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RESEARCH TRENDS IN HIGH-ALTITUDE TRAINING AND ENDURANCE PERFORMANCE: A BIBLIOMETRIC ANALYSIS (2011–2025)

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A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection.

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ABSTRACT

Background: High-altitude training (HAT) has emerged as a critical performance enhancement strategy for endurance athletes, with the "live high-train low" (LHTL) approach gaining widespread acceptance in sports science. Understanding research trends in this domain is essential for identifying knowledge gaps and future research directions.

Objective: This study conducts a comprehensive bibliometric analysis to map research trends, identify influential publications, examine collaboration networks, and explore thematic patterns in high-altitude training and endurance performance literature from 2011 to 2025.

Methods: A systematic Scopus search used keywords on high-altitude training and endurance performance, following PRISMA. It included 136 open-access English articles from 2011- 2025. VOSviewer visualized citations, keywords, author networks, and publication locations.

Results: Utilizing advanced visualization tools to analyze influential authors, organizations, and keywords, the paper highlights the leading publications and essential research clusters that are shaping the future of endurance performance research.

Conclusion: This bibliometric analysis shows ongoing growth and rising interdisciplinary interest in high-altitude training research, dominated by countries with advanced sports science. It highlights key research themes and lesser-explored areas for future study, offering

guidance for researchers, coaches, and athletes aiming to improve endurance with altitude training.

KEYWORDS: High-Altitude Training, Endurance Performance, Bibliometric Analysis, hypoxic training, aerobic capacity

INTRODUCTION

High-altitude training refers to planned periods of living and/or training at moderate altitude to induce acclimatization responses that may enhance subsequent endurance performance, particularly when athletes return to sea level (Płoszczyca et al., 2018). This training strategy exploits the physiological adaptations triggered by reduced oxygen availability, such as increased red blood cell production and enhanced mitochondrial efficiency. These adaptations can improve oxygen transport and utilization, thereby boosting endurance capacity. Consequently, high-altitude training has gained popularity among athletes aiming to optimize performance in competitive events (Mckenzie, 2012). This approach also stimulates angiogenesis, leading to increased capillary density in muscle tissue and facilitating better oxygen delivery during exercise. Additionally, high-altitude training can enhance muscle buffering capacity, reducing fatigue by more effectively managing acid-base balance (Gejl & Nybo, 2021) However, the benefits depend on factors such as altitude level, duration of exposure, and individual athlete response. These adaptations collectively contribute to enhanced endurance and performance in athletes training at high altitudes. However, improper acclimatization or excessive exposure can lead to altitude sickness, negatively impacting training outcomes. Therefore, individualized training protocols and careful monitoring are essential to maximize benefits while minimizing risks (Rusko et al., 2004).

Endurance performance, especially in elite sport, is commonly explained by the interaction of a few key physiological characteristics that determine how fast an athlete can sustain work for a given duration (Chycki et al., 2018). (Joyner & Coyle, 2008) highlight three major contributors: maximal oxygen uptake (VO2max), the “lactate threshold” (reflecting the highest sustainable metabolic steady state), and efficiency/economy (the oxygen or energy cost of producing a given speed or power). In this framework, VO2max and lactate threshold influence the highest sustainable oxygen consumption (sometimes described as “performance VO2”), while efficiency determines the speed or power that can be produced at that sustainable oxygen consumption (Vorup et al., 2016). Athletes should undergo gradual exposure to high altitudes to allow their bodies to adapt safely. Monitoring physiological

markers, such as oxygen saturation and heart rate, can help tailor training intensity and duration, minimizing the risk of altitude sickness and enhancing overall performance. (Fulco et al., 2013) Athletes should incorporate rest periods to facilitate recovery and acclimatization. Proper hydration and nutrition are crucial for supporting physiological adaptation during high-altitude training. Integrating rest periods and hydration strategies further supports effective acclimatization and performance optimization (Muza et al., 2010).

Athletes should also consider individual variability in response to altitude training, as genetic factors can influence acclimatization rates and performance outcomes. Employing a multidisciplinary approach involving coaches, medical professionals, and sports scientists ensures comprehensive support throughout the training process. Ultimately, optimizing altitude training protocols requires balancing physiological stress with adequate recovery to achieve sustainable performance improvements (Burtscher et al., 2018; Saunders et al., 2019).

