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Sleep at high altitude: A bibliometric study and visualization analysis from 1992 to 2022

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ABSTRACT

Background: As an important monitoring index for adaptation to hypoxia, sleep may reflect the adaptive state of the body at high altitudes. The literature has shown a link between altitude and sleep problems, and sleep changes have become a common problem for individuals at high altitudes, negatively impacting their physical and mental health. As research on high-altitude sleep has gained attention in recent years, the publishing volume has increased worldwide, necessitating a more comprehensive understanding of this field. This manuscript evaluates the key themes and emerging trends in high-altitude sleep over the past few decades and predicts future research directions.
Methods: Articles related to high-altitude sleep published from 1992 to 2022 were retrieved from the Web of Science Core Collection, and the relevant literature characteristics were extracted after the screening. Then, bibliometric analyses and visualizations were performed using Microsoft Excel, CiteSpace, VOSviewer, and an online analysis platform (http://bibliometric.com).
Results: A total of 1151 articles were retrieved, of which 368 were included in the analysis, indicating a gradually increasing trend. The United States, Switzerland, and China have made significant contributions in this field. Bloch KE from the University of Zurich was determined to be the most productive and academically influential author in this field. The highest-yielding journal was *High Altitude Medicine & Biology*. Initially, altitude training was the primary research topic. Currently, research focuses on sleep disorders and sleep apnea. In the coming years, keywords such as “sleep quality,” “prevalence,” and “obstructive sleep apnea” will attract more attention.
Conclusion: Our findings will assist scholars to better understand the intellectual structure and emerging trends in this field. Future developments in high-altitude sleep research are highly anticipated, particularly in terms of sleep quality at high altitudes and its associated prevalence. This research is also crucial for the improvement and treatment of symptoms during nocturnal sleep in patients with chronic hypoxia due to cardiopulmonary diseases at high altitudes.

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1. Introduction

Globally, more than 400 million individuals live above 1500 m [1], and over 140 million residents live above 2500 m [2]. In addition, an increasing number of individuals commute to high-altitude regions for commercial, scientific, and travel. The definition of high altitude varies in the literature [3–5]; an altitude higher than 2500 m in the case of rapid ascent is currently widely recognized as high altitude [4]. Exposure to high altitude can directly impact respiratory physiology, and both sleep structure and continuity have been confirmed to be damaged as a result. Research on high-altitude sleep has important implications for improving sleep health and the quality of life in individuals living in or traveling to high-altitude environments.

The effects of high altitudes on sleep and breathing are primarily due to a decrease in atmospheric pressure, which proportionally reduces the available oxygen (low pressure and low oxygen), resulting in a decrease in the partial pressure of inhaled oxygen and an immediate trigger for respiratory compensation and gradual adaptation, which typically occurs within days to weeks. These effects will change the respiratory pattern and increase the hourly apnea and low respiratory index, resulting in periodic breathing (PB) [6]. PB is considered to be caused by the instability of the respiratory control systems driven by anoxia or a response to carbon dioxide [7]. Nocturnal PB can cause frequent awakening, leading to sleep structure fragmentation. The effect of hypobaric hypoxia (HH) on nocturnal breathing and sleep structure was found to be more significant than that of normobaric hypoxia (NH), which is more likely to cause PB [8]. Hypoxia reduces total sleep time (TST), sleep efficiency (SE), slow wave sleep (SWS), and rapid eye movement (REM), and increases arousal time and frequency of arousal [9]. Most individuals (32–74 %) have poor sleep quality or insomnia at high altitudes, especially during the first few days [10–12]. Changes in sleep pattern regulate mood and cognition. Poor sleep quality can affect cognitive ability during the day, cause general discomfort, promote the onset of acute mountain sickness (AMS), and aggravate anxiety, depression, and other negative emotions [13]. Sleep disorders are the most common and major complaints following high-altitude stress [14]. Changes in sleep associated with low pressure and low oxygen have become a common problem for individuals at high altitudes, negatively impacting their physical and mental health [15,16].

With increasing attention being paid to sleep at high altitudes in recent years, this field has warranted further study. However, the rapid growth in publishing volume makes it increasingly difficult for researchers, particularly new researchers, to fully understand, evaluate, and identify the most relevant and valuable information [17]. Unclear hotspots and developmental trends in the field of high-altitude sleep are not conducive for researchers to fully understand the dynamics and developmental direction. Thus, we need new methods to review and analyze this field of knowledge. Compared to traditional reviews, analyses based on bibliometric tools can provide better insight into evolving research focuses and trends, as well as relatively comprehensive and objective data analysis. However, to the best of our knowledge, no complete bibliometric research has been conducted in this field. Although previous reviews [6,7,12,18–20] have provided basic information for researchers and have improved the understanding of the effects of high altitude on sleep and the respiratory system and their adaptations, relying only on individuals to summarize and extract the relevant contents cannot fully reflect the temporal and spatial distribution of the research field. In addition, the performance of research components, cooperative network, internal structure of the knowledge base, and research focus are difficult to visualize. Therefore, there is a lack of systematic, macroscopic, and visual studies on high-altitude sleep.

The bibliometric study and visualization analysis we have conducted is a feasible method for quantitative and qualitative analysis of published scientific literature in the field of high-altitude sleep research [21]. It provides researchers with an objective and comprehensive overview of the field and maps scientific knowledge to show the development process and structural relationships of a knowledge domain, which helps us quickly grasp the evolution of the characteristics of the research topic over time [22]. Numerous science mapping tools are currently in existence, each with its advantages and characteristics [23]. For example, CiteSpace, a citation network visualization tool developed by Dr. Chaomei of Drexel University in the United States [24], can generate co-occurrence maps, cluster maps, citation burst maps, and other visualizations, focusing on tree graphs and lines to represent the strength of the relationship between each topic [25]. VOSviewer is visual software developed by Van Eck and Waltman of Leiden University in the Netherlands [26]. It enables network, overlay, and density visualizations of the author, citations, and keywords based on text, network, and bibliographic data, and decomposes the clustering relationship between nodes mainly by distance and density [27]. Bibliometric.com, an online bibliometric analysis platform for publication analysis collected by the China Science Digital Library, can be used to analyze the volume of publications, cooperative relations, influence, and keywords, and assist in the online generation of various visual atlases based on bibliometrics [28]. Researchers can leverage the strengths of different analytical tools to gain a more accurate understanding of the research topic and present it in a visually compelling manner.

Therefore, the primary aim of this study was to use all the tools mentioned above to evaluate the research trends and development of the high-altitude sleep field in recent decades and identify research hotspots and frontiers. The secondary aim was to measure research performance and impact from the perspectives of countries, institutions, authors, and journals to provide references for follow-up research collaborations and grant applications.

2. Materials and methods

2.1. Data source

The data analyzed were based on the Science Citation Index Expanded (SCI-EXPANDED) in the Web of Science Core Collection (WOSCC) database of the Institute of Scientific Information (ISI). We chose WOSCC as the data source because it is more selective in its scientific inclusion than other databases. WOSCC is considered to contain not only the most comprehensive publications and high-quality indexes [29] but also complete references and citations [30], covering the oldest publications (1900–present) and citation records (1900–present). In contrast, complete reference texts and citation lists cannot be analyzed in PubMed or Embase, which are mandatory for bibliometric analysis. Although Scopus contains publications published from 1966 to the present, only articles published after 1996 included citation analysis data [31]. Thus, the WOSCC provides a more comprehensive source of data and is the most widely used database in bibliometric studies. Fig. 1 shows the overall organization of the developed methodology in our research.

