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A comparative study of Ocean Literacy features in the science curricula of China and the United States: promoting oceanic power through formal education

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Introduction: Ocean Literacy (OL), as a core element in enhancing citizens' Ocean Awareness, has gained wide attention in the field of education. However, existing studies indicate that the integration of OL into formal education remains insufficient. To address this gap, this study conducts a comparative analysis of the extent to which OL is incorporated into the science curriculum standards of China and the United States, and further examines the underlying ocean education philosophies in both countries.

Methods: This study employed content analysis and Epistemic Network Analysis (ENA). Using content analysis, we examined the science curriculum standards of China and the United States with respect to: (1) the scope of coverage — the presence of the seven principles of the Ocean Literacy Framework (OLF) in the documents; (2) the quantity distribution — the occurrence frequency of each principle; and (3) the grading ranks — the forms in which the principles are represented. Using ENA, we treated the OL principles as network nodes and compared the structural differences between the two countries' OL epistemic networks based on node size and inter-node relations, thereby illuminating each country's underlying ocean education philosophy.

Results and Discussion: The results showed that the science curriculum of both countries covered the seven principles, yet exhibited notable similarities and differences across different educational stages and subject areas, thereby revealing the respective strengths and weaknesses in fostering OL. In addition, the ENA results highlighted distinctive emphases in the two countries' ocean education philosophies: China stresses the "human–sea relationship," while the United States focuses on an "interdisciplinary perspective to explain the principles of ocean system and ocean science." Finally, the ENA results also pointed out specific shortcomings in the connections among OL principles within the science curriculum standards of both countries. Based on these findings, this study offers concrete recommendations for policy-makers, curriculum developers, and practitioners in ocean science research and education to further promote the integration of OL into formal curricula.

KEYWORDS

Ocean Literacy, science curriculum, formal education, content analysis, China, the United States

1 Introduction

As a unique and irreplaceable natural system on Earth, the ocean has formed an inseparable symbiotic relationship with human civilization through the provision of ecosystem functions, economic value, and resources (Costanza, 1999; Sala et al., 2021). However, citizens in many countries around the globe still have a superficial level of knowledge about the ocean (Steel et al., 2005; Fletcher et al., 2009; National Marine Awareness Development Index Study Group, 2017; Wootton et al., 2024). Meanwhile, the ocean is vast but finite, and the global ocean environment is already in crisis. The blue homeland on which humanity depends for survival is facing a series of persistent social, health, and economic challenges, such as land-based pollution entering the ocean (Landrigan et al., 2020), unsustainable fisheries management undermining marine biodiversity (Gaillet et al., 2022), and ocean acidification threatening coral reef systems as well as marine food chains (Hoegh-Guldberg et al., 2017). Considering the tangible impacts and potential threats posed by changes in the ocean environment, the international community has gradually reached a broad consensus on the urgency of ocean conservation (Bennett, 2018).

In the face of the ocean crisis, Education and Ocean Literacy (OL) are widely recognized by nations and international organizations as effective pathways for addressing the challenges of sustainable ocean development and for enhancing public awareness and participation in ocean conservation (Costa and Caldeira, 2018; Kelly et al., 2022). The General Assembly of UN (2015) adopted *Transforming our world: the 2030 Agenda for Sustainable Development*, which incorporated SDG 14 "Life Below Water" as a stand-alone goal within the global sustainable development framework and highlighted the significance of Ocean Education for sustainability (UN, 2015). In 2017, the United Nations General Assembly proclaimed 2021–2030 as the United Nations Decade of Ocean Science for Sustainable Development, with the expectation that by 2025, Ocean Literacy Framework (OLF) would be integrated into the Formal Education Curriculum Systems of the vast majority of countries worldwide (UNESCO-IOC, 2021). In these representative international initiatives, enhancing citizens' understanding of the ocean and fostering pro-environmental behavioral intentions have been regarded as key intervention strategies (Schubel and Schubel, 2008; McKinley and Fletcher, 2012). Among these, the formal education curriculum system, due to its broad coverage and high implementation efficiency, is regarded as a key pathway for integrating and promoting the framework of OL (Pazoto et al., 2021).

Existing research has generally focused on the current status of integrating OL into formal education curricula. For example, Gough (2017), through an analysis of school curriculum in the United Kingdom, New Zealand, and Australia, found that the existence of ocean education themes in these nations was rather limited, and suggested strengthening the inclusion of OL in formal curricula. However, existing research primarily focus on analyzing the status of ocean education within the individual national or regional education system, while comparative research on the incorporation of OL across countries remains relatively limited. Given the significant differences among countries in understanding and implementing OL education, the findings of comparative studies should be regarded as a reflective tool or benchmark for improving national OL education (Chang et al., 2021).

To this end, this study compares the presence of OL in the science curriculum standards of China and the United States, with the aim of identifying the scope of coverage (the inclusion of the seven principles of the OLF in the documents), the distribution of categories (the frequency with which each principle appears), and the grading ranks (the forms in which the principles are represented). Based on quantitative data, this study further reveals the current state of OL cultivation in the science curricula of China and the United States at the overall, educational stage level, and subject levels. Furthermore, by utilizing the results of the co-occurrence frequencies among OL principles, this study constructs the OL epistemic networks of the two countries and compares their structural differences to explore the similarities and differences in their ocean education philosophies. Through this investigation, we aim to identify the strengths and weaknesses of OL cultivation in both countries, thereby providing empirical evidence for improving OL within formal education.

2 Literature review

2.1 OL and formal education curriculum system

OL has been defined as "an understanding of the ocean's influence on you and your influence on the ocean." In 2005, the first edition of *Ocean Literacy: The Essential Principles of Ocean Sciences K-12* was released, clearly specifying the fundamental body of knowledge that an OL citizen should master by the end of secondary education, thereby establishing the original framework for OL (Payne et al., 2022). In 2017, the United Nations Educational, Scientific and Cultural Organization (UNESCO) released the *Global Strategy for OL: Raising Awareness of the Importance of the Ocean and Its Resources for Sustainable Development*, and simultaneously launched the *Ocean Literacy for All-A toolkit*, marking the official establishment of OL as a global priority action area for Ocean Education (Santoro et al., 2017). Against this backdrop, multiple countries and researchers have begun to focus on the presence of OL within formal education curricula. Curriculum standards and school textbooks serving as the primary objects of examination. At present, a systematic framework for review has been established in this field, and a body of research findings has been accumulated.

The first type of review focuses on the direct examination of ocean-related content in formal education curriculum materials, aiming to identify the presence or absence of OL. Gough (2017), through a keyword-based review of multiple national curricula, found that the themes of "Ocean" and "Marine" were marginalized in the national curricula of the United Kingdom, New Zealand, and Australia. McPherson et al., (2018) review of high school science curricula in Nova Scotia, Canada, found that only the courses in Ocean, Science, and Geology achieved limited inclusion of OL among the 11 courses. Mogias et al. (2021) revealed through reviews of Greek primary and secondary school science textbooks that the textbooks provided only limited and fragmented information on OL, with significant disparities across subjects in the incorporation of the OLF. Pazoto et al. (2022) reported the differences in OL across various Brazilian federal units and pointed out that OL remains underrepresented in Brazil's science education and falls below the minimum standard required for OL individuals. These studies collectively reveal the weak presence of OL education within formal education curriculum systems worldwide.

The second review system, building upon the first, further evaluates the degree of relevance between the identified content and OL. The approach was first introduced by Hoffman and Barstow (2007) in their review of the Earth Science Education Standards of the 50 States, where they developed the DIF grading scale and found that standards contained insufficient content directly related to OL. Similarly, the National Marine Educators Association (NMEA), in evaluating the alignment between OL and the Next Generation Science Standards (NGSS), developed a 4-point scale rating system (National Marine Educators Association Ocean Literacy Committee, 2015). In the point 2 review, it was found that numerous Disciplinary Core Ideas (DCI) and Performance Expectations (PE) exhibited a terrestrial bias and neglected the uniqueness of ocean systems. Building on the work of Hoffman and Barstow, Chang et al. (2021) introduced a new grading scale, "Collective," to review the Indian National Standards, and the results showed that 8% of the identified OL content was rated as Collective. These studies, through the establishment of distinct grading scale, evaluated the extent to which OL has been incorporated into formal education curriculum system.

