complex attitudes, and scientific process understanding. Self-developed tools, designed for specific citizen science projects, are more sensitive but difficult to apply to other projects, preventing generalization of research findings. How to transition from relatively sensitive self-developed measurement tools to standardized assessment tool development, validation, and promotion is currently under active discussion among foreign scholars.

For measuring volunteers' scientific literacy in China's citizen science projects, tool design should proceed from two aspects: scientific literacy connotation in citizen science contexts and volunteer training. First, scientific literacy measurement tool design in citizen science projects is influenced by scientific literacy connotation and project goals. Based on existing research, we categorize scientific literacy connotation into generalized and specific types, and project goals into scientific and educational goals. Measurement tool design should combine scientific literacy connotation with citizen science project goals. For example, for volunteers' specific scientific literacy, more specific items and content should be developed to create context-appropriate measurement tools. Since research on scientific literacy in China's citizen science context remains exploratory, scholars can begin with self-developed measurement tools and, based on maturing research, evolve toward general, standardized tools. Second, the accuracy of scientific literacy measurement in citizen science projects depends on volunteer quality. On the basis of ensuring professional, high-quality citizen science projects, enhancing volunteer training can ensure efficient use of developed measurement tools after task completion, improving measurement accuracy and reliability.

5.3 Strengthening Influence Mechanism Research

At the factor level, strengthen research on influence mechanisms of volunteers' scientific literacy. Research on influencing factors of volunteers' scientific literacy remains exploratory, with inconsistent conclusions across studies. Exploring the impact of potential influencing factors on scientific literacy, relationships among factors, and reasons for different conclusions represents future research directions. Due to differences in culture, education forms, and public cognition, China's citizen science projects have unique characteristics; foreign research conclusions on influencing factors cannot be directly applied to China but can provide references.

First, for factors identified in literature, Chinese researchers can verify their effects using existing or specially designed projects and analyze underlying mechanisms to promote these factors' roles in enhancing scientific literacy. Second, for factors with established influence, further exploration of their relationships with other factors and mathematical models of scientific literacy changes can systematically construct influence relationship models. Additionally, Chinese researchers should consider characteristics of Chinese citizen science projects to further explore undiscovered influencing factors of scientific literacy, establishing systematic and complete scientific literacy influence mechanism models by introducing relevant theories from information science, education, and behavioral science.

5.4 Emphasizing External Environment

At the external environment level, emphasize cooperative participation among universities, research institutes, libraries, social organizations, and government agencies. Currently, high-quality, influential citizen science projects feature cross-national, cross-laboratory, cross-disciplinary, and cross-institutional characteristics. For example, over half of countries have cooperative relationships with the U.S., forming relatively stable citizen science project development camps. In laboratory cooperation, centered on Cornell University, a strong co-authorship network includes Colorado State University, University of Wisconsin, and other institutions, producing systematic research with consistent directions. In project initiator cooperation, government agencies focus on guidance and support, forming division-of-labor systems among university research institutes, libraries, and social organizations.

To establish high-quality, sustainable citizen science projects, China's scientific literacy cultivation in citizen science contexts should strengthen multi-party cooperation. With government agencies and policies providing support, university libraries can serve as links coordinating university research institutes and social organizations. First, research institutions focus more on scientific goals and task effects but are not skilled in user education, scientific literacy measurement, or project content development for educational goals. Libraries, as important spaces for informal learning, pay close attention to citizen science project development and user scientific literacy cultivation, serving as crucial links connecting research institutions and social organizations. Moreover, libraries possess large user bases, scientific data management experience, information literacy training experience, and rich information resources, enabling them to assume important responsibilities in scientific literacy education within citizen science projects.

References

[1] SIAROVA H, STERNADEL D, SZŐNYI E. Research for CULT Committee—Science and scientific literacy as an educational challenge[R]. Belgium Brussels: European parliament, policy department for structural and cohesion policies, brussels, 2019.

[2] Wang Chunli, Gu Xiaoqing. The impact of middle school students' information technology use on scientific literacy—A comparative study of China and Finland based on PISA data[J]. China Distance Education, 2019(5): 47-56.