Literature Related to Bibliometric Analysis

Bibliometric analysis, a pioneering methodology introduced by Pritchard (1969), quantifies written communication processes (Matorevhu, 2024). By employing a suite of rigorous quantitative techniques, researchers can effectively measure, monitor, and evaluate academic literature (Jayaratne & Zwahlen, 2015). This approach identifies key publications, influential authors, and leading journals and uncovers the methods and significant findings that drive scholarly progress (Ninkov et al., 2021). Metadata offer a comprehensive overview of any research field (Milian et al., 2019), and bibliometric techniques have proven essential for analyzing vast amounts of bibliographic data across diverse topics (Blanco-Mesa et al., 2017), journals (Martínez López et al., 2018), countries (Mas-Tur et al., 2019), and beyond, making them indispensable tools for advancing scholarly insight.

These methods enable researchers to identify emerging trends, influential authors, and collaboration networks within specific disciplines. (Erdyneeva et al., 2024) By systematically mapping the intellectual structure and evolution of research areas, bibliometric analysis supports strategic decision-making for funding agencies and academic institutions. Consequently, it fosters a data-driven approach to understanding scientific impact and guiding future investigations (Mekimah et al., 2024)

Search Strategy and Study Selection

Selecting an appropriate search engine for data extraction is essential. We opted for Scopus for several reasons: 1) It is Elsevier's citation database and is widely recognized as a leading index; 2) it features high-quality, peer-reviewed publications; and 3) Scopus evaluates the quality of each title using four metrics: h-index, Citescore, SCI Imago Journal Rank (SJR), and Source Normalized Impact per Paper (SNIP) (Alfirević et al., 2023)**.**

A total of 136 papers on endurance performance and high-altitude training were published in Scopus. The search utilised keywords such as "high-altitude training," "altitude training," "hypoxic training," "live high train high," and "intermittent hypoxic training," combined with terms like "endurance performance," "endurance athlete," "aerobic capacity," "VO2max," "maximal oxygen uptake," and "aerobic power." These studies span from 2011 to 2025. This review draws on prior bibliometric research (Luo et al., 2023). We included only open-access articles and review papers written in English, excluding non-English works.

Table 1:Inclusion and Exclusion Criteria.

Criteria	**Inclusion**	**Exclusion**
Language	English	Other than English
Time period	2011-2025	<2011
Literature	Articles, Reviews	Editorial, short survey, letter, book chapter, retracted, final stage publication, conference paper, note and animal studies
Publication stage	Final	Article in press
Subjects	Human	Animals