Existing research indicates that while OL education across countries shares common challenges, it also exhibits distinctive national features, with different grading scale yielding divergent evaluation outcomes. It is therefore essential to recognize the practical achievements of various countries in advancing OL within formal education curriculum systems and to promote mutual learning for complementary strengths. Accordingly, it is not only necessary to sustain ongoing reviews of OL in formal education curriculum system but also imperative to emphasize international comparative studies, which will facilitate the effective dissemination and adoption of successful experiences in integrating OL into formal education worldwide.

2.2 OL and science curriculum

Within the formal education curricula of major countries, the science curriculum, as a core subject area, is widely recognized as a key vehicle for delivering OL education (Schoedinger et al., 2005). Empirical studies have also shown that "science" is the most frequently appearing keyword in OL-related research (Costa and Caldeira, 2018).

From the perspective of the relationship between science and OL, science is essential to understanding and addressing ocean-related problems, and one of the core goals of acquiring OL is specifically to solve these problems; thus, the two are closely interconnected. As a discipline that investigates natural phenomena and their laws through observation, experimentation, and theorization, science regards the ocean as a key object of study and offers systematic solutions for achieving ocean sustainability (Boesch, 1999; Kelly et al., 2022). Against this backdrop, ensuring strong scientific integration has been identified as a critical area of action in promoting sustainable ocean development, providing clear direction for the scientific orientation of OL (Claudet, 2021). At the same time, OL is an important component of scientific literacy, not only because key scientific concepts can be taught through ocean-based examples, but also due to the high degree of alignment in their educational aims, which are namely, to cultivate individuals' capacity to make informed decisions on scientific issues of significant societal relevance (Strang et al., 2007).

From a developmental standpoint, OL was jointly proposed by ocean scientists and educators, and one of the primary motivations for its emergence was to address the lack of ocean-related content in U.S. science education standards (McKinley et al., 2023). The proposal of OL was not merely intended to fill a gap. From its inception, it was conceived as an interdisciplinary educational framework (National Marine Educators Association, 2024). This is evident in its inclusion of content that goes beyond the boundaries of traditional scientific disciplines and emphasizes integrative science. In practice, OL encompasses content from physical science (PS), life science (LS), geographical science, environmental studies, and other subjects, most of which are generally classified under the science curriculum at the basic education level.

The interdisciplinary nature of OL indicates that examining a single discipline alone cannot fully capture the actual status of OL education; therefore, a comprehensive review across all science-related disciplines is required. Moreover, since OL itself is an integrated interdisciplinary framework, evaluating the individual OL principles in isolation is insufficient. Instead, a methodological approach is needed to uncover the implicit networks of OL embedded within existing science curricula, thereby fostering a more holistic understanding.

2.3 Development and practice of ocean education in China and the United States

Although all human beings share the same ocean, the environmental challenges and governance needs of the ocean demonstrate significant regional heterogeneity, and governance rights are distributed among sovereign states, regional organizations, and international institutions (Chen and Liu, 2023). As two of the world's leading maritime powers, China and the United States both play critical roles in the global ocean governance system, yet each faces distinct crises in ocean governance and development challenges. Consequently, based on their respective geographical features and governance demands, the two countries have evolved distinctive national paradigms for ocean education.

In response to ocean crises and challenges, the United States was the first to recognize that limited public awareness of ocean issues had become a major obstacle to governance, as it restricted both public participation and effective ocean management (Steel et al., 2005; Perry et al., 2014). To address this, the U.S. government has successively launched various ocean education initiatives and programs. For instance, in 1966, the U.S. Congress approved the National Sea Grant College Program, which provided ocean education training and assistance to K–12 and university level educators (National Oceanic and Atmospheric Administration Sea Grant, 1966). This program is widely regarded as an early and representative case of promoting ocean education in the United States. In 2004, the Bush administration submitted the *U. S. Ocean Action Plan* to the U. S. Commission on Ocean Policy, which, at the national level, explicitly called for the promotion of "lifelong ocean education" through formal education and outreach components (United States Executive Office of the President, 2004). In 2010, the Obama administration released the country's first national ocean policy—*Stewardship of the Ocean, Our Coasts, and the Great Lakes*—and in the 2013 *National Ocean Policy Implementation Plan Appendix*, further emphasized the need to support the inclusion of ocean content in the NGSS and to develop a "skilled ocean workforce" (National Ocean Council, 2013). At present, the United States has established a comprehensive ocean education framework encompassing basic education, career development, and lifelong learning through a combination of legislative and administrative measures.

Similar to the United States, the *National Ocean Awareness Development Index Report* (《国民海洋意识发展指数报告》) released in mainland China also reveals the problem of weak ocean awareness among the general public (National Marine Awareness Development Index Study Group, 2017). Over the years, the Communist Party of China and the central government have attached great importance to maritime rights and interests, emphasizing that the 21st century is a "maritime century." In the report of the 18th National Congress of the CPC, the phrase "building a strong maritime nation" was, for the first time, written into a programmatic document of the Party, underscoring its strategic importance in the overall development of the country (Hu, 2012). To realize this vision, in 2016, the State Oceanic Administration (now merged into the Ministry of Natural Resources), together with the Ministry of Education, the Ministry of Culture, the State Administration of Press, Publication, Radio, Film and Television, and the State Administration of Cultural Heritage, jointly issued the document entitled 《提升海洋强国软实力——全民海洋意识宣传教育和文化建设"十三五"规划》. This plan explicitly proposed the incorporation of ocean knowledge into textbooks, classrooms, and campuses, thereby promoting the development of ocean education within the field of basic education (The State Oceanic Administration, The Ministry of Education, The Ministry of Culture, The State Administration of Press, Publication, Radio, Film And Television, The State Administration of Cultural Heritage, 2016). In 2017, the General High School Curriculum Plan issued by the Ministry of Education of the People's Republic of China listed "strengthening education on maritime rights and interests" as one of the basic principles of the new round of curriculum reform, further integrating ocean education into the formal national education system (The Ministry of Education of the People's Republic of China, 2020a). At present, mainland China has gradually developed a distinctive educational system of "Chinese Ocean Consciousness," which centers on cultivating awareness of ocean nature, economy, politics, and culture (Mallory et al., 2022).

China and the United States have followed entirely different developmental trajectories in ocean education, yet both have made notable achievements in building their respective ocean education systems. Accordingly, this study conducts a comparative analysis of the incorporation of OL into the science curricula of the two countries. Such an analysis not only helps to address the research gap in comparative studies on OL between China and the United States, but also provides empirical evidence and constructive insights for further improving marine education strategies in both nations.

3 Materials and methods

3.1 Analytical materials

The materials analyzed in this study are the science curriculum standard documents (Table 1) spanning grades 1–12 in China and the United States. These documents, respectively, represent the most influential and widely adopted current curriculum standards in each countries. The findings derived from this analysis describe and contrast the current status of OL cultivation within science curricula of the two nations.