2.2. Search strategy

After carefully selecting and verifying the search terms in WOSCC, “altitude*” and “sleep*” were used for “Topic” retrieval. The scopes of “Topic” retrieval include the following fields: title, abstracts, author keywords, and keywords plus. The filter was applied to restrict document types to “article” and “review”, and the language was limited to English. Although the earliest literature in this field was published in 1958, the cumulative number of papers published from 1958 to 1991 was less than 30 and most lacked abstracts. Furthermore, relevant literature published in 2023 was not included because of the limitation of the last retrieval date (January 24, 2023). Therefore, we determined the research period to be from 1992 to 2022. More details on literature retrieval are presented in Supplementary Material Table S1.

2.3. Inclusion and exclusion criteria

Peer-reviewed articles or reviews published in English from 1992 to 2022 on high-altitude sleep topics were included in our study. To ensure the accuracy and reliability of the analysis results, we clarified the exclusion criteria for the literature, which included the following: 1) duplicate publications, 2) unavailable abstracts, 3) non-human species, 4) topics unrelated to sleep, and 5) non-real or simulated high-altitude environments.

2.4. Data extraction

Data extraction was performed independently by two researchers and any disagreements during the process were discussed with a third researcher until a consensus was reached. After reviewing titles and abstracts based on the inclusion and exclusion criteria, 368 articles were retained in the form of “Full Record and Cited References” and exported in both plain text files and tab delimited files. The total and average citations, Hirsch index (H-index), and Journal Citation Indicator (JCI) were obtained using the WOSCC. Journal information, including the impact factor (IF) and category quartiles (CQ), which are important measures of the scientific value of research, were collected from the 2021 Journal Citation Report (JCR) [32]. All data were obtained and exported within the last retrieval date (January 24, 2023) to reduce bias caused by frequent database updates.

2.5. Data analysis and visualization

The analytical features of the WOSCC database were used to thoroughly extract and scrutinize the retrieved literature, including

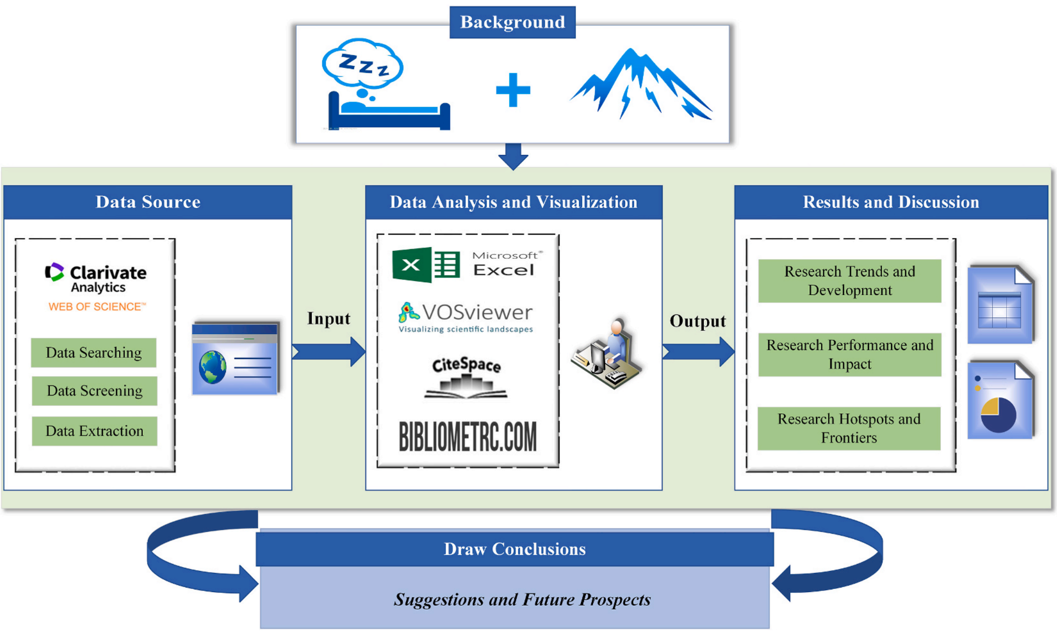


Fig. 1. The overall organization of the developed methodology.

publication quantity and citations, countries and regions, institutions, authors, and journals. Microsoft Excel was used for the statistical analysis and data processing. All data were converted into.txt format and subsequently imported into the website (http://bibliometric.com/), CiteSpace V.6.1.R2 (64-bit) and VOSviewer 1.6.18 visualization software. CiteSpace and VOSviewer were used to analyze the scientific cooperation networks among countries, institutions, and authors, as well as the analysis of journals, references, and keywords [33,34]. As a complement, the online platform bibliometric.com was used to analyze publication volume, keyword variations, and international collaboration across different countries throughout the years [35]. The combination of the aforementioned tools aims to present a comprehensive overview of the trends, research performance, and hotspots in high-altitude sleep research from 1992 to 2022. Fig. 2 illustrates the literature retrieval, screening, and analysis steps.

3. Results

3.1. Publications and citations

A comprehensive search yielded 1151 publications. After applying the filters and reading the titles and abstracts, 368 articles were analyzed, including 344 original studies (93.48 %) and 24 reviews (6.52 %). The 368 articles have been cited a total of 8054 times, with an average of 22 times per item. Meanwhile, 1564 authors and 705 institutions were identified in 43 countries. Changes in the