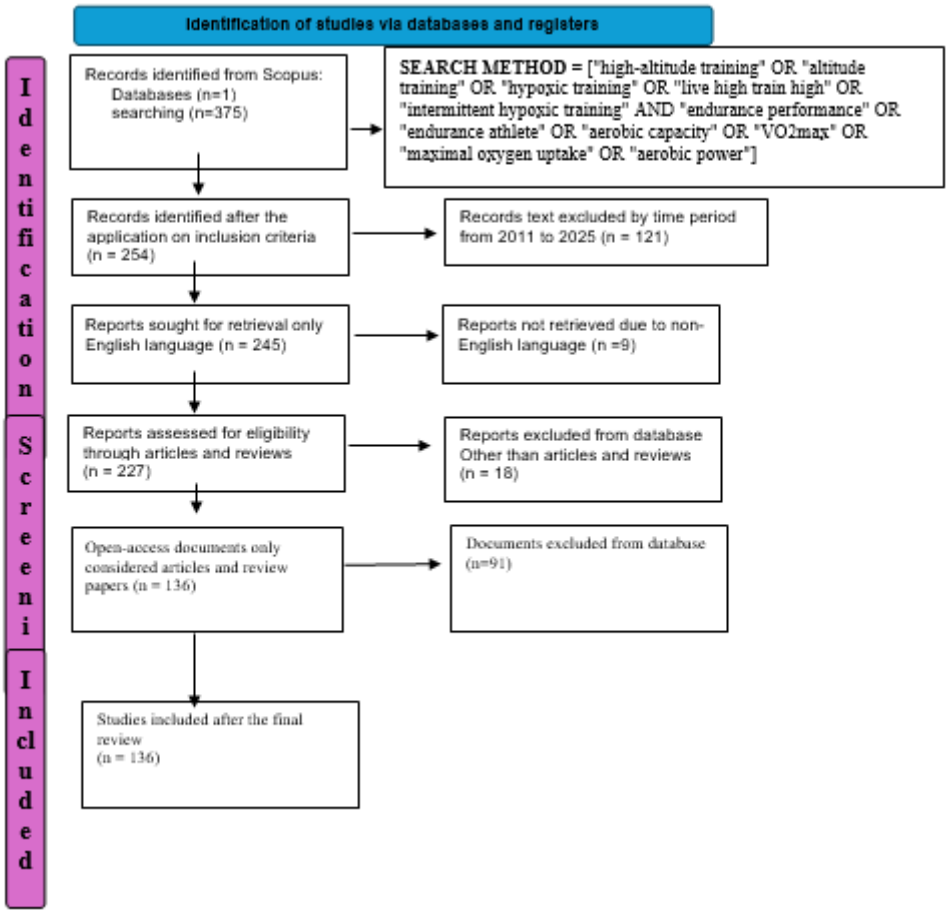

Figure 1: Prisma Flowchart of The Included Studies.

Analysis Tool

The study utilized VOSviewer to thoroughly examine the extensive body of literature on the crucial connection between high-altitude training (HAT) and enhanced endurance performance. The visualizations compellingly highlighted leading authors, groundbreaking publications, and core research themes, demonstrating the depth and breadth of ongoing investigations. VOSviewer's citation analysis pinpointed the most influential papers, showcasing the field's pivotal developments. This approach not only uncovered significant advancements and impactful studies but also revealed emerging research directions, positioning this review as an essential resource for anyone interested in the future of endurance training at high altitudes. The visualizations provide a clear, persuasive overview of the key themes and focus areas, solidifying VOSviewer's analysis as an invaluable tool for understanding the evolving landscape of high-altitude training research.

RESULTS

Citation Analysis

The study "Research Trends in High-Altitude Training and Endurance Performance: A Bibliometric Analysis (2011–2025)" provides a thorough overview of research patterns, including yearly publication counts, cited documents, notable authors, key journals, and the top contributing countries.

Table 2: Analysis of citations from various authors.

S. No.	Authors	Source/Journal	Total Citations
1	Faiss (2013)	Plos one	248
2	Sim (2019)	European Journal of Applied Physiology	224
3	Hawley (2015)	Cell Metabolism	143
4	Stellingwerff (2019)	Sports Medicine	108
5	Mujika (2019)	Sports Medicine	106
6	Saunders (2013)	British Journal of Sports Medicine	102
7	Sylta (2014)	International Journal of Sports Physiology and Performance	99
8	Płoszczyca (2018)	Frontiers of physiology	98
9	Khodaee (2016)	Sports Health: A Multidisciplinary Approach	78
10	Hauser (2016)	Medicine & Science in Sports & Exercise	68

Table 3 presents a summary of the top 10 most cited publications in the field of high-altitude training (HAT) and endurance performance. This information provides an overview of the leading publications across various journals and addresses the research gaps concerning endurance performance and HAT. The study by Faiss (2013) has received the most citations in PLOS ONE, totalling 248. The study concluded that HAT can significantly enhance the ability to perform repeated sprints in normoxic conditions, with benefits achieved through unique molecular and systemic adaptations distinct from traditional hypoxic training approaches. Sim et al. (2019) performed a narrative review comprehensively addresses the critical importance of iron regulation in athletic populations; this publication has garnered 224 citations and is published in European Journal of Applied Physiology. The paper titled “Maximizing Cellular Adaptation to Endurance Exercise in Skeletal Muscle” by Howley et al. (2015) has received 143 citations in the Cell Metabolism Journal. The study by Stellingwerff et al. (2019), published in Sports Medicine, received 108 citations. Additionally, Mujika's (2019) study on Contemporary Periodization of Altitude Training for Elite Endurance Athletes: A Narrative Review, also published in Sports Medicine, has

gathered 106 citations. Furthermore, the study conducted by Saunders et al. (2013), published in the British Journal of Sports Medicine, received 102 citations.