[3] Yan Xiaomei, Wan Qingqing, Gao Bojun, et al. EU scientific literacy cultivation trends under digital transformation—Interpretation of the report *Science and Scientific Literacy as an Educational Challenge*[J]. Open Education Research, 2020, 26(4): 37-44.

[4] WANG Y, LAVONEN J, TIRRI K. An assessment of how scientific literacy-related aims are actualised in the National Primary Science curricula in China and Finland[J]. International journal of science education, 2019, 41(11): 1435-1456.

[5] KELLING S, JOHNSTON A, BONN A, et al. Using semistructured surveys to improve citizen science data for monitoring biodiversity[J]. BioScience, 2019, 69(3): 170-179.

[6] JENNETT C, KLOETZER L, SCHNEIDER D, et al. Motivations, learning and creativity in online citizen science[J]. Journal of science communication, 2016, 15(3): 1-23.

[7] RADDICK M J, PRATHER E, WALLACE C S. Galaxy zoo: science content knowledge of citizen scientists[J]. Public understanding of science, 2019, 28(6): 636-651.

[8] IRWIN A. Constructing the scientific citizen: science and democracy in the biosciences[J]. Public understanding of science, 2001, 1(10): 1-18.

[9] CHAI Y, MIAO C, SUN B, et al. Crowd science and engineering: concept and research framework[J]. International journal of crowd science, 2017, 1(1): 2-8.

[10] ZENG Q, WEI Q, LEI G. Contribution of citizen science towards cryptic species census: 'many eyes' define wintering range of the scaly-sided merganser

in Mainland China[J]. Avian research, 2018, 1(9): 1-10.

[11] Zhao Yuxiang, Liu Zhouying, Liu Wei, et al. Construction and determination of evaluation indicator system for creative open data competition works—Taking digital humanities projects as examples[J]. Journal of Library Science in China, 2020, 46(2): 75-95.

[12] Liu Wei, Xie Rong, Zhang Lei, et al. National data infrastructure construction for humanities research[J]. Journal of Library Science in China, 2016, 42(5): 29-39.

[13] Zhao Yuxiang. Discussion on citizen science projects from the perspective of crowdsourced research: concept analysis, model exploration, and disciplinary opportunities[J]. Journal of Library Science in China, 2017, 43(5): 42-56.

[14] Jin Ying, Zhang Xiaolin, Hu Zhihui. Development and challenges of citizen science[J]. Library and Information Service, 2019, 63(13): 28-33.

[15] Zhong Qiquan. Foreign theories of "scientific literacy" and science curriculum reform[J]. Comparative Education Review, 1997(1): 16-21.

[16] MILLER J D. Scientific literacy: a conceptual and empirical review[J]. Daedalus, 1983, 112(2), 29-48.

[17] MILLER J D. Public understanding of, and attitudes toward, scientific research: what we know and what we need to know[J]. Public understanding of science, 2004, 9(13): 273-294.

[18] PELLA M O, OTHERS A. Scientific literacy in the aerospace age[R]. America Wisconsin Madison: Citizenship responsibility, 1966.

[19] SHEN B S P. Science literacy and the public understanding of science[M]//DAY S B. Communication of scientific information. Basel: Karger Publishers, 1975: 44-52.

[20] LAUGKSCH R C. Scientific literacy: a conceptual overview[J]. Science education, 2000, 84(1): 71-94.

[21] MAIENSCHEIN J. Commentary: to the future-arguments for scientific literacy[J]. Science communication, 1999, 1(21): 75-76.

[22] JORDAN R, GRAY S, HOWE D V, et al. Knowledge gain and behavioral change in citizen-science programs[J]. Conservation biology, 2011, 25(6): 1148-1154.

[23] HSU C, CHANG Y, LIU C. Can short-term citizen science training increase knowledge, improve attitudes, and change behavior to protect land crabs?[J]. Sustainability, 2019, 11(14): 1-15.

[24] BONNEY R, BALLARD H, JORDAN R, et al. Public participation in scientific research: defining the field and assessing its potential for informal science education. a cAISE inquiry group report[J]. Online submission, 2009, 7(1): 58-70.

[25] PITT A, SCHULTZ C A, VASKE J J. Engaging youth in public lands monitoring: opportunities for enhancing ecological literacy[J]. Environmental education research, 2020, 8(2): 229-240.

