

Global Research Trends on the Effects of Cold Exposure on Fat Metabolism (1995–2025) A Bibliometric Analysis

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Abstract: This bibliometric analysis (1995–2025) highlights exponential growth and evolving trends in cold exposure research on fat metabolism. Key topics include brown adipose tissue activation, mitochondrial biogenesis, and metabolic regulation, influenced by advances in imaging technologies and translational research demands. North America and Europe lead global contributions, while collaboration across disciplines and regions remains limited. Future efforts should prioritize interdisciplinary collaboration, precision medicine approaches, and clinical translation to maximize therapeutic benefits for metabolic diseases.

Keywords: Cold exposure, Fat metabolism, Brown adipose tissue, Thermogenesis, Energy expenditure, Obesity, Bibliometric analysis.

1. Introduction

Fat metabolism is a fundamental physiological process that maintains the body's energy balance (1). It is dynamically regulated through storage, lipolysis, and oxidation (2). Its primary functions include energy provision, thermoregulation, and metabolic homeostasis (3). Among these processes, fat oxidation and lipolysis determine the efficiency of fat utilization (4). The body's energy supply is derived from the dynamic circulation of lipid molecules, including free fatty acids, lipoprotein lipase, triglycerides, and other lipid-related compounds (5). In adipose tissue, white adipose tissue (WAT) serves as the primary site for energy storage, whereas brown adipose tissue (BAT) is involved in thermogenesis, particularly in response to cold exposure—a process known as cold-induced thermogenesis (6).

Since the late 20th century, with the improvement in material living standards, obesity and metabolic disorders have become increasingly prevalent (7). Consequently, non-pharmacological interventions have gained significant research interest (8). Among these, cold exposure has emerged as a promising approach to enhance fat oxidation, increase basal metabolic rate (BMR), and elevate resting metabolic rate (RMR) (8). Exposure to cold environments has been recognized as an effective strategy for modulating metabolic processes (9). Through the activation of the sympathetic nervous system, norepinephrine stimulates the release of free fatty acids, which serve as an energy source and contribute to thermogenesis (10). Additionally, cold exposure activates the PPAR α and PGC-1 α signaling pathways, promoting mitochondrial biogenesis and lipid metabolism remodeling, thereby enhancing the body's adaptation to cold environments (11). As a result, various cold exposure interventions, such as cold water immersion, cryotherapy, cold treatment, and precooling, have been utilized to regulate physiological recovery, energy expenditure, and fat metabolism (12).

Although numerous studies have demonstrated that cold exposure increases energy expenditure and promotes fat

oxidation (13,14), significant uncertainties remain regarding optimal intervention strategies, individual differences in cold adaptation, and the long-term physiological effects (15).

Given this context, bibliometric analysis serves as a powerful tool for identifying research hotspots, mapping scientific networks, and predicting emerging trends (16). In this study, we employ bibliometric methods to analyze the research landscape of cold exposure, systematically examining its development trajectory, interdisciplinary relationships, and scientific impact. By analyzing key journals, publications, keywords, authorship networks, and institutional collaborations, we aim to elucidate the intervention trends in this field. Despite growing interest in the metabolic effects of cold exposure, no comprehensive bibliometric analysis has been conducted on its role in fat metabolism. Consequently, the research structure and evolutionary trends in this domain remain unexplored.

To address this gap, we conducted a systematic search in the Web of Science (WoS) database and utilized VOSviewer and CiteSpace for bibliometric analysis. Our study examined keyword co-occurrence patterns, temporal research trends, and collaboration networks to identify key research areas, leading institutions, and future directions in cold exposure and fat metabolism research. The findings of this study will provide a scientific foundation for the application of cold exposure in metabolic health and offer strategic guidance for future research in this field.

2. Materials and Methods

(1) Data Source and Acquisition Process

The search strategy employed to identify relevant publications included the following terms: Topic (“Cold water immersion” OR “CWI” OR “Ice therapy” OR “Cold treatment” OR “Ice bath” OR “Cold bath” OR “Ice ingestion” OR “Ice slurry” OR “Pre-cooling” OR “Precooling” OR “Cold exposure” OR “Cryotherapy” OR “Ice pack” OR “Cold compression”) AND Topic (“Fat oxidation” OR “Lipolysis” OR “Energy expenditure” OR “EE” OR “White adipose tissue” OR “WAT” OR “Beige adipose tissue” OR “BeAT”