Likewise, Sylta et al. (2014) conducted a study to examine "From Heart-Rate Data to Training Quantification: A Comparison of 3 Methods of Training-Intensity Analysis." Their research received 99 citations and is published in the International Journal of Sports Physiology and performance. Additionally, research by Płoszczyca et al. (2018) received a total of 98 citations and was published in Frontiers of Physiology. Furthermore, the study by Khodaee et al. (2016), published in Sports Health: A Multidisciplinary Approach, received 78 citations. Hauser et al. published a scholarly article entitled “Similar Haemoglobin Mass Response in Hypobaric and Normobaric Hypoxia in Athletes” in the Journal of Medicine & Science in Sports & Exercise, which received a total of 68 citations. This citation analysis highlights the most impactful research and authors in the field of high-intensity interval training and oxidative stress.

3.2 Yearly Publications

Figure 2 shows the annual count of publications on high-altitude training and endurance performance indexed in Scopus from 2011 to 2025. From 2011 to 2016, the number of yearly publications ranged from 0 to 7, reflecting a limited focus on this area. After 2016, there is a clear upward trend, with publication counts rising from 7 to 20 between 2016 and 2024. In 2024 and 2025, the number slightly declined to 20 and 11 articles, respectively, marking a decrease from previous years. The peak occurred in 2024 with 20 publications. Currently, in 2024, the publication trend remains positive, with 20 articles, and it is likely to reach similar numbers as in 2024. Overall, the data indicate a steady increase in publication volume over the past 14 years, despite yearly fluctuations.

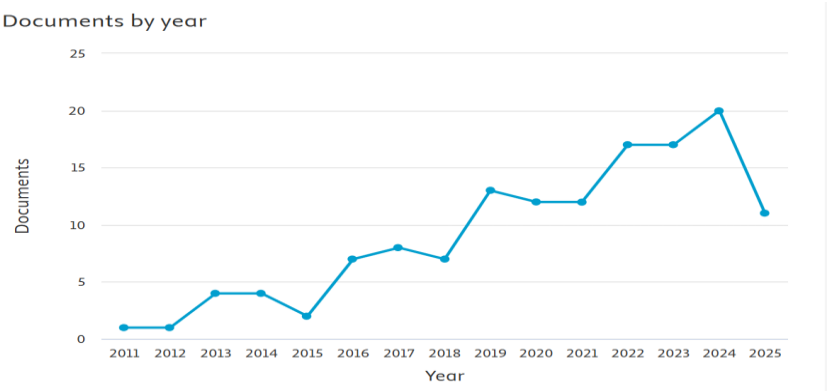

Figure 2: Yearly publications.

Subject Area Analysis

Figure 3 illustrates key subject areas in High-altitude Training (hat) and endurance performance. Medicine and Health professions lead with 105 and 54 publications, highlighting their prominence. Biochemistry and Social sciences contributed 46 and 11 publications, focusing on health parameters. Multidisciplinary and environmental sciences had fewer, with 10 and 8. Nursing and Computer Science each contributed 5, indicating less focus on muscle and motor parameters.

Agriculture and Biological Sciences, and Physics and Astronomy, with 5 and 4 publications, show interdisciplinary contributions. Overall, HAT and endurance are interdisciplinary, requiring knowledge from various fields.

