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Comparative Study on Development of Science Education Worldwide: Advance in Ideas, Themes and Practice

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Abstract

The importance of science education lies not in delivering factual knowledge to learners, but in using knowledge as a way for them to know the world and cope with the uncertainty. The development of science education worldwide in the 21st century presents the following themes:the sustainable development of human beings as the main context, cultivating scientific literacy as the goal, paying attention to understanding the nature of science, building a "common foundation" for science learning through in-depth and coherent curriculum, using information technology to stimulate and integrate science education innovation, emphasizing the unity of science and humanities, giving full play to informal learning, and improving quality through international assessment programs. The advance in understanding science education and its importance is pushing forward the continuous innovation in science education worldwide. The strategic transformation of science education in China can get informed from these trends.

Keywords

science education; K-12 students; science literacy; innovation

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Comparative Study on Development of Science Education Worldwide: Advance in Ideas, Themes and Practice

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Abstract: The importance of science education lies not in delivering factual knowledge to learners, but in using knowledge as a way to know the world and cope with the uncertainty. The development of science education worldwide in the 21st century presents the following themes: the sustainable development of human beings as the main context, cultivating scientific literacy as the goal, paying attention to understanding the nature of science, building a common foundation for science learning through in-depth and coherent curriculum, using information technology to stimulate and integrate science education innovation, emphasizing the unity of science and humanities, giving full play to informal learning, and improving quality through international assessment programs. The advance in understanding science education and its importance is pushing forward the continuous innovation in science education worldwide. The strategic transformation of science education in China can get informed from these trends. **DOI:** 10.16418/j.issn.1000-3045.20210517001-en

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The increasingly fierce competition in comprehensive national strength has won science education unprecedented attention, and the meaning, goal, content, and method of science education have been constantly changing. This study analyzes the science education policies adopted by major developed countries and international organizations and their practice in the past two decades, summarizes the basic consensuses on science education, outlines the key themes and development characteristics of international science education in an effort to provide reference for the research and policy-making on science education in China.

1 Basic understanding of science education

In the modern Western context, science is widely recognized as the basic way of knowing about the world. Correspondingly, three basic consensuses have been reached. (1) Science is a process, product, and institution [1]. (2) The progress of science entails being known and mastered by people [2]. In other words, science education needs to be oriented towards every member in the society. (3) Science education should not only commit to the delivery of factual knowledge but also inform people about the production of scientific knowledge, the role and limit of science, and how the community of scientist work, which is exactly the foundation of and the key to fostering scientific literacy, promoting the prosperity of science and technology, and advancing social development. To this end, it is necessary to vigorously popularize and improve science education at all levels, and guide people’s behavior, which can make the world move towards sustainability and stimulate fair social and economic development [2]. The arising concept of high-quality science education not only relates to education in science (science as content) but also involves education for science and through science [3]. The United Nations Educational, Scientific and Cultural Organization (UNESCO), the European Commission, the United States, and other developed countries have introduced a series of policies [4,5], launched a global action to popularize high-quality science education, with the emphasis on the use of cultural power in science education and the construction of public science literacy.

Science education is indispensable for the mental growth of children and adolescents, of which the main channel is the science curriculum in school. Effective science education can reflect the actual working methods of scientists, and connect itself with the world of children and adolescents. Therefore, many developed countries have determined scientific inquiry/practice as the basic paradigm of science curriculum to pursue the true value of science education, which is not in delivering factual knowledge to students, but in using

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knowledge as a way to know the world and cope with the uncertainty in this dynamic and complex world and inheriting the spirit of science. The implementation of science curriculum serves to impart knowledge to students, and more importantly show them how the knowledge is produced. Hence, it has become the overarching goal of science education in many developed countries to develop students' essential understanding of science and technology (namely, epistemic belief), which is of far-reaching significance for cultivating scientifically literate citizens and scientific and technological professionals. Correspondingly, inquiry–participation has been at the forefront of today's science education. It puts the emphasis on the integration of scientific language with inquiry mode and enables students to experience science in immersive inquiry. Students can thus be engaged in science in the process of studying and using scientific methods to fulfill a task and mastering representations, thereby developing a scientific attitude and spirit. Moreover, inquiry–participation emphasizes that every student gives play to the role of cognitive subject in all possible learning environments. In general, it is the core pursuit of global science education research, policy-making, and practice in the 21st century to expand the learning in science, technology, engineering, mathematics (STEM), facilitate students' inquiry–participation in science curriculum, and continuously help them make achievements and improve ability.