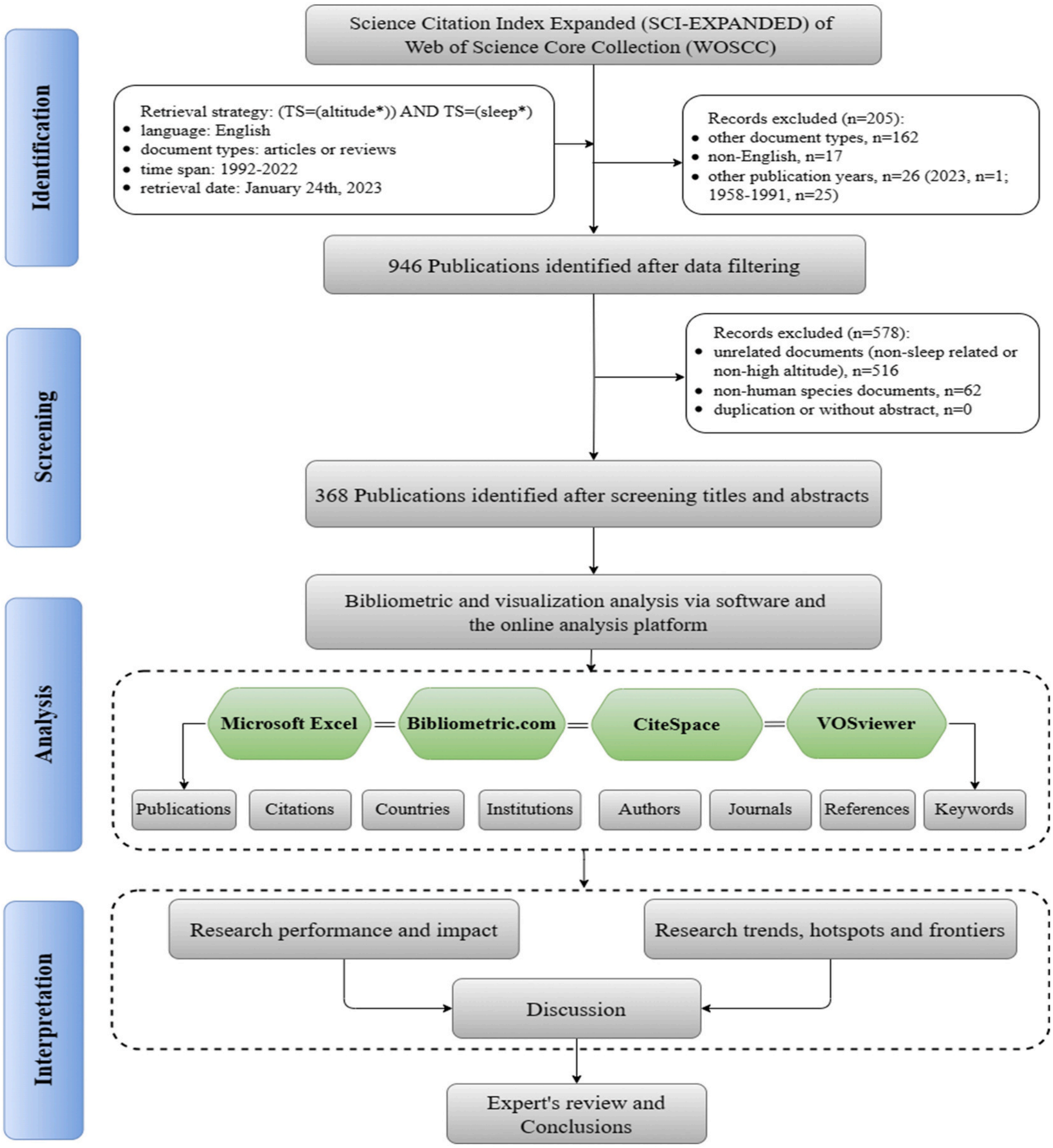


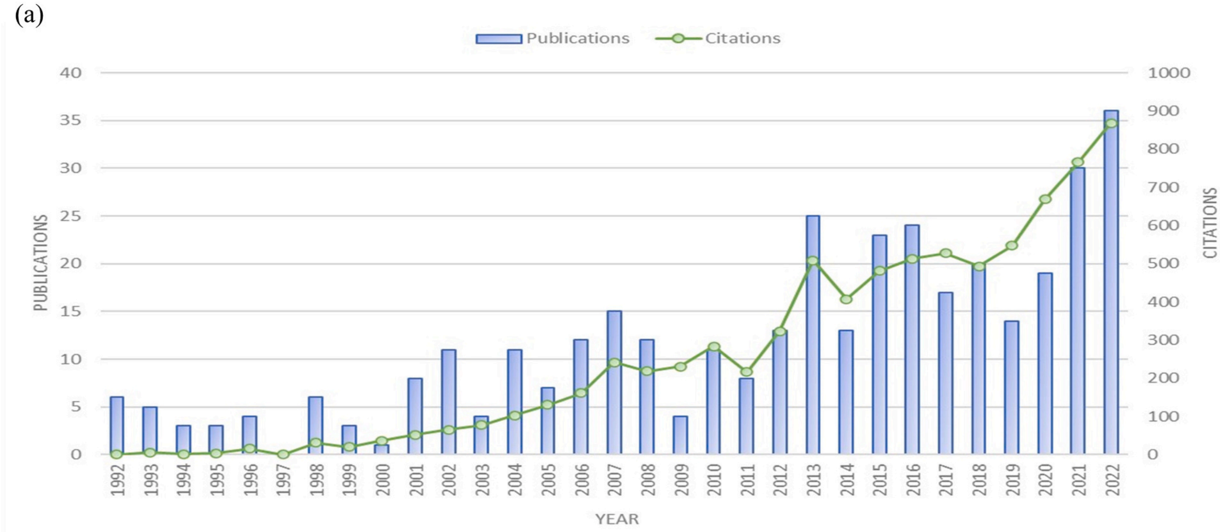
Fig. 2. Flow chart of literature retrieval, screening, and analysis steps.

number of published papers serve as a significant indicator for visually assessing trends in scientific research. From 1992 to 2022, the number of studies on high-altitude sleep showed an overall upward trend, although it was slow for the first 15 years and then fast during 2008–2022. Fig. 3(a) shows that the number of citations increased with the growth in publications from 1992 to 2022, and both publications and citations proved the activity of this research field in the past 10 years. Fig. 3(b) indicates that the development of China in the field of high-altitude sleep has outpaced that of the United States and Switzerland over the past 3 years, showing significant potential for development.

3.2. Core countries and regions, institutions, authors, and journals

We sorted the distribution information and characteristics of the top ten countries, institutions, authors, and journals. The United States contributed the largest output of publications (95, 25.8 %), followed by Switzerland (56, 15.2 %) and China (46, 12.5 %), which together accounted for more than 50 % of the total number of publications. The University of Zurich in Switzerland is the most productive and academically influential research institution, while Bloch KE is the most representative author. The top ten research institutions were located in the United States (n = 3), Switzerland (n = 3), France (n = 2), Peru (n = 1), and China (n = 1). In addition to research institutions, Switzerland has the largest number of core authors, with more than half of the top ten authors being affiliated with the University of Zurich. See Tables 1–3.

(a)



(b)

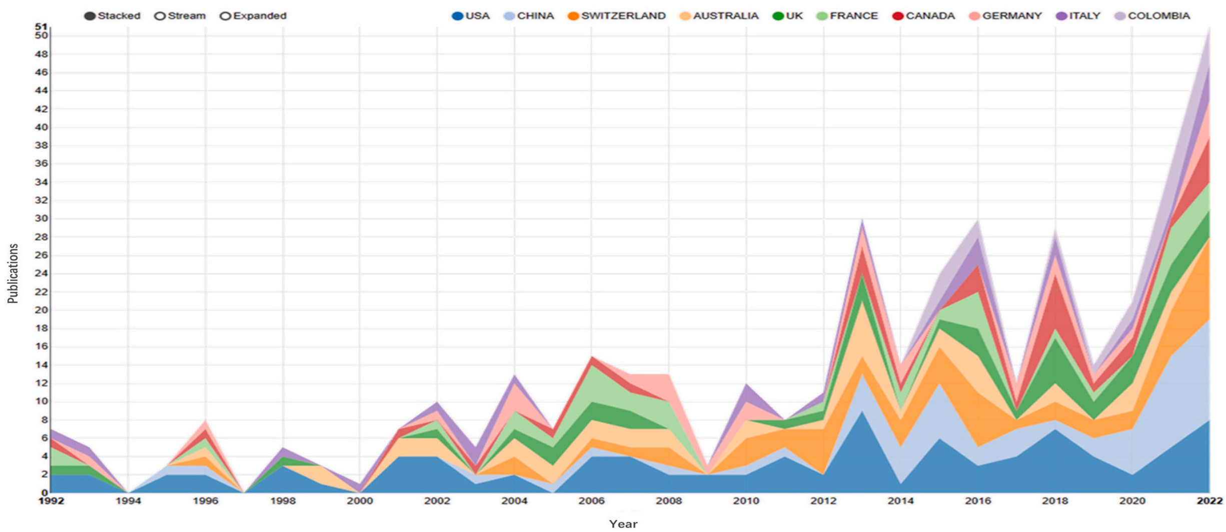


Fig. 3. Trends in publications and citations of sleep at high altitude. (a) Trends in global publishing and citation on an annual basis. (b) The temporal trends of publications across the top ten countries.

Table 1
The top ten countries in terms of publications.