To facilitate international academic understanding and comparative research, it is necessary to explain the structure of the science curriculum within the formal education system of mainland China (Figure 1). Mainland China follows a branched system of education, where all school age children follow the same curriculum structure during the compulsory education phase (Grades 1–6 as primary school, Grades 7–9 as junior high school). The branching occurs in Grades 10–12, where students are admitted into either general senior high schools or vocational senior high schools based on their performance in the Senior High School Entrance Examination. The complete science curriculum is implemented throughout the entire compulsory education phase and in general senior high schools, whereas vocational high schools offer only partial science subjects with simplified content compared to those in general senior high schools. During compulsory education, all school age students receive a uniform science curriculum. At the primary level, an integrated science course is provided under the unified subject title "Science" (The Ministry of Education of the People's Republic of China, 2022a). At the junior high school level, the science curriculum is generally subject based, with biology and geography taught in Grades 7–8, physics introduced in Grades 8–9, and chemistry taught in Grade 9. At the senior high school level, the science curriculum continues to follow a subject structure, covering physics, chemistry, biology, and geography, and is further divided into three modules: compulsory courses, selective compulsory courses, and elective courses (The Ministry of Education of the People's Republic of China, 2020a). Under this framework, all students are required to complete the compulsory modules in Grade 10 and pass the Senior High School Academic Proficiency Test, which serves as a basic requirement for graduation. Students who choose certain science subjects as part of their elective selection for the Nationwide Unified Examination for Admissions to General Universities and Colleges will systematically study two additional types of course modules in that subject, namely selective compulsory courses and elective courses, during Grades 11–12. The elective courses are not mandatory.

Against this background, nine curriculum standard documents issued by the Ministry of Education of the People's Republic of China were reviewed (Table 1). For the United States, the review of science curriculum standards was based on the NGSS, developed by the Lead States under the coordination of Achieve Inc. (Table 1). To ensure the reliability and validity of the comparative study between the two countries' science curriculum standards, this study standardized the science curriculum standards of the two countries:

1. The scope of curriculum content reviewed is limited to the disciplines of PS, LS, and Earth and Space Science (ESS) under the science curriculum standards of both countries;
2. To align the grade level structures of the two countries' science curriculum standards, the Kindergarten's standards in the United States are excluded from this study;
3. To align the disciplinary structures of both curriculum systems, the physics and chemistry standards for Grades 7–9 and Grades 10–12 in China are consolidated into the PS subject for the purposes of this study, while the geography standards are limited to only include the ESS DCI ("Earth in the Universe,"

TABLE 1 Research documents (the discrepancy in the number of curriculum standards documents reviewed between China and the United States does not affect the validity of the study's findings).

Country	Stage	Curriculum standards	Publisher
China	1–6	Compulsory Education Curriculum Standards for Science (The Ministry of Education of the People's Republic of China, 2022f)	The Ministry of Education of the People's Republic of China.
	7–9	Compulsory Education Curriculum Standards for Physics (The Ministry of Education of the People's Republic of China, 2022e) Compulsory Education Curriculum Standards for Chemistry (The Ministry of Education of the People's Republic of China, 2022c) Compulsory Education Curriculum Standards for Biology (The Ministry of Education of the People's Republic of China, 2022b) Compulsory Education Curriculum Standards for Geography (The Ministry of Education of the People's Republic of China, 2022d)	
	10–12	General Senior High School Curriculum Standards for Physics (The Ministry of Education of the People's Republic of China, 2020e) General Senior High School Curriculum Standards for Chemistry (The Ministry of Education of the People's Republic of China, 2020c) General Senior High School Curriculum Standards for Biology (The Ministry of Education of the People's Republic of China, 2020b) General Senior High School Curriculum Standards for Geography (The Ministry of Education of the People's Republic of China, 2020d)	
United States	1–12	Next Generation Science Standards (National Research Council, 2013)	The Lead States under the coordination of Achieve

"Earth Systems," and "Human Environment Interactions"), excluding all other curriculum components.

4 To align the scope of textual review between the two countries' science curriculum standards, adjustments were made to accommodate structural differences in their document' statement. Although the curriculum standards of both countries generally follow the Audience–Behavior–Condition–Degree (ABCD) framework for formulating learning objectives, significant differences remain in the statement of these standards. In the U.S. standards, PE often express Behavior content using more generalized and abstract formulations (e.g., "Analyze and interpret data from maps to describe patterns of Earth's features"), while the Chinese standards tend to describe Behavior content using more concrete and specific expressions (e.g., "Identify the distribution of major landforms and seafloor features on a world relief map, and observe the general patterns of topographic distribution"). Therefore, to ensure fairness and consistency in the review of OL, it is necessary to include the statements of both the DCI and Clarification Statements (Figure 2) associated with the PE in the United States standards within the scope of analysis. Otherwise, the instructional intent of the United States standards would appear ambiguous, and the resulting discrepancy in information density between the two systems could distort the validity of the comparative analysis.

3.2 Analytical methods

3.2.1 Review of science curriculum standards based on OL

This study employs content analysis (Hsieh and Shannon, 2005) methodology to examine the features of the scope of coverage and quantity distribution of OL in the science curriculum standards of China and the United States. *Ocean Literacy: The Essential Principles and Fundamental Concepts of Ocean Sciences for Learners of All Ages* Version 3.2 (National Marine Educators Association, 2024), promulgated by the NMEA in 2024, is adopted as the review criteria, and the review content mainly includes the seven essential principles and 45 fundamental concepts of OL (Table 2).

3.2.2 Grading rank of review results based on the grading scale

To ensure the internal discriminability of the OL review results, this study integrates the DIF grading scale proposed by Hoffman and Barstow in *Revolutionizing Earth System Science Education for the 21st Century* (Hoffman and Barstow, 2007), and the 4-point scale rating system proposed by NMEA in *Alignment of the ocean literacy framework to the NGSS* (National Marine Educators Association Ocean Literacy Committee, 2015), to develop a grading scale applicable to the OL review in this study. This grading scale was established through a consultative process with experts in the field of science education. The Directly and Indirectly levels were inherited from the DIF grading scale, but their scope of application was refined to focus specifically on instructional content. The Case level is derived from point 3 in the NMEA grading scale, with its applicability further restricted, assigned only when the science curriculum standards explicitly include instructional cases related to OL. All grading ranks were revised according to the statements of the Chinese and U.S. science curriculum standards. Figure 2 presents the detailed structure of this grading scale.

The primary rationale for these modifications of the grading scale described above is as follows: the focus of our study was to examine which principles of OL are explicitly communicated to teachers by the curriculum standards and in what form they are presented. It was therefore necessary to distinguish whether OL was presented in each