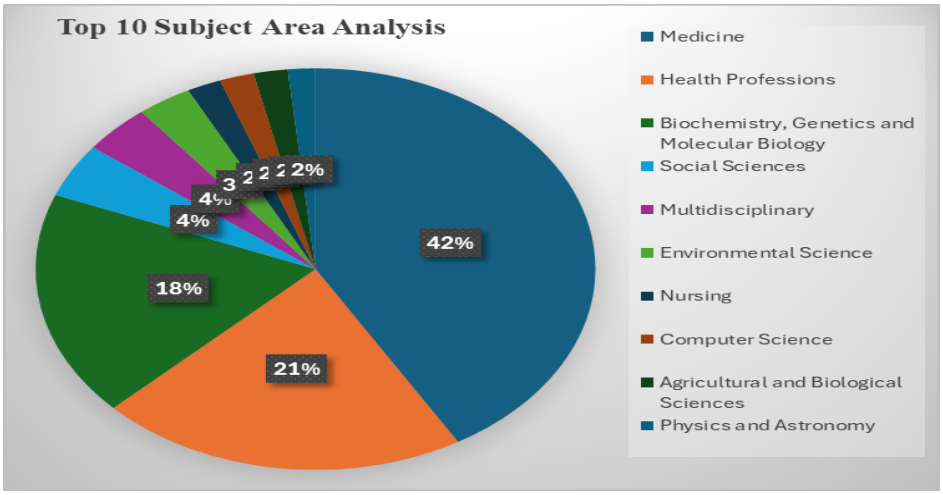

Figure 3: Subject area analysis.

Co-occurrence of keywords

Figure 4 demonstrates the clustering of keywords based on their co-occurrence. An appropriate method was deployed to analyse the co-occurrence of keywords related to high-altitude training and endurance performance. A total of 1120 keywords were extracted from 136 research articles, with 118 keywords occurring a minimum of 5 times. The selected keywords were classified into 4 clusters. Cluster one consists of 41 items. In general, a larger circle indicates more frequent use of that keyword in scholarly work. It is evident that the circles representing "oxygen consumption", “hypoxia training”, "aerobic capacity", "human", "exercise intensity", "male", and "metabolism" are larger than those representing other categories. Less frequently occurring keywords include "erythropoietin", "haemoglobin mass", "body composition", and "haematocrit". In the future, scholars may conduct research

using these less frequently occurring keywords to explore the field further and also to understand the current trends in the context of HAT and endurance performance.

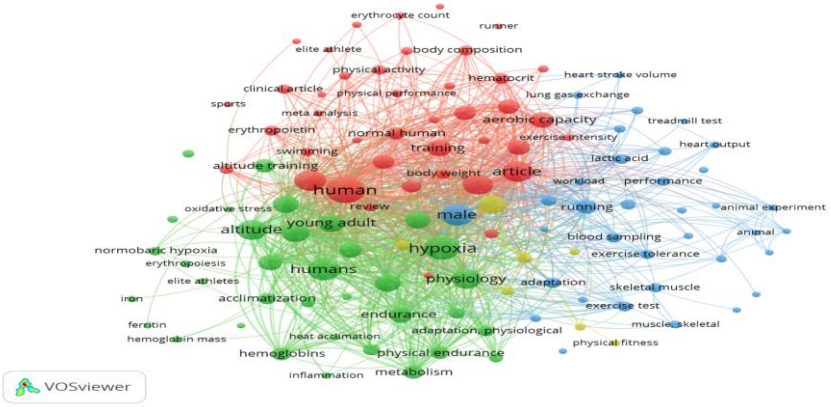

Figure 4: Co-occurrence of Keywords.

Country Analysis

Figures 5 and 6 present a list of countries with the highest numbers of publications on high-altitude training and endurance performance from 2011 to 2025. Australia leads with the most publications in this field, totalling 24 documents, owing to its advanced technology and research infrastructure in sports sciences. Poland follows closely with 18 documents, reflecting significant advancements in research. Spain and Switzerland have published 16 documents each, respectively, indicating substantial contributions to the field of high-altitude training and endurance performance. France, the United States, and China have contributed 15, 15, and 14 documents, respectively. Additionally, Norway, Canada and Germany have 8, 8, and 7 publications, respectively, demonstrating growing investments in sports sciences and research. These nations are characterized by advanced technology and substantial research investments, which have positioned them at the top of this research area.