2 Key themes of the international science education

2.1 Goals and content of science education in the context of sustainable development of human beings

Under the guidance of the United Nations Decade of Education for Sustainable Development (2005–2014) Framework for the International Implementation Scheme [6], many developed countries, especially the United States, Finland, Canada, the United Kingdom, Germany, Japan, and Singapore, have included sustainable development and environmental education in their basic science curriculum standards. It is emphasized that science and science education should ultimately serve to achieve the sustainable development of human beings and that science curriculum should help students to get aware of the importance of environmental sustainability, build an ecosystem view, understand the meaning of lifecycle, and actively participate in social decision-making on the basis of mastering basic scientific knowledge. The science curriculum mainly includes the contents of environment, peace, rights, biodiversity, tolerance, disaster mitigation, health, and climate change. Students are encouraged to learn sufficient scientific knowledge, participate in decision-making on safety or biological issues, and make wise decisions on science and technology [7]. The American K-12 science curriculum aims to convey the message to students that the sustainable human development and the protection of biodiversity depend on the responsible management of natural resources and reducing negative influence, to which scientists and engineers can make major contribution [8]. Finland takes the participation in building a sustainable future as a horizontal capability index [9]. Other countries like Germany have even integrated STEM education with sustainable development education, and set up special incentive plans[10] ①. After the promulgation of the UNESCO's Education 2030 Incheon Declaration and Framework for Action [11], many countries re-examined the existing policies and formulated new visions for science education to respond to the rapidly changing world, emphasizing more on interdisciplinary teaching, systematic thinking, lifetime learning, cooperation, multi-culture, and autonomy.

2.2 Strengthening the cultivation of science literacy

Science literacy, the basic goal of science education, is intertwined education about the nature of science. The development of science literacy in school science education should enable students to understand the nature of science and think critically [8,12,13], and grow into responsible and informed citizens [14]. The corresponding effective way is to use scientific knowledge and engage in scientific inquiry [15,16], participate in discussion of social scientific issues [17], and solve scientific problems [7]. The consensus report Science Literacy: Concepts, Contexts and Consequences [1] issued by the National Academies of Sciences, Engineering, and Medicine of the United States [1] proposes a broad conceptual framework of society–community–individual, calling on the scientific community, research community, and other stakeholders to work together to build a scientifically literate society. The science literacy of individual includes foundational literacies, content knowledge, understanding of scientific practices, epistemic knowledge, identification and judging appropriate scientific expertise, cultural understanding of science as well as dispositions and habits of mind. In the second decade of the 21st century, the United States promulgated A Framework for K-12 Science Education [8] and the Next Generation Science Standards [18], where science literacy was defined as the performance expected of students, and the core contents of science learning were designed around the three dimensions of scientific and engineering practices, crosscutting concepts, and disciplinary core ideas and further determined as requirements for learning progression. The Organisation for Economic Cooperation and Development (OECD) pays much attention to the

① Such as the Germany's Little Scientists' House Programme (https://www.haus-der-kleinen-forscher.de/en/)

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predictive value of science literacy for a country's economic development and education quality, holding that people with science literacy are willing to engage themselves in rational dialogue about science and technology, and therefore need to possess three competencies—explaining phenomena scientifically, evaluating and designing scientific inquiry, and interpretating data and evidence scientifically [7]. Accordingly, the Programme for International Student Assessment (PISA) initiated by the OECD has introduced a science literacy test for students who have completed compulsory education. In 2019, the European Parliament (EP) stressed that science literacy is not confined to scientific knowledge but also includes the abilities to be critically engaged in science-related issues and make wise decisions. It called on schools to incorporate this new science literacy approach into curriculum and stressed the importance of fundamental literacy, scientific knowledge and competences, and contextual understanding of science [19].

2.3 Science education activity design integrated with the nature of science

If science literacy is the key ability in the future society, then the understanding of the nature of science is the key element of science literacy [15]. The understanding of the nature of science usually involves the cognitive-epistemic and social-institutional epistemology. The science education activity design usually relates to 8 aspects of the nature of science. (1) Scientific knowledge is based on empirical study. (2) Science is reliable but temporary (continuously revised). (3) Scientific knowledge is obtained through observation and inference. (4) Creativity is important to knowledge development. (5) Science is subjective, and theoretical as well. (6) Scientific theories and laws are different scientific knowledge, but are open to revision by new evidence or data interpretation. (7) Science is rooted in society and culture. (8) Scientists try to answer questions about the natural world by a variety of methods [20–22]. PISA mainly investigates 15-year-old students' understanding of the nature of science through epistemic knowledge test and epistemic belief survey.