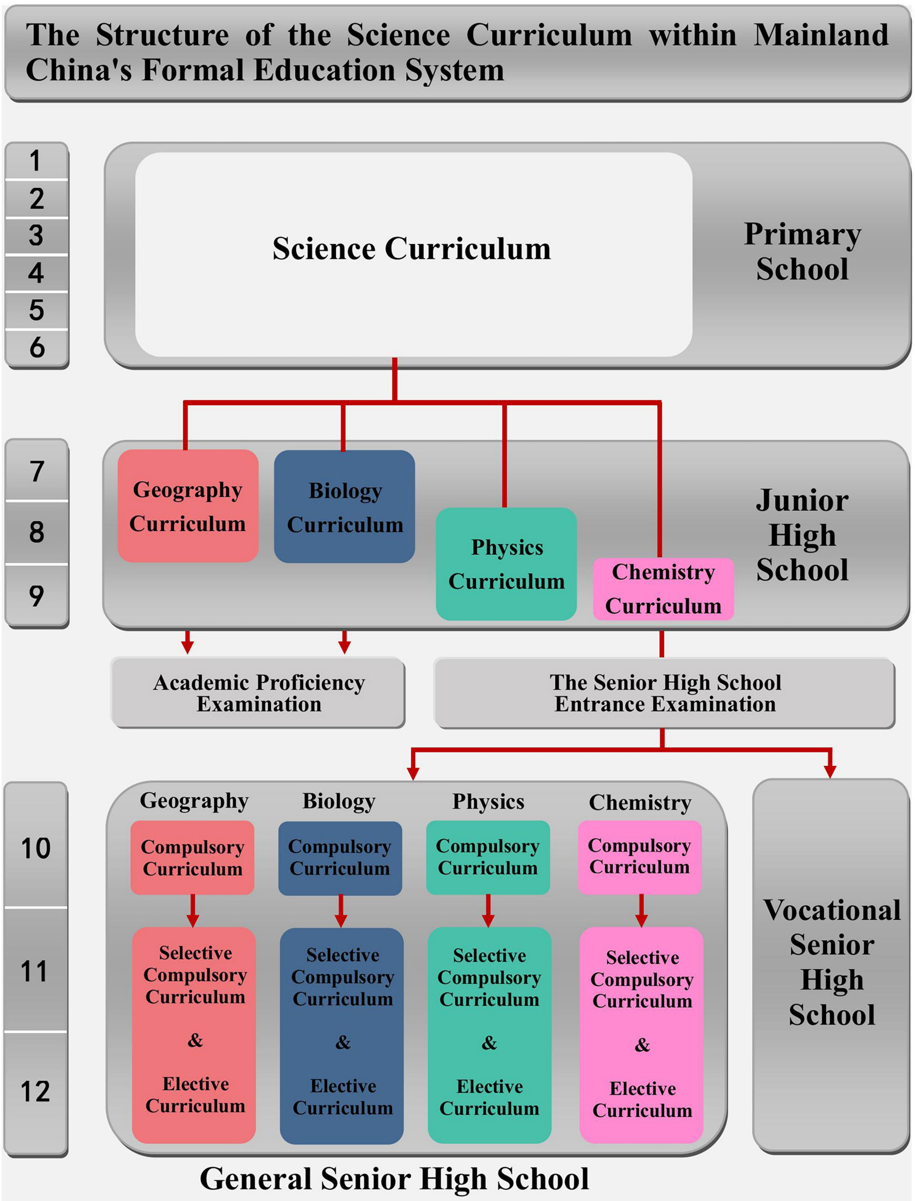

FIGURE 1
The structure of the science curriculum within Mainland China's formal education system.

curriculum standard as instructional content or merely as a supplement to instructional examples. This requirement led to the clarification that the Directly/Indirectly grade proposed by Hoffman and Barstow should be limited in scope to instructional content, and also provided justification for the revision and specification of the applicability of Point 3 proposed by NMEA.

Ultimately, the coding process for the OL review and grading rank consisted of the following steps: (1) Processing the textual materials of the Chinese and U.S. science curriculum Standards; (2) Three researchers collaboratively studied the content of OL and reached a shared understanding of its meaning through consultation; (3) Jointly reviewing each item in the curriculum standards to identify text segments related to OL; (4) Coding each relevant segment individually: if the text corresponds to a specific essential principle of OL, it is coded as 1; if it does not correspond, it is coded as 0. When a single curriculum standard involves multiple principles, more than one essential principle may be applied in the coding. (5) Assigning grading ranks to the categorized segments. The importance of the grading ranks decreases progressively from D to C, and only one grading ranks is assigned per curriculum standard. A total of 82 and 55 OL related curriculum standards were identified in the reviewed Chinese and U.S. Science Curriculum Standards, respectively.

To ensure the reliability of the research results, we employed Fleiss's kappa coefficient to evaluate the consistency of the review and grading rank results among the three researchers (Fleiss, 1971). The analysis revealed that the Fleiss's kappa coefficients between the researchers were K1 = 0.985 and K2 = 0.851, indicating that the consistency of all results passed the evaluation. Here, K1 and K2 represent the consistency of the results from the two researchers in steps (4) and (5) of the review and grading rank process. During the review and grading rank process, after completing each step, the three researchers engaged in in-depth discussions to resolve any differences that arose, reaching a full

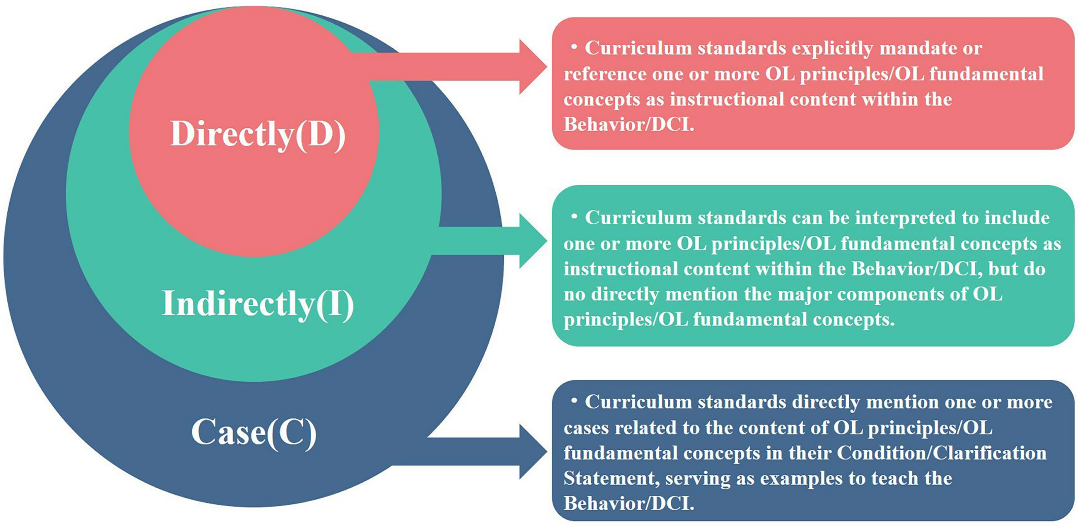

FIGURE 2
Grading scale of OL review results.

TABLE 2 OL review criteria.

Principle	Content
OL1	Earth has one big ocean with many features.
OL2	The ocean and life in the ocean shape the features of the Earth.
OL3	The ocean is a major influence on weather and climate.
OL4	The ocean makes Earth habitable.
OL5	The ocean supports a great diversity of life and ecosystems.
OL6	The ocean and humans are inextricably interconnected.
OL7	The ocean is largely unexplored.

Detailed descriptions of each OL Fundamental Concept will be provided on *Ocean Literacy: The Essential Principles and Fundamental Concepts of Ocean Sciences for Learners of All Ages* (https://repository.library.noaa.gov/view/noaa/67228/noaa_67228_DS1.pdf).

consensus before proceeding to the next step. This process effectively ensured the objectivity and accuracy of the research results.

3.2.3 Epistemic network analysis of OL

As with the interconnected ocean, the principles of OL do not exist in isolation, but as an interconnected organic whole (National Marine Educators Association, 2024). In this study, Epistemic Network Analysis (ENA) (Shaffer et al., 2016) was used to explore the linkage differences between the OL principles in the science curriculum of China and the United States, aiming to reveal the deeper ocean education philosophy of the two countries. Previous studies have employed ENA to analyze interaction patterns between different Nature of Science contents in Science Curriculum (Gao et al., 2023; Xie et al., 2025). Although this method has not yet been applied to the field of OL, it provides important theoretical and methodological support for this study due to the commonalities between the two in terms of analytical principles and methodology. In the specific process, we used ENA Website platform[1] to analyze the OL coded data from the review results. "Country," "Discipline," and "Specific Entry" were set as Units; "Country" was used as the Conversation; and OL principles served as Codes to construct the association network. Finally, using "Country" as the Group, we generated the Epistemic Network structures and overlap subtraction diagrams for China and the United States, and conducted a comparative analysis of the OL Epistemic Network structures in the science curricula of both countries.

4 Results

4.1 Overall features of OL in the science curriculum of China and the United States

Figure 3 illustrates the scope of coverage and quantity distribution of OL in the science curriculum of China and the United States. The Chinese and U.S. science curricula exhibit complete consistency in the scope of coverage of OL. In terms of quantitative distribution, China demonstrates greater prominence across most OL principles, which is consistent with the disparity in the number of entries identified during the previous review process. Moreover, both countries show a common overall tendency to focus primarily on OL1 and OL6, while OL4 and OL7 are underrepresented.

However, the two countries display distinct patterns in the quantitative distribution of OL. Specifically, the Chinese science curriculum shows a pronounced peak, with the greatest emphasis placed on OL6. This finding is consistent with previous research (Chang et al., 2021; Mogias et al., 2021), as OL6, being closely related to everyday life, is typically well represented in curricula. In contrast, the distribution of OL within the U.S. science curriculum is relatively balanced, except for the underrepresentation of OL7. Such balance may stem from the use of more abstract concepts in the U.S. curriculum standards, caused a single standard can simultaneously correspond to multiple OL principles.