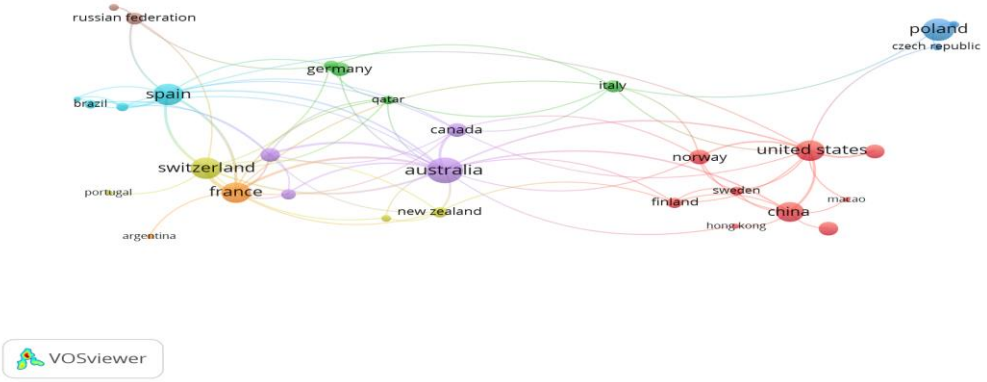

Figure 5: Top most contributed countries.

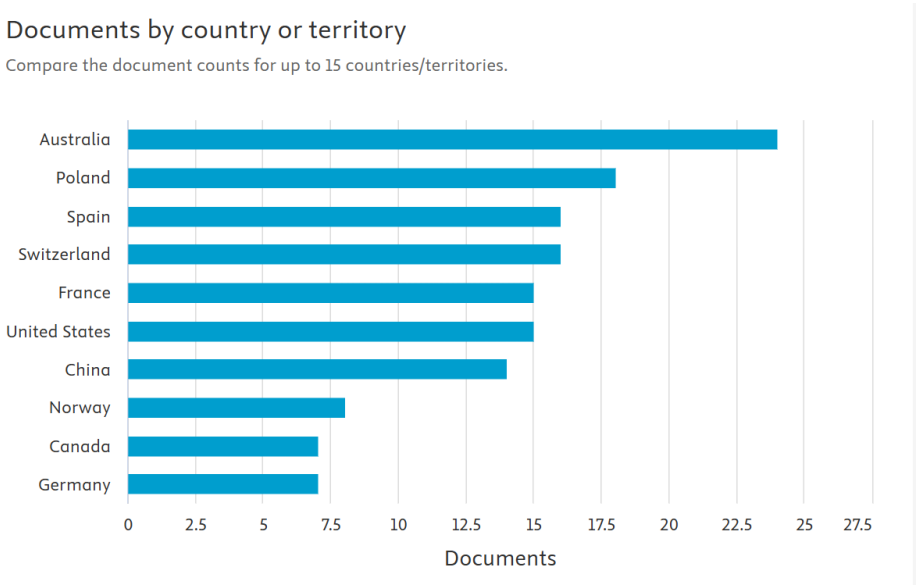

Figure 6: No. of document published by top 10 countries.

Top Authors

Figure 7 presents the top authors and the number of publications they have produced in the field of high-altitude training and endurance performance. The top author Millet, G.P. leads significantly with an impressive total of 8 documents, highlighting its prominence. Czuba, M. and Faiss, R. each contribute a solid 7 documents, underscoring their key roles. Park, H.Y., Saugy, J.J., and Schmitt, L. each add 6 documents, demonstrating substantial engagement. Hauser, A., Kim, S.W., Langfort, J., and Maciejczyk, M. each have 5 documents, reflecting consistent contributions across the board. Figure 8 illustrates the clusters of authors who are

actively involved in this research area, highlighting their significant contributions to the field of high-intensity interval training and oxidative stress.

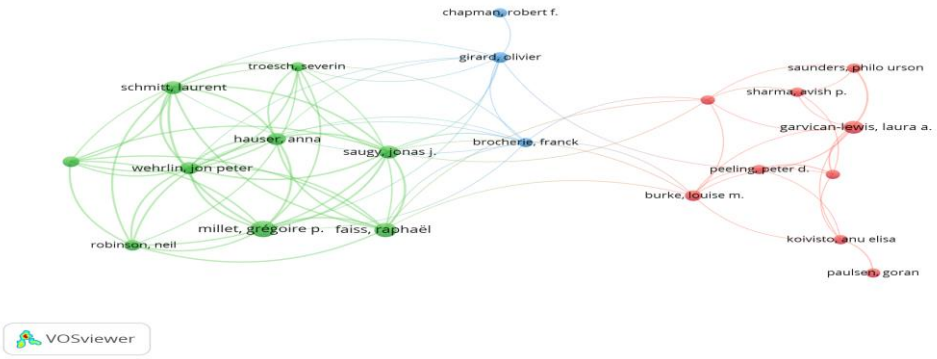

Figure 7: Co-authorship between authors.