Rank	Countries	Articles (%)	Times Cited	Average per item	H-Index	Top Institutions	Top Institution Articles (%)	Top Authors	Top Author Articles (%)
1	USA	95 (25.815 %)	2505	26.37	27	University of Colorado	22 (23.158 %)	West JB	7 (7.368 %)
2	Switzerland	56 (15.217 %)	1550	27.68	21	University of Zurich	41 (73.214 %)	Bloch KE	36 (64.286 %)
3	China	46 (12.500 %)	722	15.7	13	Army Medical University	12 (26.087 %)	Huang L	8 (17.391 %)
4	Australia	40 (10.870 %)	1333	33.33	19	University of Sydney	19 (47.500 %)	Gore CJ	13 (32.500 %)
5	England	34 (9.239 %)	482	14.18	14	University of London	10 (29.412 %)	Hill CM	6 (17.647 %)
6	France	34 (9.239 %)	900	26.47	17	Udice French research universities	11 (32.353 %)	Richalet JP	14 (41.176 %)
7	Canada	30 (8.152 %)	804	26.8	14	University of British Columbia	11 (36.667 %)	Ainslie PN	9 (30.000 %)
8	Germany	27 (7.337 %)	955	35.37	16	Ruprecht Kars University Heidelberg	6 (22.222 %)	Bartsch P	6 (22.222 %)
9	Italy	24 (6.522 %)	445	18.54	14	University of Milano Bicocca	8 (33.333 %)	Lombardi C & Parati G	6 (25.000 %)
10	Colombia	18 (4.891 %)	96	5.33	6	Pontificia Universidad Javeriana	8 (44.444 %)	Ucros S	4 (22.222 %)

Table 2
The top ten institutions in terms of publications.

Rank	Institutions	Articles (%)	Countries	Times Cited	Average per item	H-Index
1	University of Zurich	41 (11.141 %)	Switzerland	1157	28.22	18
2	University Zurich Hospital	40 (10.870 %)	Switzerland	949	23.73	17
3	University of Colorado Anschuz Medical Campus	22 (5.978 %)	United States	844	38.36	15
4	University of Colorado System	22 (5.978 %)	United States	844	38.36	15
5	Zurich Center Integrative Human Physiology Zihp	20 (5.435 %)	Switzerland	633	31.65	13
6	University of Sydney	19 (5.163 %)	Australia	624	32.84	15
7	Universidad Peruana Cayetano Heredia	15 (4.076 %)	Peru	283	18.87	10
8	University of California System	15 (4.076 %)	United States	319	21.27	10
9	Australian Institute of Sport	13 (3.533 %)	Australia	693	53.31	11
10	Army Medical University	12 (3.261 %)	China	191	15.92	8

Table 3
The top ten authors in terms of publications.

Rank	Authors	Articles (%)	Institutions	Countries	Times Cited	Average per item	H-Index
1	Bloch KE	36 (9.783 %)	University of Zurich	Switzerland	763	21.19	16
2	Latshang TD	23 (6.250 %)	University of Zurich	Switzerland	459	19.96	12
3	Ulrich S	21 (5.707 %)	University of Zurich	Switzerland	341	16.24	11
4	Furian M	16 (4.348 %)	University of Zurich	Switzerland	93	5.81	6
5	Richalet JP	14 (3.804 %)	Université Sorbonne Paris Nord	France	514	36.71	10
6	Gore CJ	13 (3.533 %)	Australian Institute of Sport	Australia	693	53.31	11
7	Ainslie PN	11 (2.989 %)	University of British Columbia	Canada	244	22.18	8
8	Burgess KR	11 (2.989 %)	University of Sydney	Australia	394	35.82	10
9	Kohler M	11 (2.989 %)	University of Zurich	Switzerland	289	26.27	9
10	Lichtblau M	9 (2.446 %)	University of Zurich	Switzerland	45	5	4

All articles were published in 141 journals, of which *High Altitude Medicine & Biology* published most (n = 55, 14.9%), followed by *Sleep* (n = 21, 5.7%) and the *Journal of Applied Physiology* (n = 15, 4.1%). A total of 162 publications were published in the top the most active journals, accounting for 44.0% of the total. Among these, the *European Respiratory Journal* had the highest IF (33.801) and JCI (3.61), followed by *Chest* (11.393, 1.88) and *Sleep* (6.313, 1.3). Based on the category quartile of the 2021 journal citation report, 80% of the top ten journals were dominated by Q1–Q2 and published 81.8% (301/368) of the relevant articles, which reflects the academic value of research results in the field of high-altitude sleep to a certain extent. See Table 4.

Table 4
The top ten journals in terms of publications.

Rank	Journals	Articles (%)	IF 2021	JCI 2021	CQ 2021	JCR Category
1	*High Altitude Medicine & Biology*	55 (14.946 %)	2.183	0.63	Q3	Biophysics
2	*Sleep*	21 (5.707 %)	6.313	1.3	Q1	Clinical Neurology
3	*Journal of Applied Physiology*	15 (4.076 %)	3.881	1.08	Q2	Physiology
4	*Frontiers in Physiology*	12 (3.261 %)	4.755	0.99	Q1	Physiology
5	*Respiratory Physiology & Neurobiology*	12 (3.261 %)	2.821	0.68	Q3	Physiology
6	*European Journal of Applied Physiology*	11 (2.989 %)	3.346	0.92	Q2	Physiology
7	*Sleep Medicine*	10 (2.717 %)	4.842	1.11	Q2	Clinical Neurology
8	*Chest*	9 (2.446 %)	11.393	1.88	Q1	Respiratory System
9	*European Respiratory Journal*	9 (2.446 %)	33.801	3.61	Q1	Respiratory System
10	*Journal of Sleep Research*	8 (2.174 %)	5.296	1.07	Q2	Clinical Neurology