Figure 4 illustrates the proportional distribution of OL grading ranks in the science curriculum of China and the United States.

1 https://app.epistemicnetwork.org/

Although both countries primarily adopt Grade I as the primarily grading rank, the proportion of Grade D in China's science curriculum is higher than in that of the United States. In addition, in the U.S. curriculum, the proportion of Grade C is nearly equal to that of Grade D. This finding diverges from the results previously reported by Chang et al. (2021), which indicated that ocean-related content in the NGSS was mostly Grade D. This may be attributed to the "Case" criterion introduced in this study, which classified content directly related to OL within the Condition and Clarification Statement into Grade C. This phenomenon also reveals the divergent pathways of incorporating OL into science curricula: China tends to integrate OL related ocean concepts directly into Behavior content, while the United States places greater emphasis on using OL based instructional cases to convey Behavior content.

4.2 Specific features of OL in the science curriculum of China and the United States

4.2.1 Specific features of OL from the perspective of educational stage

Table 3 reveals the scope of coverage, quantity distribution, and grading ranks of OL in the science curriculum of China and the United States from the perspective of educational stage. The data of OL-S1 indicate that the OL scope of coverage in both countries includes six or more OL principles across all educational stages. The analysis of OL-N-A1 data across educational stages shows that China's OL quantity exhibits a clear stepwise increase and surpasses that of the United States at the junior and senior secondary stage, whereas the U.S. demonstrates a more balanced distribution across all stages. This difference may stem from the divergent approaches to the development of science curriculum standards in the two countries. In mainland China, the unified science curriculum standard implemented in primary education shifts to subject based curriculum standards at the secondary stage. This allows curriculum developers of each subject to elaborate on subject knowledge in greater detail, thereby providing broader opportunities for the inclusion of OL. By contrast, the United States adopts a continuous K–12 science curriculum standards, which maintains the continuity and coherence of the science education. Finally, a comparison of the grading ranks of OL in different educational stages reveals that Grade I is the primarily grading rank in both countries across all stages.

4.2.2 Specific features of OL from the perspective of subject

The data in Table 4 reveal the scope of coverage (OL-S2), quantity distribution (OL-N-A2), and grading rank (OL-N-D2, OL-N-I2, OL-N-C2) of OL from the subject perspective in the science curricula of China and the U. S. The data indicate that the ranking of subject importance in OL scope of coverage and quantity distribution generally follows the pattern: ESS > LS > PS in both countries. It is important to note that the Chinese science curriculum exhibits a unique feature in the ordering of the scope of coverage, where the ranking is ESS > PS > LS, which is the only dimension where a difference exists. The data for OL-N-D2, OL-N-I2, and OL-N-C2 reveal the similarity in the primarily OL grading rank for the same subject in both countries: the primarily grade for ESS is Grade D, for LS is Grade I, and for PS is Grade C in both countries.

The results of the above analysis reveal the following significant facts: (1) ESS occupies a core position in OL cultivation in both China and the U.S., which is highly consistent with the findings of previous studies (Chang et al., 2021; Pazoto et al., 2023); (2) The LS teaching content in both countries lacks sufficient direct integration of OL, which leaves room for optimization; (3) Both countries show a

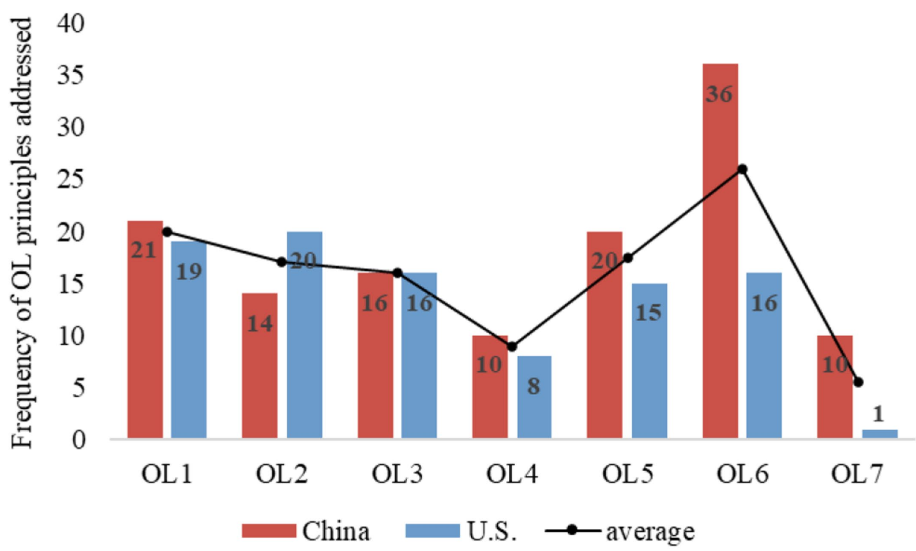

FIGURE 3
Scope of coverage and quantity distribution of OL principles in the science curriculum of China and the United States.

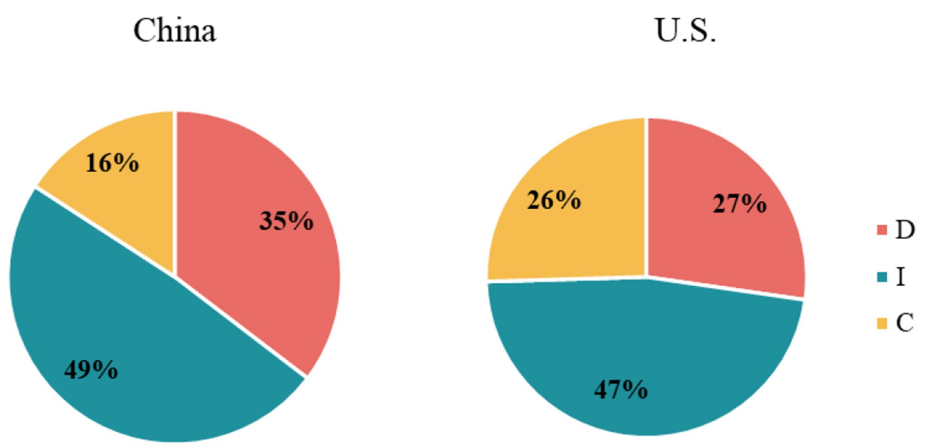

FIGURE 4
Grading ranks of OL in the science curriculum of China and the United States.

common orientation toward integrating OL into PS training in the form of "OL teaching cases."

Continuing with a comparative analysis of how OL is incorporated into the PS, LS, and ESS in China and the United States. First, in PS, China places greater emphasis on OL. In this subject, China retrieved six OL principles (OL1, 2, 3, 4, 6, and 7) and 16 curriculum standards, whereas the United States retrieved only one OL principle (OL1) and one curriculum standard. This is an notable finding, as previous studies have consistently reported difficulties in retrieving evidence of OL in PS curriculum documents (McPherson et al., 2018; Pazoto et al., 2021). Second, in LS, a contrast emerges between the two countries: the United States addresses OL more comprehensively, encompassing six OL principles (OL1, 2, 3, 4, 5, and 6) through 20 curriculum standards, whereas China, despite retrieving 30 curriculum standards in total, incorporates only four OL principles (OL2, 4, 5, and 6). Notably, three of the four Grade D curriculum standards identified in China fall within the senior secondary elective module Marine Biology, whose non-compulsory nature may constrain the effective implementation of OL in this subject. Third, in ESS, the two countries exhibit the closest overall performance. The United States covers all seven OL principles in this subject, while China includes six (OL1, 2, 3, 4, 6, and 7). In terms of quantity, China retrieved 36 curriculum standards, slightly exceeding the 34 identified in the United States; however, 12 of these belong to senior secondary elective geography modules, whose non-compulsory status may constrain effective implementation. A more detailed comparison shows that both countries prioritize OL1 in ESS, with China placing greater emphasis on OL3, OL6, and OL7, while the United States focuses more on OL2, OL4, and OL5.