2.4 Building a common foundation for science learning through in-depth and coherent curriculum

School curriculum needs to be designed based on the logic and nature of science, and be comprehensible to students. The overall curriculum design has transferred from the discrete knowledge presentation by subjects to the coherent content system that serves the deeper thinking and exploration of science and learning. In the United States, the United Kingdom, Canada, and Japan, deeper learning or deeper understanding is regarded as an important goal of science curriculum, with the emphasis on the conceptual understanding of scientific content and the exploration of underlying patterns and principles. It is advocated that authentic learning, integrated learning, evaluative learning, and argumentative learning should be employed to critically test the logical relationship of arguments and enable students to reflect on their processes of understanding and learning [23]. Coherence is the curriculum principle for realizing deeper learning, which is manifested in such expressions as coherent and consistent approach, horizontally coherent, vertically coherent, learning progression, big ideas, unifying ideas, and crosscutting concepts in national or regional curriculum documents. This coherence is even embodied in the form of a "big" learning area in the new French compulsory education regulations [14]. A coherent curriculum offers students opportunities for independent and interdisciplinary exploration and helps them transfer among multiple learning contexts [24]. This kind of curriculum is consistent with the inquiry–participation learning approach. In the United States and Canada, the use of inquiry-based methods is stressed to develop deeper understanding of big ideas (core concepts or crosscutting concepts) [8,25]. The United Kingdom has formulated an inquiry skill list at all stages of primary school to enable students to work scientifically, understand the nature of science, and form a coherent and advanced conceptual understanding [12].

2.5 Using information technology to stimulate and integrate science education innovation

Science education in the technological age develops in three trends. (1) Technology is incorporated into science education as content and subject, and integrated with traditional science subjects. (2) Information technology, as a tool for science learning, supports students' inquiry process and problem solving, promotes collaboration, and stimulates reflection on the formation of knowledge. For example, the United States and other countries have built a systematic digital learning environment compatible with elementary and secondary school science courses to achieve the goals beyond the traditional classrooms (providing multiple models to help learners characterize and explain scientific phenomena, and accomplish tasks with ease in the change of models [8]; helping students exchange discoveries, and providing them with complex methods for data analysis and variable relation reasoning [26]). (3) With the advocation of interdisciplinary learning, information technology can be taken as the key to develop integrated STEM programs for developing students' abilities in collaboration and creative problem solving, so that they can develop the sense of personal identification with STEM learning and become interested in science. European countries such as France integrate science education with technical education (junior high school) to foster students' capability of scientific inquiry [27]. In summary, the technological reform of science education has been a global trend, with the emphasis on supporting independent and innovative learning and following the principles of the learning sciences [28].

2.6 Emphasizing the unity of science and humanities

Science and humanities, as both sides of science education, are embodied in the integration of scientific and humanistic methods to realize the sustainable development of education, cultivate science literacy, and understand the nature of science. For example, it is emphasized that the learning of social sciences (scientific and technological ethics, health care, climate change, etc.) and the training of critical thinking should be immersed in the historical and cultural context, with drama, literature, and debate introduced. The European Commission proposed that science education should link arts and humanities with STEM, and encourage professionals in different fields to be engaged in dialogues to understand what is effective, what is ineffective, and how to improve people's quality of life [17]. The United States and the United Kingdom have included the scientists' qualities—seeking truth and being pragmatic, freedom and reflection, and critical and questioning—in the science curriculum goal to help students understand the nature of scientific practice and truly learn to think, act and express as scientists do. For example, the construction of psychological and conceptual model of phenomena helps generate a science explanation system; by interpreting data through establishing tables and graphs or using statistical analysis, exchanging ideas and research results in oral or written form, and conducting evidence-based arguments and defending opinions [8], students will truly realize that scientific concepts are not unchangeable [12]. The history of science and philosophy of science methods are used in science education design in formal and informal (e.g., science museum) learning environments. By establishing connections between concepts (within a certain scientific discipline, between different scientific disciplines, between science and other disciplines), this method exposes students to a broad connection of sciences and the long-lasting development of science by connection with social and cultural environments [29].

2.7 Giving full play to informal learning

Emphasis on informal learning means that teachers should not only pay attention to class teaching but also fully integrate formal with informal learning opportunities. What informal learning values is the intrinsic interest-driven learning, free participation or choice in learning, open curriculum, no scoring or competition, no confinement to homogeneity, and free access to organization regardless of ages or disciplines [30]. The places for off-campus informal learning include science and technology museums, non-profit organizations (such as community science clubs and university laboratories), natural and social circumstances, and media. Scientific activities in these informal learning circumstances can contribute to the following goals: developing scientific interest, understanding scientific knowledge, engaging in scientific reasoning, reflecting on science, doing scientific practice, and identifying with a scientific career [31].

Developed countries attach great importance to the quality of off-campus science education, and have frequent participation of scientific communities. In the United States, France, Japan, and South Korea, the inquiry–participation mechanism in their national science museums has become an important component of the basic science curriculum. Science museums have turned into an indispensable third space besides the school and daily life, where students meet scientists and science communicator, perceive science, and engage in scientific dialogue and practice.