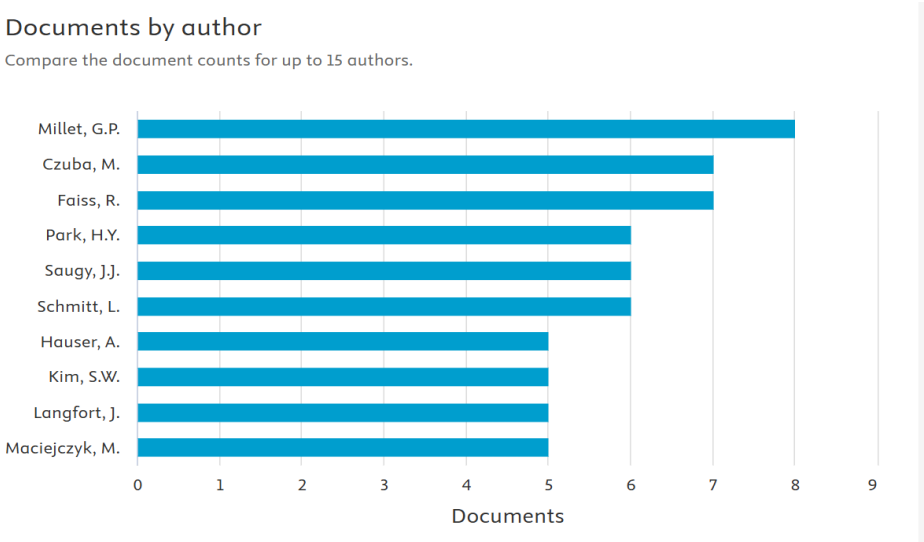

Figure 8: Top Authors and their publication counts.

DISCUSSION

This bibliometric analysis provides a comprehensive overview of research trends in high-altitude training and endurance performance from 2011 to 2025, revealing significant insights into publication patterns, influential contributions, thematic evolution, and geographic distribution of scholarship in this critical area of sports science.

Publication Trends and Research Growth

The analysis shows a research interest shift after 2016, with annual publications rising from 7 to 20 by 2024. Earlier research (0-7 annually) focused on foundational methods and physiology. The surge aligns with advances in hypoxic training tech, better access to altitude

chambers, and understanding of hypoxia adaptations. The 2024 peak (20 publications) and slight drop in 2025 (11) may reflect research cycles, with data for 2025 partial and likely exceeding 2024. This 14-year trend highlights altitude training's ongoing importance in sports science.

Citation Analysis and Influential Research

The citation analysis ranked Faiss (2013) highest with 248 citations, showing high-altitude training boosts repeated sprint ability in normoxia via unique molecular and systemic changes, different from hypoxic training. This impacts team sport athletes needing aerobic and high-intensity efforts. Sim et al. (2019), with 224 citations, focused on iron regulation in athletes, vital for nutrition and altitude response. Hawley's (2015) work (143 citations) explains how altitude prompts muscle adaptations. Publications in Sports Medicine, European Journal of Applied Physiology, and PLOS ONE highlight altitude training's multidisciplinary research. The range from molecular to practical studies indicates the field combines science and practice, supporting evidence-based coaching.

Interdisciplinary Nature of Research

Analysis shows Medicine and Health Professions lead with 105 and 54 publications, focusing on health and physiological adaptation in altitude training. Biochemistry (46) and Social Sciences (11) also contribute, highlighting interdisciplinary nature. Environmental Sciences (8) indicates rising ecological interest, while Agricultural and Biological Sciences, Physics, and Astronomy (4-5) suggest emerging links. Nursing and Computer Science (5 each) are potential growth areas, with Nursing aiding health monitoring and Computer Science improving predictive modeling. Ongoing interdisciplinary integration is vital.