4.3 Epistemic network structure of OL in science curricula of China and the United States

Based on the idea that the structure of connections between cognitive elements is more important than the way these elements appear individually (Shaffer et al., 2016), we utilized the OL coding data from the science curriculum review process in both the United States and China. Using the ENA algorithm, we generated epistemic network maps reflecting the association features of OL principles in the science curriculum of both countries, respectively (Figures 5a,b). At the same time, in order to obtain a more distinct comparison effect, we performed a superimposed subtraction analysis of the OL epistemic network maps of the two countries (when there is an overlap of the connecting lines between the OL nodes of the two countries, the visualization results will preferentially display the color of the side with the higher connection frequency, and the thickness of the connecting lines will reflect the result of the subtraction of frequencies). The superimposed subtraction of the epistemic networks of the two countries is demonstrated in Figure 5c.

The size of the nodes and the thickness of the connecting lines reflect the similarities and differences between the OL epistemic networks of China and the United States at the micro level (Shaffer et al., 2016). China's OL cognitive network demonstrates a strong central structure: with OL6 serving as the core hub, it forms high-intensity associations with OL1 and OL2, and also shows moderate radial connections with other nodes (OL3, OL4, OL5, OL7); while only weak connections or no direct associations are found among the remaining nodes (e.g., OL3–OL5, OL4–OL7, OL5–OL7). In contrast, the OL epistemic network of the United States exhibits a polycentric structure, where OL1, OL2, OL3, and OL6 are interconnected through dense links, forming a high-intensity "ocean system" epistemic network. However, OL7 shows low connectivity with other OL principles.

In addition, the node distribution pattern reveals the clustering features of OL principles in the coordinate system and their potential quadrant implications (Shaffer et al., 2016). As shown in Figure 5c, OL principles exhibit significant spatial differentiation along the X-axis. Specifically, OL6 and OL7 are mainly located in the positive direction of the X-axis, while OL1 to OL4 are more concentrated in the negative direction, and OL5 is positioned off the X-axis. Based on the implications of each OL principle,

TABLE 3 Distribution of the scope of coverage, quantity distribution, and grading ranks of OL across educational stages.

Principle	Grade	primary school		Junior high school		Senior high school	
		China	US	China	US	China	US
OL1	D	1	4	6	4	7	3
	I	0	2	1	1	2	2
	C	0	1	4	1	1	1
OL2	D	0	2	1	1	4	4
	I	1	2	2	3	5	3
	C	0	3	0	1	1	1
OL3	D	1	1	2	4	7	2
	I	0	0	0	1	5	3
	C	0	1	1	1	0	3
OL4	D	0	2	2	0	0	0
	I	2	0	3	1	3	3
	C	0	1	0	0	0	1
OL5	D	0	2	0	1	3	1
	I	1	2	10	3	6	5
	C	0	0	0	1	0	0
OL6	D	2	1	4	0	11	0
	I	0	1	2	3	9	5
	C	0	1	3	2	3	3
OL7	D	0	0	1	0	3	0
	I	0	0	0	0	2	1
	C	0	0	4	0	0	0
OL-S1		6	6	7	6	7	7
OL-N-D1		3	6	8	5	18	4
OL-N-I1		5	6	14	8	21	12
OL-N-C1		0	5	8	4	5	5
OL-N-A1		8	17	30	17	44	21

The scope of coverage of OL in the table is marked with "S": the scope of coverage of OL under the educational stage (OL-S1); the quantity distribution of OL is marked with "N": the number of OL under the educational stage at Grade D (OL-N-D1), the number of OL at Grade I (OL-N-I1), the number of OL at Grade C (OL-N-C1), and the total number of OL across all Grades (OL-N-A1).

we propose that the X-axis may represent a continuous explanatory dimension: the positive direction indicates the "interaction between the ocean and human activities and future development," reflecting the humanistic value and social attributes of the ocean; whereas the negative direction reflects the "features of the ocean system and its interactions with the Earth system," highlighting the natural attributes of the ocean. On the basis of this inferred explanatory dimension of the X-axis, the statistical results of the two-sample t-test reveal macro-level differences in the OL cognitive networks between the two countries: the center of gravity of China is significantly oriented toward the positive direction of the X-axis, indicating that China places greater emphasis on the "interaction between the ocean and human activities and future development"; in contrast, the center of gravity of the United States is skewed toward the negative direction, suggesting greater attention to the "features of the ocean system and its interactions with the Earth system."

5 Discussion

5.1 Common gaps in OL cultivation within the science curricula of China and the United States

The findings reveal common gaps in OL cultivation within the science curricula of China and the United States, with both exhibiting insufficient emphasis on OL4 and OL7 in their overall features. This issue is not unique to these two countries, as OL4 and OL7 are likewise rarely reflected in reviews of science curricula and textbooks from other nations (McPherson et al., 2018; Chang et al., 2021; Mogias et al., 2021).

The limited presence of OL4 in science curriculum standards may be influenced by several factors. On the one hand, OL4 contains only three fundamental concepts, which objectively limits its representation in the curriculum (National Marine Educators Association, 2024). On

TABLE 4 Distribution of the scope of coverage, quantity distribution, and grading ranks of OL across subjects.

Principle	Grade	PS		LS		ESS	
		China	US	China	US	China	US
OL1	D	1	0	0	1	13	10
	I	1	0	0	0	2	5
	C	4	1	0	1	1	1
OL2	D	0	0	0	2	5	5
	I	0	0	3	2	5	6
	C	1	0	0	1	0	4
OL3	D	0	0	0	2	10	5
	I	0	0	0	1	5	3
	C	1	0	0	0	0	5
OL4	D	0	0	1	0	1	2
	I	1	0	5	2	2	2
	C	0	0	0	1	0	1
OL5	D	0	0	3	3	0	1
	I	0	0	17	9	0	1
	C	0	0	0	1	0	0
OL6	D	2	0	1	0	14	1
	I	3	0	4	3	4	6
	C	4	0	1	1	1	5
OL7	D	0	0	0	0	4	0
	I	1	0	0	0	1	1
	C	3	0	0	0	1	0
OL-S2		6	1	4	6	6	7
OL-N-D2		2	0	4	3	23	12
OL-N-I2		4	0	25	14	11	12
OL-N-C2		10	1	1	3	2	10
OL-N-A2		16	1	30	20	36	34

The scope of coverage of OL in the table is marked with "S": the scope of coverage of OL under the subjects (OL-S2); the quantity distribution of OL is marked with "N": the number of OL under the subjects at Grade D (OL-N-D2), the number of OL at Grade I (OL-N-I2), the number of OL at Grade C (OL-N-C2), and the total number of OL across all Grades (OL-N-A2).

the other hand, these concepts are largely obscured by terrestrial bias (National Marine Educators Association Ocean Literacy Committee, 2015). For instance, China's Biology curriculum standards emphasize only the concept that "plants provide oxygen to other organisms in the biosphere," while overlooking the critical role of ocean algae in producing atmospheric oxygen. This curricular deficiency weakens the presence of marine ecosystems. Curriculum developers should consider incorporating fundamental concepts into the curriculum, such as most oxygen on earth from photosynthesis in ocean and the ocean, as the cradle of life, provides water, oxygen, and nutrients, because these are vital for fostering students' intrinsic motivation to protect the ocean (Tsai and Chang, 2024).

The presence of OL7 in the Science Curriculum is likewise extremely limited. This may be due to the fact that the fundamental concepts of OL7 do not focus on pure ocean science knowledge, but instead emphasize real world needs such as ocean exploration, the application of emerging ocean technologies, and interdisciplinary collaboration among ocean professionals (Mogias et al., 2021). Such content is typically difficult to convey through standardized instructional materials and relies more on teaching cases. We recommend that teachers emphasize the cultivation of OL7 in classroom instruction, as understanding the future of ocean exploration, technology, and careers is considered to positively influence students' career choices and nation's economic outcomes (Guest et al., 2015).