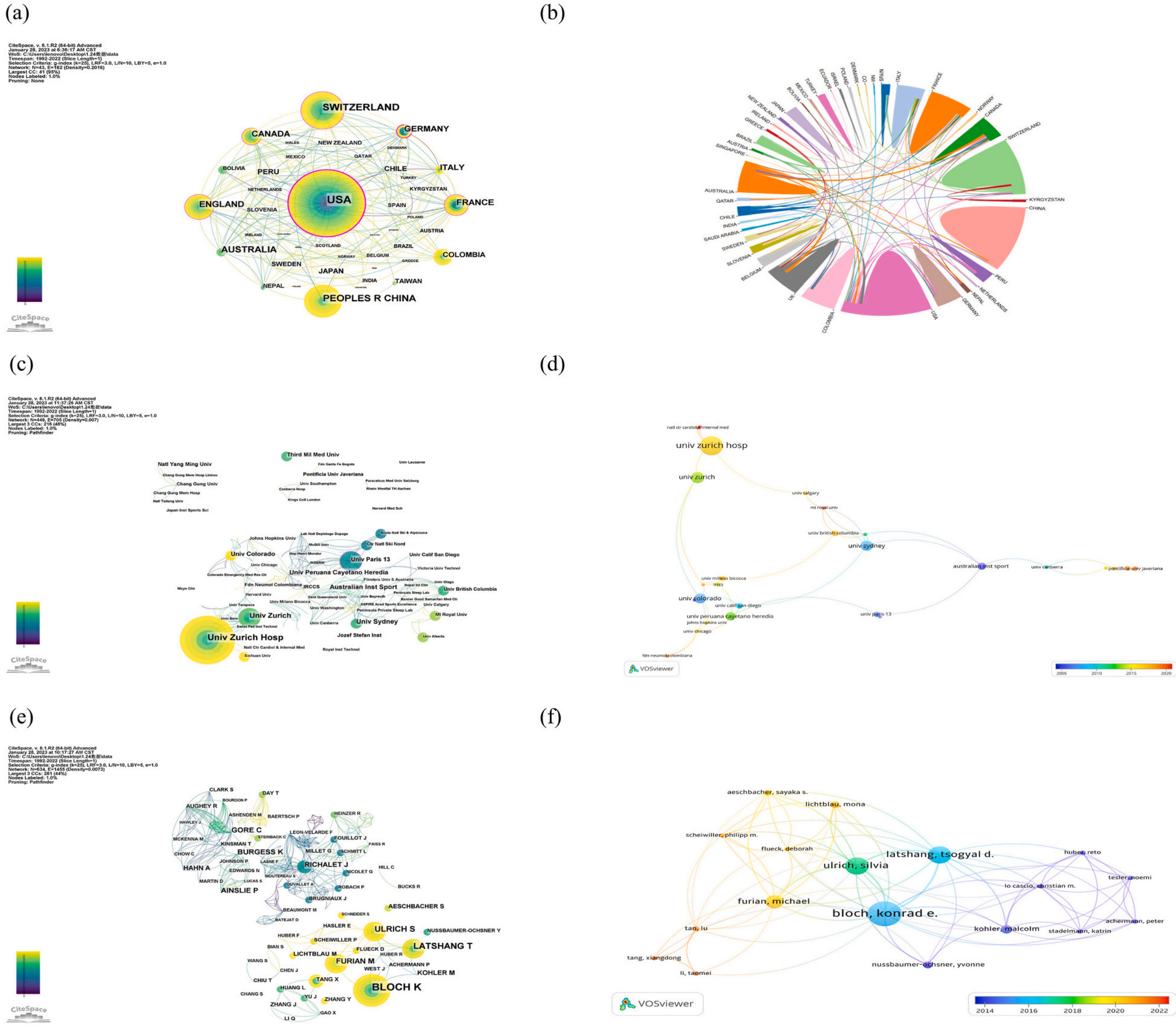


Fig. 4. Visualization map of scientific cooperation networks. (a) Collaboration between coutries based on CiteSpace; (b) Collaboration between coutries based on online bibliometric analysis platform; (c) Collaboration between institutions based on CiteSpace; (d) The largest institutional cooperation network based on VOSviewer; (e) Collaboration between authors based on CiteSpace; (f) The largest author cooperation network based on VOSviewer.

3.3. Scientific cooperation networks

Scientific collaboration networks through the relationship between the countries/regions, institutions, and the author of the comb, can make the researchers understand the state of research, identify gaps, identify lead authors and research groups publishing on certain topics, and find potential cooperation teams [36]. The cooperative network diagram made by CiteSpace shows that the circle size represents the frequency, the link between nodes represents the cooperative relationship, and the node with a purple outer circle haswith high betweenness centrality, which reflects its ability to transmit information [37]. As shown in Fig. 4(a), seven countries have a high betweenness centrality: the USA (0.58), Germany (0.21), Canada (0.20), India (0.18), England (0.17), France (0.15), and Switzerland (0.13). The United States ranks first in terms of the total number of documents and betweenness centrality. As shown in Fig. 4(b), the size of the color block represents the number of documents issued, and the width of the lines between countries represents the extent of cooperation between the two countries, thus reflecting the intensity of cooperation. The United States, United Kingdom, Australia, Canada, and other countries are more closely connected with other countries, with the United States being the most prominently connected. The two institutions with high betweenness centrality were the University of Peruana Cayetano (0.18) and the University of Paris 13 (0.13), as shown in Fig. 4(c). None of the authors had high betweenness centrality. This is illustrated in Fig. 4(e).

The collaboration networks help to understand how scholars interact amongst themselves (including affiliated institutions and countries). Contributions from various scholars contributed to greater clarity and richer insights into a research field, and collaboration among researchers can also promote research advancements [21]. Through further analysis using VOSviewer, the largest cooperative networks of the research institutions and the authors were obtained. As shown in Fig. 4(d), the research institutions are mainly from Western countries. The University of Colorado System, University of Sydney, Australian Institute of Sport, and University of Paris 13 constituted the early institutional cooperation network in the field of high-altitude sleep research. In addition, we determined that Bloch KE, Latshang TD, Ulrich S, and Furian M from Switzerland are the core members of the largest research team. Similarly, Chinese research groups led by Tang XD and Tan L have become increasingly active in recent years and cooperative links exist between the two research teams. This is illustrated in Fig. 4(f).

3.4. Analysis of references

References reflect the relationships between articles, which is valuable in the academic research field. In this study, we used

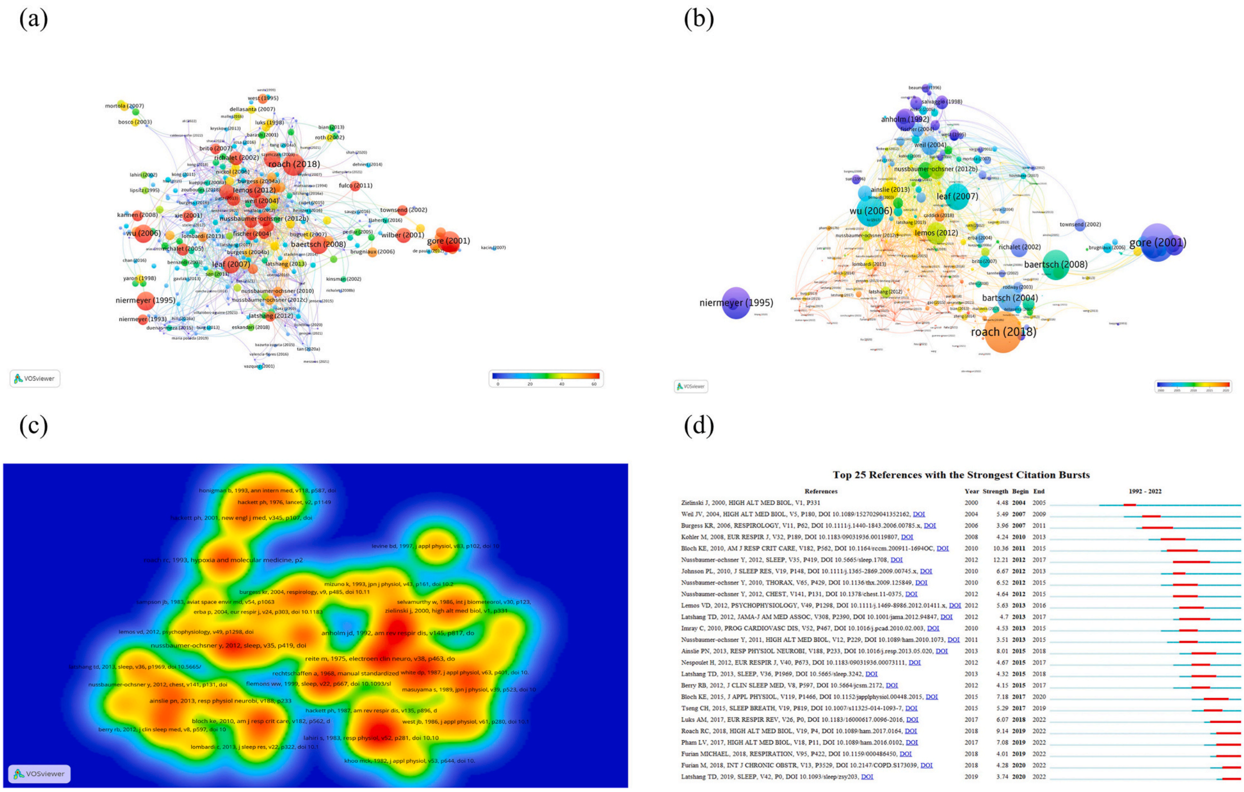


Fig. 5. Visualization map of references. (a) Literature citation analysis based on VOSviewer; (b) Literature bibliographic coupling analysis based on VOSviewer; (c) Literature co-citation analysis based on VOSviewer; (d) Top 25 references with the strongest citation busts (1992–2022) based on CiteSpace.