[26] SCHNEIDERHAN-OPPEL J, BOGNER F X. Future Forest: promoting biodiversity literacy by implementing citizen science in the classroom[J]. The American biology teacher, 2020, 82(4): 234-240.

[27] KLOETZER L, COSTA J D, SCHNEIDER D. Not so passive: engagement and learning in volunteer computing projects[J]. Human computation, 2016, 1(3): 25-68.

[28] SILVA P D D, HEATON L. Fostering digital and scientific literacy: learning through practice[J]. First Monday, 2017, 22(6): 21-37.

[29] BROSSARD D, LEWENSTEIN B, BONNEY R. Scientific knowledge and attitude change: the impact of a citizen science project[J]. International journal of science education, 2005, 27(9): 1099-1121.

[30] CRONJE R, ROHLINGER S, CRALL A W, et al. Does participation in citizen science improve scientific literacy? a study to compare assessment methods[J]. Applied environmental education & communication, 2011, 10(3): 135-145.

[31] CRALL A W, JORDAN R, HOLFELDER K, et al. The impacts of an invasive species citizen science training program on participant attitudes, behavior, and science literacy[J]. Public understanding of science, 2013, 22(6): 745-764.

[32] PRICE C A, LEE H S. Changes in participants' scientific attitudes and epistemological beliefs during an astronomical citizen science project[J]. Journal of research in science teaching, 2013, 50(7): 773-801.

[33] CRONIN D P, MESSENGER J E. Elevating adult civic science literacy through a renewed citizen science paradigm[J]. Adult learning, 2013, 24(4): 143-150.

[34] WESTLAND J H. The effect of a citizen science project conducted in the classroom on students' age 9-13 on attitudes toward science and connection to nature[D]. Netherlands Utrecht: Utrecht University, 2019.

[35] EVANS C, ABRAMS E, REITSMA R, et al. The Neighborhood Nestwatch program: participant outcomes of a citizen-science ecological research project[J]. Conservation biology, 2010, 19(3): 589-594.

[36] CROWSTON K, ÖSTERLUND C, LEE T K, et al. Knowledge tracing to model learning in online citizen science projects[J]. IEEE transactions on learning technologies, 2019, 1(13): 123-134.

[37] TRUMBULL D J, BONNEY R, BASCOM D, et al. Thinking scientifically during participation in a citizen-science project[J]. Science education, 2000, 84(2): 265-275.

[38] BONNEY R, PHILLIPS T B, BALLARD H L, et al. Can citizen science enhance public understanding of science?[J]. Public understanding of science, 2016, 25(1): 2-16.

[39] MAHAJAN S, KUMAR P, PINTO A, et al. A citizen science approach for enhancing public understanding of air pollution[J]. Sustainable cities and society, 2020, 11(52): 101-180.

[40] WOLFSON K B. Citizen science: a tool for scientific discovery and influencing science attitudes in museums[D]. America Boulder Colorado: University of Colorado at Boulder, 2015.

[41] ARISTEIDOU M, HERODOTOU C. Online citizen science: a systematic review of effects on learning and scientific literacy[J]. Citizen science: theory and practice, 2020, 5(1): 1-12.

[42] LAND-ZANDSTRA A M, DEVILLEE J L A, SNIK F, et al. Citizen science on a smartphone: participants' motivations and learning[J]. Public understanding of science, 2016, 25(1): 45-60.

[43] SAGY O, GOLUMBIC Y N, ABRAMSKY B H, et al. Citizen science: an opportunity for learning in the networked society[M]//KALI Y, BARAM-TSABARI A, SCHEJTER A M. Learning in a networked society. Gewerbestrasse Cham: Springer, 2019: 97-109.

[44] LLORENTE C, REVUELTA G, CARRIÓ M, et al. Scientists' opinions and attitudes toward citizens' understanding of science and their role in public engagement activities[J]. Plos one, 2019, 11(14): 1-20.

[45] VIANNA N, LOBAO C, AGUIAR M, et al. Citizen science and scientific literacy: public engagement strategies in urban air pollution[J]. Environmental epidemiology, 2019, 12(3): 413-432.

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Note: Figure translations are in progress. See original paper for figures.