The results also indicate that in both countries, Grade I is the predominant grading rank in the overall features and educational stage features of OL. This phenomenon may be attributed to the deliberate blurring of the boundary between terrestrial systems and ocean systems in the science curriculum of both countries. For example, one of the standards in the U.S. science curriculum states: "Develop a model to represent the shapes and kinds of land and bodies of water in an area," which includes both inland and oceanic water bodies. Similarly, a standard in the Chinese science curriculum requires: "analyzing the morphological structure, physiological features, and distribution features of organisms in different communities that are adapted to the environment of the community," where both terrestrial and ocean biomes can be used to teach the

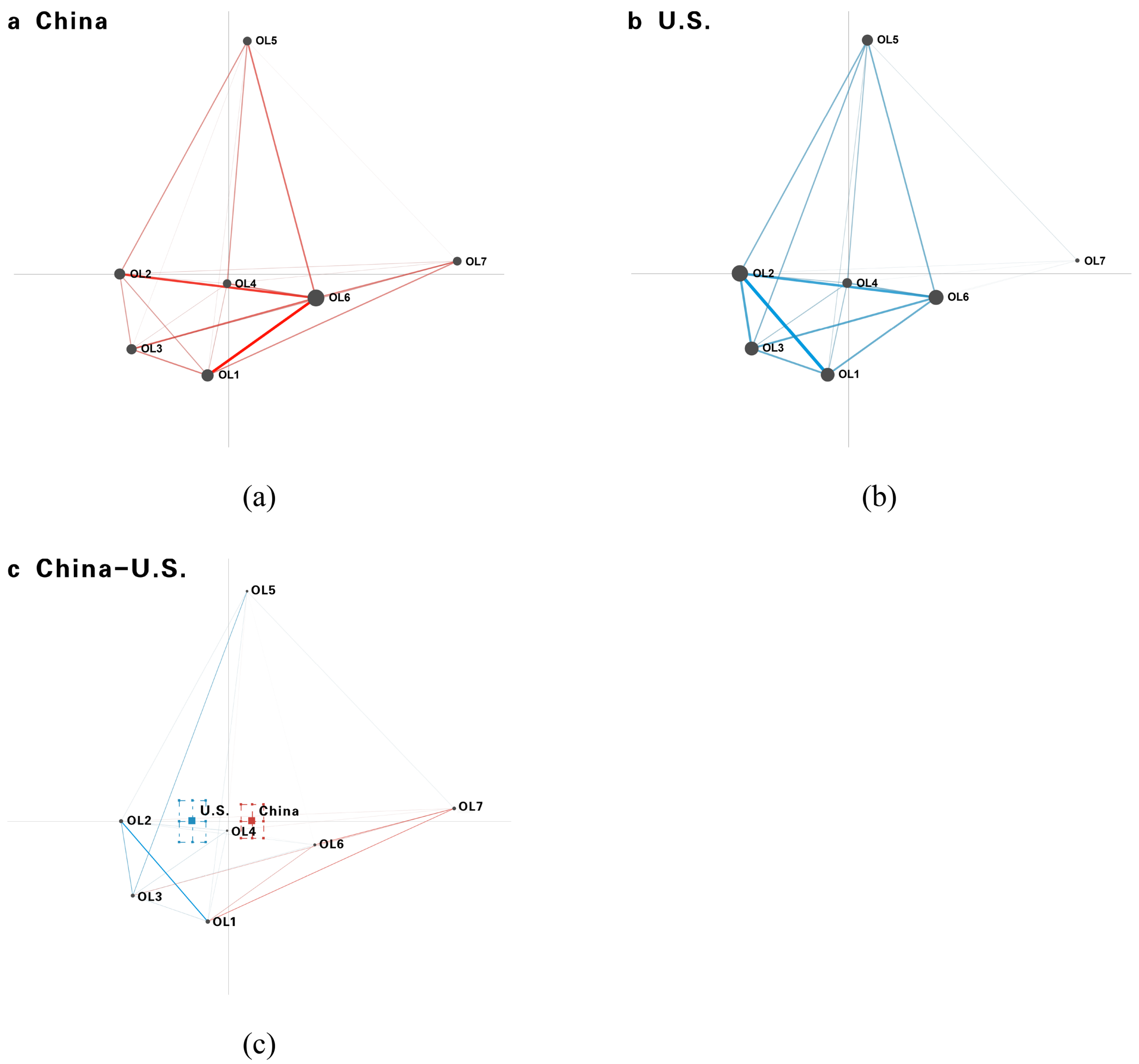

FIGURE 5
Epistemic network structure between OL in the science curricula of China and the United States: **(a)** China; **(b)** U.S.; **(c)** superimposed subtraction of the epistemic networks of the two countries.

content. While this conceptual blurring expands the flexibility for integrating OL into the science curriculum, it may also cause teachers to overlook the uniqueness of ocean systems during instruction, potentially marginalizing ocean content within science curricula.

Finally, the results of the study also revealed that, in the subject features of both countries, the direct incorporation of OL into LS teaching content is insufficient. The reason for this is also the blurring of the boundary between terrestrial systems and ocean systems. However, previous studies have shown that students exhibit greater interest in topics related to ocean life and its biodiversity (Marrero, 2010).

In light of these challenges and the feasibility of potential solutions, we call on curriculum developers to prepare a new teacher's guide for the science curriculum, building upon the existing curriculum documents in both countries. This guide should emphasize supplementing missing OL principles, balancing the representation of different OL principles, eliminating terrestrial bias in the standards, and carefully interpreting Grade I curriculum standard entries, particularly in LS, to support the explicit integration of more "ocean" and "ocean life" content. Such efforts will ensure that OL is effectively achieved and reinforced through clearer learning objectives. Furthermore, we recommend that ocean science researchers and educators establish a regular monitoring and evaluation system to track students' OL development and provide targeted interventions to support its enhancement.

5.2 Individual features of OL cultivation in science curricula of China and the United States

The results of the study show that OL in the science curriculum of China and the United States exhibit their individual features, and ultimately reveal the differences in the philosophies of ocean education between the two countries.

The individual features of OL cultivation in the United States are as follows. First, the number of entries for each OL principle is relatively balanced, except for OL7. Second, OL is cultivated continuously across all educational stages, beginning systematically in primary school and embedding early impressions during the critical period of value formation. Third, in LS, OL exhibits an interdisciplinary nature, extending beyond OL4 and OL5 to integrate complex concepts such as biogeochemical cycles (e.g., the carbon cycle). Fourth, the Epistemic Network shows strong connectivity among OL nodes, emphasizing the ocean system's intrinsic features and its interactions with the Earth system. These features collectively reflect the United States' distinctive ocean education philosophy: an emphasis on an interdisciplinary perspective to explain the principles of ocean system and ocean science, deepening the understanding of the natural properties of the ocean, while also attaching importance to early childhood ocean education.

The individual features of OL cultivation in China are mainly focused on: First, OL6 is highly emphasized. Second, the number of OL entries increases progressively across educational stages, aligning with students' cognitive development. Third, the PS curriculum incorporates numerous cases of ocean exploration and development, such as using "tidal energy" to illustrate sustainable energy and the "Striver" submersible to explain liquid pressure and buoyancy. Fourth, the Epistemic Network emphasizes the interaction between the ocean, human activities, and future development. The above features eventually converge into the distinctive philosophy of ocean education in China: centering on the "human–ocean relationship," it emphasizes the humanistic values and social attributes of the ocean on the foundation of understanding its natural properties.

In comparison with the individual features of OL cultivation in the United States, we recommend that Chinese curriculum developers pursue a more balanced distribution across all OL principles and construct a more strongly interconnected cognitive network, avoiding an excessive focus on OL6. Regarding articulation across educational stages, Chinese curriculum developers should ensure continuity of OL, with particular attention to strengthening OL initiation in elementary education. In addition, Chinese curriculum developers should support teachers in designing effective ocean education programs, identifying essential OL knowledge, and facilitating smooth transitions between different educational stages.