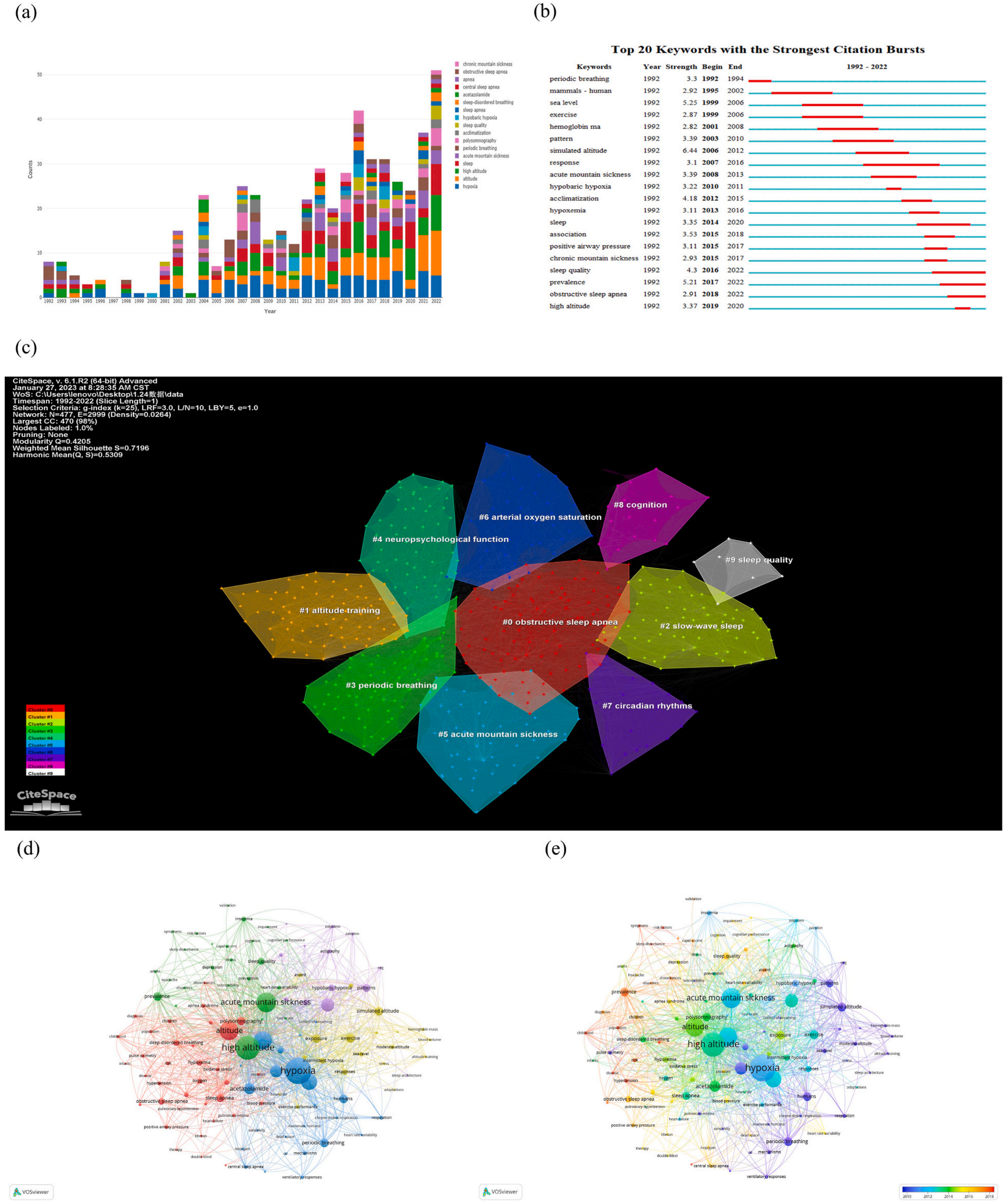


Fig. 6. Visualization map of keywords. (a) Keywords change over the years (1992–2022); (b) Top 20 keywords with the strongest citation bursts (1992–2022) based on CiteSpace; (c) Cluster analysis of keywords based on CiteSpace; (d) The network visualization map of five clusters of 118 keywords created by VOSviewer; (e) The overlay visualization map of 118 keywords with more than 6 co-occurrences by VOSviewer.

VOSviewer for literature citation, bibliographic coupling, and co-citation analysis. As shown in Fig. 5(a), the size and color of the node can reflect the frequency of citations in the literature; from blue to red, the frequency increases gradually. It can be seen that the larger red nodes are the most frequently cited articles in the study of high-altitude sleep. “The 2018 Lake Louise Acute Mountain Sickness Score” published in *High Altitude Medicine & Biology* in 2018 had the highest number of citations (208 citations). Fig. 5(b) shows an overlay visualization of the bibliographic coupling analysis (links, 17916; total link strength, 35541), which measures the similarity between the literature by referring to the number of the same references. Based on the literature citation relationship drawing, each node represents the literature, the node color reflects the average time of the literature, and the connection strength represents the coupling strength. A review by Ainslie PN published in *Respiratory Physiology & Neurobiology*, “Breathing and Sleep at High Altitude,” had the highest coupling strength (total link strength, 1316). Fig. 5(c) shows the density visualization of the co-citation analysis (links, 859; total link strength, 4238), which is used to promptly observe the knowledge and research density of the research field, and the similarity between the literature was measured by the number of times both were cited together. “Operation Everest II: Arterial Oxygen Saturation and Sleep at Extreme Simulated Altitude”, published in *The American Review of Respiratory Disease* in 1992 by Anholm JD, had the highest co-citation strength (total link strength, 412). As shown in Fig. 5(d), two articles with the strongest citation bursts. The first was “Effect of Short-Term Acclimatization to High Altitude on Sleep and Nocturnal Breathing,” published in *Sleep* in 2012 by Nussbaumer-Ochsner Y, and the citation bursts lasted the longest, up to 6 years. The second was “Nocturnal Periodic Breathing during Acclimatization at Very High Altitude at Mount Muztagh Ata (7546 m),” published by Bloch KE in the *American Journal of Respiratory and Critical Care Medicine* in 2010, which also had the second longest citation bursts, lasting for 5 years. The map reveals that six popular articles in the field of high-altitude sleep research are still in the stage of citation bursts.

3.5. Analysis of keywords

Keywords are the core words of a condensed literature topic, that summarizes the main points of research in a certain field of knowledge. Fig. 6(a) shows changes in the annual distribution of keywords over time. Over the years, keywords have continuously been enriched. Hypoxia, altitude, high altitude, and sleep are keywords that continue to be of concern and show an increasing trend over a certain range of fluctuations. The emergence of keywords refers to a sudden appearance or sharp increase in the frequency of keyword use over a short period. It can determine whether a certain research field is a hotspot during a certain period and highlight emerging topics [38]. As shown in Fig. 6(b), the keyword with the strongest strength of citation burst is the simulated altitude (strength, 6.44), and sleep quality, prevalence, and obstructive sleep apnea are the emergent keywords that last until 2022; this reflects the latest research trend and can predict the future research topic.

The log-likelihood ratio (LLR) was selected for clustering calculation in CiteSpace, and in the obtained cluster graph (Q, 0.4205; S, 0.7196), $Q > 0.3$ indicates that the clustering structure was significant, and $S > 0.7$ indicates that the nodes in the cluster had a high degree of homogeneity and good reliability [39]. Fig. 6(c) shows ten clustering tags containing the most important research topics in this field (see Supplementary Material Table S2 for details), with #0 sleep apnea being the largest and most recent topic in terms of the average number of years.