2.8 Improving science education through international assessment programs

In recent years, the international education assessment programs represented by PISA and Trends in International Mathematics and Science Study (TIMSS) have become important tools for measuring and monitoring the science education quality in the basic education in many countries, and are beneficial for the curriculum reform of elementary education. Reflecting on the results of international education assessment and their scientific and technological competitiveness, the United States, the United Kingdom, France, Germany, Russia, Japan and others have been committed to facilitating the reform of science education. For example, according to the PISA results, Germany emphasizes the dimension of inquiry methodology in its science education standards [32]; France has spared no efforts to facilitate school education reform centering on fairness and quality; the EU countries have implemented science inquiry capacity improvement program for teachers; South Korea has integrated art into STEM education, and offered scientific inquiry and scientific experiment for students in compulsory education, trying to stimulate greater interest in science; Russia has initiated innovative education actions, including the priority measures in the pre-school, general, and supplementary education, to improve its ranking in the international assessment programs [33]. In addition to PISA and TIMSS, the United States has carried out other international science competitions and the National Assessment of Educational Progress (NAEP) to test the quality and policy effectiveness of the science education for adolescents. The United States is the first country to launch the STEM national strategy and continuously reinforces the idea of science and scientific education is at the heart of Americans' life [18].

Of note, PISA's survey of science career orientation and science education methods for 15-year-olds has attracted wide attention worldwide. The indicators such as teacher classroom teaching (teaching methods, application of information technology, etc.), science literacy results (scientific knowledge performance, percentage of outstanding students, scientific cognition, and belief index, etc.) have become the barometers for measuring the fairness and quality of education. The TIMSS assessment is concerned with how effective the school science curriculum is implemented in various

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countries. Its results of curriculum structure, students' performance in different cognitive fields, learning background and support from teachers exert a direct impact on the reform of science curriculum and provide a solid foundation for countries to formulate policy on science education.

3 Conclusions and recommendations

3.1 Development trend of science education

The study of science education policies and practices in major developed countries and international organizations gives the following results. (1) The development of science education is oriented towards the sustainable development of human beings, with the cultivation of science literacy as its goal. In practice, science education pays attention to the nature of science and the common foundation for science learning through in-depth and coherent curriculum, explores how to use information technology to stimulate and integrate science education innovation, emphasizes the unity of science and humanities, and reinforces the importance of informal learning, and tries to improve quality through international assessment programs. (2) Science education is not only a curriculum but also a culture of participation, exploration, truth-seeking, cooperation, and critical innovation. (3) Instead of confining to school, science education requires the participation of the community and the society. It is not the specialized work of science teachers, but involves the professional effort of scientists and scientific community.

3.2 Problems and suggestions of China's science education

In comparison with the overall trend of the science education worldwide and the performance of powerful science and technology nations in international assessment programs, China has the following shortcomings in its basic science education: (1) insufficient understanding of students for scientific methods and the nature of science, less interest in science, and poor expectation in science career; (2) limited opportunities for scientific inquiry and scientific practice, or training scientific thinking; (3) lack of diversity in science curriculum and less autonomy of students; (4) few opportunities for children's science education (such as few science class hours in elementary school), and low efficiency of science learning in middle school; (5) inadequate richness, broadness, and appropriateness of informal learning for the development of science education. How to promote the innovative development of science education, cultivate more students with excellent science literacy, and train top-notch research talents is therefore the problems that need to be tackled urgently.

These issues also shed light on the reform direction of China's science curriculum: (1) focusing on stimulating children's interest in science and developing cognitive curiosity; (2) cultivating a culture of participation in science education, improving students' understanding of scientific methods and the nature of science, making a solid foundation of logical thinking, and comprehensively improving their scientific thinking and scientific literacy; (3) creating more opportunities for science education, including increasing the diversity of science curriculum, ensuring the access to high-quality science education, and optimizing the integration of formal and informal learning opportunities. To this end, systemic support from resource input and institution construction is required.

The construction of high-quality science education shall be a major strategy for talents cultivation and education development. Efforts should be made to encourage science educators to explore innovation and stimulate the scientific community and private sectors to get involved in the noble cause of science education. In particular, it is necessary to guarantee the science education system for adolescents and clearly implement the responsibility, and to effectively improve the sense of responsibility of universities and give full play to their knowledge production and services in science education and popularization. Besides, we shall vigorously enhance the construction of science education, set up special funds for scientific research (e.g., the long-term programs sponsored by government in the United States and European countries), support innovative research in science education and communication, provide fund support in a longer and consistent term, and coordinate resource construction as a whole.

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