Regarding the strong emphasis on OL6 in China's science curriculum, we argue that such emphasis may entail potential environmental ethical risks. During the review process, this study found that most of the standardized entries related to OL6 in the Chinese science curriculum were concentrated on the fundamental concept of OL6b (the ocean provides food, medicine, minerals, and energy resources). This excessive focus on the economic value and resource attributes of the ocean, treating the ocean system as a "resource base" while ignoring its intrinsic life network, may cause students' understanding of ocean conservation to remain at the level of the sustainable use of ocean resources, resulting in a utilitarian tendency of Shallow Ecology (Spash, 2013). This, in turn, may weaken students' ability to establish a natural connection with the vibrant ocean. We recommend that policy-makers, at the level of value orientation, guide students to return to the fundamental stance of Deep Ecology (Luke, 2002), which affirms that the health and prosperity of both human and non-human life on Earth possess intrinsic value. At the same time, efforts should be made to coordinate the strategic goal of building a "oceanic power" with the practical imperative of "oceanic conservation."

Compared with the United States, another distinctive individual feature of China's OL education lies in the subject structure of the science curriculum and the elective course system. Although the subject based arrangement of science curriculum at the junior and senior secondary stages provides broader opportunities for the incorporation of OL, it has also led to an inevitable fragmentation of subject, a limitation that is already reflected in the relatively weak connectivity within certain OL epistemic networks. Accordingly, curriculum developers should actively break down subject barriers and, even under a subject based curriculum structure, consider the connections among ocean knowledge in PS, LS, and ESS, so as to construct an interdisciplinary ocean science knowledge system. With regard to elective courses, given their non-compulsory nature, we recommend that teachers ensure the effective implementation of OL by actively developing school-based curricula on ocean-related themes.

5.3 Factors influencing the differences in ocean education philosophy in science curricula of China and the United States

From a national perspective, the core objective of ocean education is to cultivate talents capable of serving national ocean governance and regional ocean development. Therefore, the fundamental reason for the emergence of distinctive ocean education philosophies in China and the United States lies in their differing national contexts.

At the political and economic level, since World War II, the United States has inherited Britain's maritime military advantage, and for a long period no state or non-state actor has been able to substantially threaten its global command of the seas (Ushirogata, 2025). The U.S. also possesses the world's largest Exclusive Economic Zone (Asgeirsdottir, 2016), giving it unique spatial advantages in ocean economic development. Moreover, the country has consistently reinforced its investment in ocean policy, with nearly half of its post–World War II ocean-related policies being introduced in the 21st century (Zhu, 2022). These factors have driven the U.S. to cultivate interdisciplinary ocean professionals capable of safeguarding its global maritime interests and maintaining its competitive edge. China, as an emerging oceanic power, advances its "Oceanic Power" strategy with pressing practical needs. As the world's largest developing country, the Chinese central government identifies the "protection of maritime rights and interests" and the "development of the blue economy" as core priorities (Mallory et al., 2022; Xie, 2014). National strategies such as the 21st-Century Maritime Silk Road have actively promoted the transformation of China's ocean economy. At the same time, China has long faced a complex regional landscape in ocean geopolitics, with ongoing maritime disputes involving multiple neighboring countries (Morton, 2016). Strengthening citizens' awareness of oceanic sovereignty has therefore become an urgent requirement for national security. These imperatives are also reflected in the emphasis placed on the social dimensions of the ocean within China's science curriculum.

From the perspective of sociocultural background, American ocean awareness originates from its colonial history and its rise through sea power. As a former colony of Britain, the United States was deeply influenced by Britain's maritime trade and military expansion, inheriting the maritime gene of oceanic exploration (Qu, 2024). This maritime gene was continually reinforced during America's rise in sea power. In the 19th century, Alfred Thayer Mahan Published *The Influence of Sea Power Upon History, 1,660–1783*, which laid the theoretical foundation for the rise of the United States as a oceanic power. Since the World War II, the United States has gradually dominated the global maritime security order, a role that has continued to the present day (Zhang and Wu, 2021). These historical experiences have shaped America's ocean awareness, embedding its connection with the sea deeply into the fabric of its social culture. China's ocean awareness has been shaped since modern times by the need to develop as an oceanic power (Zheng, 2014). As a typical land-based civilization, China's thousands of years of civilizational development were primarily sustained by an agricultural economy and the expansion of land territory, with "continentalism" as its core cultural trait (Zheng, 2014). This land-oriented cultural tradition has profoundly influenced China's historical perception of the ocean and its developmental trajectory, forming a cultural cognitive bottleneck for advancing as an oceanic power. Consequently, China's current science curriculum underscores the necessity of highlighting the "human-ocean relationship."

From the perspective of curriculum development, the development of U.S. science curricula has been closely intertwined with the advancement of OL. In 1996, marine science researchers and educators, during their review of the *National Science Education Standards*, identified a severe lack of ocean-related themes (Schoedinger et al., 2005). This finding directly catalyzed the OL movement. Subsequently, the National Geographic Society, COSEE, NMEA, NOAA, and the U.S. Commission on Ocean Policy all urgently advocated for the integration of ocean concepts into science curriculum standards (Schoedinger et al., 2005). These efforts may have influenced the 2013 NGSS drafting process, leading to more comprehensive consideration of OL. By contrast, China's science curriculum is mainly influenced by the framework of "Chinese Ocean Consciousness," which classifies ocean consciousness into four domains: natural, economic, political, and cultural (National Marine Awareness Development Index Study Group, 2017). This structural orientation has, to some extent, resulted in the current disproportion, whereby humanistic dimensions of the ocean are emphasized more significantly than its natural dimensions.

6 Conclusion

The science curricula of China and the United States encompass all OL principles, indicating a shared national emphasis on ocean education. Simultaneously, the OL features exhibit both differences and similarities, reflecting each country's distinctive ocean education development and general trends. Through content analysis, this study provides detailed quantitative data on the extent to which OL principles are incorporated in the science curricula of both countries, as well as their specific distribution across educational stages and subjects. Combined with ENA, the study identifies distinctive emphases in each country's ocean education and reveals specific gaps in the connections among OL principles within the curricula, particularly the weak or absent links among certain OL principles in China. These insights are especially significant, as these science curriculum standards have shaped science instruction in both countries, highlighting areas where the curriculum may need further development to foster a more comprehensive understanding of OL.

The innovations of this study are as follows: it refines the grading scale of OL, providing a reference for examining the forms of OL in curriculum standards. It introduces ENA in an innovative way, which helps to clarify the relationships among OL within the curriculum and the ocean education philosophies they reflect. These approaches can be extended to other studies to promote a more comprehensive understanding of OL. Nevertheless, this study has several limitations. First, the research materials are limited to the science curriculum standards of China and the United States, without including supporting textbooks or classroom observation data. Second, although content analysis provides a systematic comparison of the OL features in the two countries' curriculum standards, it may not fully correspond to the OL actually developed among students. Finally, the results, derived from the specific educational policies and cultural contexts of the two countries, may be constrained in their cross-cultural applicability.

To further advance the cultivation of OL in formal education, future research should broaden its scope to include interdisciplinary studies of OL across curricula and textbooks beyond the science curriculum. Comparative studies of OL features across different countries, particularly developing coastal nations, are also warranted to facilitate the assessment and enhancement of OL in these regions. Moreover, considering the distinctive ocean education philosophies of each country, future research should examine national educational systems and pedagogical approaches in depth, and conduct OL assessments based on students' actual learning conditions to gain a deeper understanding of how national educational contexts influence students' OL development.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YL: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft. JC: Data curation, Formal analysis, Resources, Validation, Writing – review & editing. KW: Data curation, Formal analysis, Resources, Validation, Writing – review & editing. MZ: Resources, Writing – review & editing. SC: Project administration, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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