We selected all keywords in VOSviewer, merged the synonymous keywords and different writing forms (shown in the **Supplementary Files**), set the minimum co-occurrence threshold to 6, and obtained a network visualization (clusters, 5; links, 2496; total link strength, 6120) composed of 118 keywords. As shown in Fig. 6(d), the keywords formed five different color categories. The largest red cluster (35 keywords) represents high-altitude sleep and breathing, including “altitude,” “sleep apnea,” “obstructive sleep apnea,” and “sleep disordered breathing”. The green cluster (27 keywords) represents acute mountain sickness and sleep quality, including “high altitude,” “acute mountain sickness,” “sleep quality,” and “prevalence”. Blue cluster (24 keywords) represents sleep and drug use under hypoxia, including “hypoxia,” “sleep,” “acclimatization,” and “acetazolamide”. Yellow cluster (19 keywords) represents high-altitude training, including “simulated altitude,” “exercise,” “exposure,” and “intermittent hypoxia”. The purple cluster (13 keywords) represents sleep monitoring and physiological performance under hypoxia, including “performance,” “hypobaric hypoxia,” “patterns,” and “ventilation”, with the smallest scale. As shown in Fig. 6(e), when keyword colors are classified based on their average publishing year (APY), red keywords appear later than blue keywords. Previously, altitude training was a primary research topic. Currently, research focuses on sleep disorders and sleep apnea at high altitudes.

4. Discussion

4.1. Research trends and development courses

Bibliometric analysis can provide visual results to help researchers new to the field improve their understanding. In this study, we collected and analyzed 368 articles in the field of high-altitude sleep research published from 1992 to 2022, including 8054 citations. This extensive synthesis enabled us to trace the research history in this field and predict the latest research trends. By analyzing the time distribution of publications, we gain insight into the research status, research level, and development speed of different periods. In recent decades, the number of publications on high-altitude sleep research has gradually increased, indicating its promising prospects. We predict that this number will continue to increase, leading to a more prosperous phase in the near future. In addition, our analysis will help researchers understand the course of development in this field and inform policymakers and funding agencies about important research topics on high-altitude sleep.

Using 2007 as the observation point, the research history of high-altitude sleep over the past 30 years can be divided into two parts. The first 15 years (1992–2006) were the early stages of development, with slower growth rates in publications and more scattered research topics. Six of the ten main topics of the CiteSpace cluster were distributed during this period, which mainly included #1 altitude training, #3 periodic breathing, #4 neuropsychological function, #5 acute mountain sickness, #6 arterial oxygen saturation, and #7 circadian rhythms. Among these, high-altitude training was the most extensively researched theme. In the nearly 15 years since 2007 (2008–2022), research has entered a stage of rapid development, and the growth of publications has accelerated. At this stage, the research topics were more focused, including #0 obstructive sleep apnea, #8 cognition, and #9 sleep quality, which were represented by the theme of obstructive sleep apnea (OSA). High-altitude training in the field of sports science has attracted more attention in the early stages. Sleep and breathing at high altitudes have always been the focus of researchers, which not only form the early foundation of this field but also remain an important direction for future research.

4.2. Research performance and impact

Performance analysis examines the contributions of research components to specific areas. Different journals have different publishing fields. Among the top ten most productive journals, physiology is the main subject, followed by clinical neurology and the respiratory system, indicating that the study of high-altitude sleep is the focus of multidisciplinary research. "*High Altitude Medicine & Biology*", "*Sleep*" and "*Journal of Applied Physiology*" have the most published articles and the highest number of citations, making them the most popular journals among scholars concerned with high-altitude sleep research. For decades, the United States has been in a leading position in high-altitude sleep research as the country with the highest productivity and citations. Recently, China has shown obvious development potential in this field. However, the level of academic research needs to be improved to produce more high-quality articles and enhance its academic influence. We find that Western countries, represented by the United States, are more concerned regarding this field than Eastern countries, and their international cooperative relations are closer than those of Eastern countries. In the future, Chinese research institutions and scholars should strengthen their intercontinental cooperation.

Professionals and research institutions in Switzerland have conducted in-depth research in this field, with the largest number of core institutions and core authors. Specifically, the research team with Bloch KE, Latshang TD, Ulrich S, and Furian M from the University of Zurich as its core was the most prominent, with high academic influence. The team focused on clinical neurology and neuroscience, working on nocturnal sleep respiration and physiological performance at high altitudes, and the results have affected the current understanding of high-altitude sleep. Most studied individuals were patients with chronic obstructive pulmonary disease (COPD), pulmonary hypertension, and OSA at high altitudes, and the intervention methods mainly included the preventive use of acetazolamide and nocturnal oxygen therapy. Although nocturnal hypoxia and sleep quality damage induced by acute high-altitude exposure can be alleviated through gradual adaptation to the environment [40], effective interventions are still necessary. Their two recent randomized controlled studies showed that prophylactic acetazolamide treatment can reduce visual motor performance in patients with COPD at high altitude [41] and improve oxygenation and nocturnal respiration but not sleep time or structure [42]. Whether oxygen therapy can reduce heart rate and arrhythmia during the high-altitude stay remains unclear [43]. Heart rate variability during wakefulness may be a marker of the severity of OSA [44]. High-altitude pulmonary hypertension (HAPH) is a high-altitude disease associated with hypoxia that can promote sympathetic nerve excitation and prolongation of the QT interval [45]. The team found that nocturnal oxygen therapy did not improve oxygenation or sleep apnea during high-altitude travel in patients with HAPA [46]. When individuals with COPD sleep at night at high altitudes, they experience high altitude-induced hypoxia and PB, accompanied by persistent and intermittent brain deoxidation, which increases the risk of brain dysfunction [47]. In the event of increased hypoxia, oxygen therapy may provide cardiovascular benefits to patients with COPD and may be considered for these patients when traveling to high altitudes [48] because nocturnal oxygen therapy can improve nocturnal dyspnea and other altitude-related adverse health effects in individuals with COPD at high altitude [49]. These studies provide valuable insights for better understanding and treatment of sleep disorders in patients with chronic hypoxia in low-altitude regions.

4.3. Knowledge basis, hotspots, and frontiers

Through citation relationships among references, highly concentrated keyword clustering, and citation bursts, we can analyze the knowledge basis of the research and further explore hotspots and frontiers in the field of high-altitude sleep. The citation frequency of references reflects the popularity and academic value of the research topic. Roach RC [50] discussed whether there was a close relationship between high-altitude sleep disturbance and AMS. Removing sleep components from the Louis Lake AMS score, modifying AMS scores, and updating usage instructions became the citation basis of many subsequent studies, which was helpful in the development of this field. The knowledge base is typically composed of co-cited literature sets, whereas the research frontier is composed of citation literature sets that quote these knowledge bases [51]. Anholm JD, as early as 1992, described the relationship between the severity of sleep disorders and the decrease in arterial oxygen saturation at extreme simulated altitudes; that is, sleep quality deteriorates gradually with a decrease in SaO_2, which is the knowledge basis of the high-altitude sleep field [52]. Ainslie PN systematically introduced research results on breathing and sleeping at high altitudes [19], which represents the cutting-edge theme of the current research. Nussbaumer-Ochsner Y and Bloch KE discussed the effects of short-term adaptation to a high-altitude environment on sleep and nocturnal breathing [53] and the pathophysiological manifestations of nocturnal PB at extremely high altitudes [54], which were important research achievements in this field. In the past 5 years, six more articles have been hot articles in the field of high-altitude sleep research, three of which focused on motor performance and symptoms of sleep dyspnea in patients with COPD at high altitude [55–57]. Two articles focused on acute mountain sickness and related scoring criteria [50,58]. One article focused on the prevalence and severity of sleep-disordered breathing (SDB) in high- and low-altitude populations [59], which also reflects the emerging themes of current research.