Geographic Distribution and Research Infrastructure

Research productivity correlates with sports science infrastructure and investment. Australia leads with 24 publications, showcasing its sports science excellence and diverse training environments. Poland's 18 publications reflect strategic altitude training investment, fueled by endurance sports success and hypoxic facilities. European nations like Spain, Switzerland, France, Norway, and Germany benefit from geographic advantages and altitude training centers. Switzerland's 16 publications come from its high-altitude locations and top research institutes. The US and China contribute 15 and 14 publications, indicating large sports science communities and Olympic focus. Canada's 8 publications align with winter sports and athlete development. The concentration in advanced nations highlights research disparities,

presenting opportunities for global collaboration and capacity building in developing countries.

Keyword Co-occurrence and Research Themes

The analysis found 118 keywords in 136 articles, organized into four clusters. Core terms like "oxygen consumption," "hypoxia training," "aerobic capacity," "human," "exercise intensity," "male," and "metabolism" highlight focus on oxygen use, metabolism, and aerobic performance in altitude training. Less common keywords—"erythropoietin," "haemoglobin mass," "body composition," and "haematocrit"—point to emerging areas needing more research. These include hematological responses and muscle mass changes during altitude exposure, offering opportunities for future studies to improve altitude training methods and understanding of individual differences.

Author Networks and Collaborative Research

Millet, G.P. leads with 8 publications, followed by Czuba, M. and Faiss, R. with 7 each. These authors are from European research hubs in Switzerland and Poland with established altitude training programs. The collaboration network shows clusters, indicating specialised expertise and potential for broader collaboration.

Park, H.Y., Saugy, J.J., and Schmitt, L. have 6 publications each, while Hauser, A., Kim, S.W., Langfort, J., and Maciejczyk, M. have 5, representing a diverse, international research community. Greater cross-continental collaboration could boost knowledge exchange and capacity.

Practical Implications

This bibliometric analysis offers practical insights for athletes, coaches, and sports scientists. It shows that altitude training, especially LHTL protocols, improves performance through various physiological pathways. Research focus on oxygen consumption, aerobic capacity, and metabolism confirms these as key monitoring targets during altitude training.

Less-studied areas, like individual variability in erythropoietin response and haemoglobin changes, suggest personalized approaches are needed. Not all athletes respond the same to hypoxia, so understanding these differences can optimize training and resource use.

The interdisciplinary research highlights that effective altitude training involves exercise physiology, nutrition (especially iron), recovery, and personalised periodization. Practitioners should use evidence-based protocols informed by this research rather than generic altitude strategies.

CONCLUSION

This bibliometric analysis of 136 publications from 2011 to 2025 explores research on high-altitude training and endurance performance. The field has grown, especially after 2016, with 2024's peak at 20 articles. It features interdisciplinary contributions mainly from Medicine and Health, with input from Biochemistry, Social Sciences, and Environmental Sciences. Citation analysis highlights influential studies on physiological and practical altitude training, notably Faiss (2013) demonstrating molecular adaptations and Sim et al. (2019) on iron regulation. These works shape current altitude training understanding. Research is concentrated in countries with strong sports science, led by Australia, Poland, Spain, and Switzerland, influenced by infrastructure and funding. Key authors like Millet, Czuba, and Faiss drive innovation. Keyword analysis shows core themes—oxygen, hypoxia, aerobic capacity, exercise—while highlighting underexplored areas such as erythropoietin, haemoglobin, body composition, and haematocrit, offering future research opportunities. The field's momentum, interdisciplinarity, and gaps suggest ongoing progress. Future studies should focus on individual responses, hematological changes, implementation, and underrepresented groups. Greater international collaboration can expand access to altitude training benefits. Practitioners learn that altitude training, especially LHTL protocols, effectively enhances performance when tailored to individuals, considering nutrition and periodization. New technologies and personalized methods could further improve results. This analysis offers a roadmap for researchers, coaches, and athletes, guiding future investigations and practical applications. As research evolves, the field is poised to address questions and translate science into tangible benefits for endurance athletes across sports and levels.

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Conflicts of Interests

The authors stated that they have no conflicts of interest concerning the study.

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