4.3.1. Altitude training

In bibliometrics, frequently occurring keywords may reveal the main themes and the process of change, which are crucial to understanding the development of the field. In its early stages, many researchers focused on high-altitude training [60–63]). Since 1960, altitude training has been used to improve endurance performance [64]. The live high-train low (LHTL) scheme, which was put forward in the early 1990s, is a high-altitude training model often used by professional athletes, including anoxic adaptation and aerobic training, that is, training in normoxia but sleeping and living in anoxia [65]. Gore CJ reported that hypoxia exposure can increase muscle buffering ability, and the improvement of exercise efficiency is the basic adaptation to LHTL training [60]. Simulated high-altitude exposure may cause endurance athletes to experience changes in their respiratory control system and increase their anoxic ventilation response when sleeping under mild hypoxia [66]. Erythrocyte production rate is related to altitude. The LHTL regimen can improve the aerobic performance of athletes, and the main mechanism of this improvement is considered to be the enhancement of erythrocyte production. Through hypoxia adaptation, erythrocyte production is promoted, the oxygen carrying capacity of the body is improved, and arterial oxygen saturation is increased to improve the maximum oxygen uptake, sprint ability, and aerobic performance of athletes [63,67]. However, the effects of the LHTL remain controversial. Two studies by Ashenden MJ showed that red blood cell production was not stimulated in male endurance athletes who spent 23 nights at a simulated altitude of 3000 m [61]. Female athletes exposed to simulated 2650 m of atmospheric hypoxia for 12 nights were not sufficient to stimulate reticulocyte production or increase hemoglobin quality [62]. Robach P found that raising the altitude to 3500 m during LHTL stimulated red blood cell production without any concurrent amelioration of aerobic performance [68]. The absence of any prolonged benefit after LHTL suggests that this LHTL model cannot be recommended for long-term purposes [69]. In recent years, the debate over the usefulness of high-altitude training for elite athletes has continued [70,71]. There is still a lack of scientific consensus regarding the effectiveness of high-altitude training [72].

4.3.2. Sleep quality during hypoxia and interventions

A rapid ascent above 2500 m can induce acute high-altitude diseases, including acute mountain sickness (AMS), high-altitude cerebral edema and high-altitude pulmonary edema [73]. Altitude symptoms increase with altitude and speed of ascent, and determining factors for acclimation include sleep height. AMS is more commonly observed in individuals who are newly arrived at high-altitude locations, and a meta-analysis showed that the prevalence of AMS typically ranges from 16.6 to 77.9 % [74], especially when accompanied by complaints of poor sleep quality. The Lake Louis Score has long been the primary assessment tool for AMS. Insomnia was used as a symptom of AMS in the Lake Louise scoring system; however, in the new version, it was removed from the diagnostic criteria scoring system (version 2018) [50]. Although isolated from the AMS scoring system, insomnia remains one of the most common symptoms in the highlands. Furthermore, although the symptoms of AMS disappear after 2–3 days, sleep disorders may persist [75]. Therefore, it is necessary to separately study the sleep problems caused by high altitudes.

When considering the effect of altitude on sleep, self-reported sleep is not a feasible substitute for objectively measured sleep at high altitudes because the subjective perception of sleep and neurophysiological-related factors may vary significantly with altitude [10]. The evaluation of high-altitude sleep should consider both subjective sleep quality reports and objective sleep monitoring [12]. At high altitudes, the adaptability of the body to long-term hypoxia gradually improves, but subjective poor quality of sleep, frequent awakening as the main manifestation of sleep changes, obvious nocturnal hypoxemia, and PB are still common experiences of new arrivals at high altitude. Due to the effects of low pressure and hypoxia, subjective sleep quality typically improves with a decrease in altitude and oxygen supplementation [76,77]. Previous studies have shown that some drugs commonly recommended for improving sleep at sea level are not recommended for use at high altitudes [78]. Only a few drugs may be helpful, including theophylline and carbonic anhydrase inhibitors (acetazolamide), which help increase ventilation and oxygenation and effectively reduce PB [79]. For example, oral acetazolamide (250 mg, twice daily) can effectively reduce PB by 50–80 % [19]. It is considered the most popular treatment for altitude sleep disorders in the early stages [18]. A recent systematic review recommended the use of zalepron and zolpidem to improve sleep quality at high altitudes without damaging ventilation [80]. In the future, more high-quality clinical intervention studies are required to complement these results and to evaluate its effectiveness and safety.

4.3.3. Sleep-disordered breathing

SDB is common after rising to high altitudes [53]. SDB may occur when hypoxia stimulates the ventilation drive, leading to hyperventilation and resulting in hypercapnia-driven hypopnea or apnea [19]. The major pathophysiological changes in SDB are hypoxemia and/or hypercapnia caused by repeated apnea or hypopnea during sleep, as well as changes in sleep structure, resulting in a series of clinical manifestations and multiorgan function impairment. SDB can accelerate the progression of cardiopulmonary diseases, thus further reducing the saturation of oxyhemoglobin and aggravating sleep dyspnea. Consequently, high altitudes may contribute to a vicious cycle of deterioration in hypoxemia, sleep dyspnea, and chronic diseases [59]. OSA, the most common form of SDB, is characterized by recurrent collapse of the upper airways, resulting in intermittent oxygen saturation and sleep fragmentation. Hypoxia at low pressure may also explain the high prevalence of OSA in high-altitude regions. Sleep interruption affects the cognitive performance of healthy individuals and individuals with diseases such as OSA during the day [81]. OSA is associated with attention, memory, executive function, and psychomotor dysfunction [82]. Nocturnal sleep dyspnea at high altitudes has adverse effects on daytime performance; therefore, it is particularly necessary to find methods to improve symptoms and implement intervention measures.

4.4. Strengths and limitations

To the best of our knowledge, this study is the first to visually display a developmental overview of high-altitude sleep over the past 30 years from a perspective of bibliometrics. Different from traditional reviews, we systematically, macroscopically, and visually described the research trends and development process of the high-altitude sleep field in recent decades and identified research hotspots and frontiers. By measuring the research performance and impact from the perspective of the countries, institutions, authors, and journals, we provide references for follow-up research collaborations and grant applications.

Nevertheless, some limitations are inevitable. **First**, our dataset was initially only gathered from WOSCC; however, actual differences in reference classification between the WOSCC and other sources, such as Scopus, and different abbreviations of authors and journal titles may result in a large number of undetected duplicates as well as differences in coverage between subject areas [83]. Merging the characteristics of literature from different databases is a significant challenge. **Second**, the limitations of language and document types in the literature may lead to incomplete data sources. **Third**, there was a citation bias related to citation indicators in the scientometric analysis because citations were affected by numerous factors, including a sufficient time window, self-citation, author authority, periodical influences, and open access status [84]. For example, several recent publications have not been fully cited, and there is a certain lag in citations. **Finally**, it is noteworthy that the evolution of knowledge may be a continuous and complex dynamic process. Our analysis of the development trend was qualitative, so it was subjective.

5. Conclusion

In summary, our research will assist scholars to better understand the intellectual structure and emerging trends in this field. Hypobaric hypoxia in high-altitude regions may raise the incidence of SDB. Our study showed that nocturnal sleep and breathing, especially SDB (including OSA), were the current research focus of high-altitude sleep. In the future, as more and more low-altitude residents move to highland areas, we suggest that more studies be conducted to explore the treatment and efficacy validation of high-altitude SDB caused by this migration. Besides, further developments in terms of sleep quality at high altitudes and its associated prevalence are much anticipated. The improvement and treatment of symptoms during nocturnal sleep in patients with chronic hypoxia due to cardiopulmonary diseases at high altitudes are also urgently needed. These findings are critical for high-altitude sleep research, and they may help identify future research topics that could be incorporated into funding proposals, as well as potential collaborators with similar interests who pursue these topics.

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Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Lixia Tan: Writing – original draft, Visualization, Software, Methodology. **Yong Li:** Writing – review & editing, Methodology, Conceptualization. **Hongxiu Chen:** Writing – review & editing, Methodology, Data curation. **Gongga Lanzi:** Data curation, Conceptualization. **Xiuying Hu:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e23041.

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