OR “Fatty acid oxidation” OR “FAO” OR “Adipose triglyceride lipase” OR “ATGL” OR “Hormone-sensitive lipase” OR “HSL” OR “Basal metabolic rate” OR “BMR” OR “Lipid metabolism” OR “Free fatty acids” OR “FFA” OR “Triglycerides” OR “TG” OR “Lipoprotein lipase” OR “LPL” OR “Resting metabolic rate” OR “RMR” OR “Cold-induced thermogenesis” OR “CIT”) AND Topic (“Human” OR “Participants” OR “Clinical study” OR “Experimental study” OR “Cohort” OR “Case-control”) AND Language (“English”) AND Document Type (“Article”). Publications from 1995 to 2025 were retrieved, with the search conducted on March 2, 2025. To ensure data quality, bibliometric analysis was performed using literature sourced from the Web of Science Core Collection, specifically including the following citation indexes: SCI-EXPANDED, SSCI, AHCI, CPCI-S, CPCI-SSH, ESCI, CCR-EXPANDED, and IC.

No duplicate publications were identified in the search. All researchers independently screened the abstracts and ultimately selected 403 publications for analysis, with detailed information provided in Appendix 2. The inclusion criteria were as follows: studies had to be original, peer-reviewed research investigating the effects of cold exposure and other relevant interventions on fat metabolism markers, including clinical studies; articles must have been published in the Web of Science Core Collection between 1995 and 2025; and only Article and Early Access document types were included. The exclusion criteria encompassed non-original research articles, including Review Articles, Proceedings Papers, Book Chapters, Editorial Materials, Meeting Abstracts, and Retracted Publications, as well as unpublished studies and articles deemed irrelevant to the research topic.

(2) Analysis Methods and Tools

This study employs bibliometric analysis, a quantitative approach utilizing digital and statistical methods to identify research hotspots, emerging trends, and academic collaboration networks, thereby providing objective data support (17). By analyzing citation counts and co-citation patterns, the study evaluates the academic influence of research teams and disciplines, establishing quantitative assessment criteria for relevant research (18).

To conduct the bibliometric analysis on cold exposure and fat metabolism research, this study utilizes CiteSpace (6.3.R1), VOSviewer (1.6.20), and SCImago Graphica (1.0.46). CiteSpace is used for keyword clustering, burst term detection, reference co-citation analysis, and the construction of national and institutional collaboration networks, enabling the identification of research hotspots, trends, and key publications (19). VOSviewer focuses on institutional collaborations, journal co-citation, and author co-occurrence analysis, providing insights into academic collaboration patterns and core journals in the field (20). SCImago Graphica is employed to generate global research distribution maps and analyze international research contributions and cooperation networks (21).

3. Results

(1) Analysis of Category

As shown in the Table 1, Web of Science (WoS) category

analysis shows that research on cold exposure and fat metabolism spans multiple disciplines, with the top categories reflecting its strong biomedical and physiological focus. Endocrinology & Metabolism (19.355%) and Physiology (18.114%) rank highest, emphasizing the biochemical and regulatory mechanisms underlying fat metabolism in response to cold exposure. Sport Sciences (14.144%) and Nutrition & Dietetics (11.414%) highlight the relevance of exercise physiology and dietary factors in cold-induced metabolic changes. Additionally, Multidisciplinary Sciences (6.948%) and Medicine, General & Internal (5.707%) indicate a broader interest in clinical and integrative research. The presence of Public, Environmental & Occupational Health (4.715%) suggests implications for occupational safety and environmental adaptation, while Biology (4.467%), Medicine, Research & Experimental (4.467%), and Cell Biology (3.474%) highlight fundamental research into cellular and molecular mechanisms.

Table 1. Top Ten Categories in Web of Science.

Web of Science Categories	Record Count	% of 403
Endocrinology Metabolism	78	19.355%
Physiology	73	18.114%
Sport Sciences	57	14.144%
Nutrition Dietetics	46	11.414%
Multidisciplinary Sciences	28	6.948%
Medicine General Internal	23	5.707%
Public Environmental Occupational Health	19	4.715%
Biology	18	4.467%
Medicine Research Experimental	18	4.467%
Cell Biology	14	3.474%

(2) Annual Trends in Publications

This study analyzed 403 relevant articles published between 1995 and 2025. As shown in Figure 1, there is an overall upward trend in research on the effects of cold exposure on fat metabolism. However, the number of publications remained in the single digits between 2000 and 2010, indicating slow growth and limited research activity. Since 2011, research in this field has gradually increased, with a significant increase starting in 2015, marking a steady rise in the number of publications. From 2019 to 2024, research output has significantly accelerated.

The exponential model shown in Figure 1 provides a more intuitive prediction of the annual publication growth trend, following the equation $y=2.2731e^{0.0951x}$, with a goodness of fit $R^2 = 71.18\%$, indicating a strong correlation between time and publication growth. Overall, these findings suggest that research on the effects of cold exposure on fat metabolism has attracted increasing attention from researchers and has great potential for continued growth in the future.

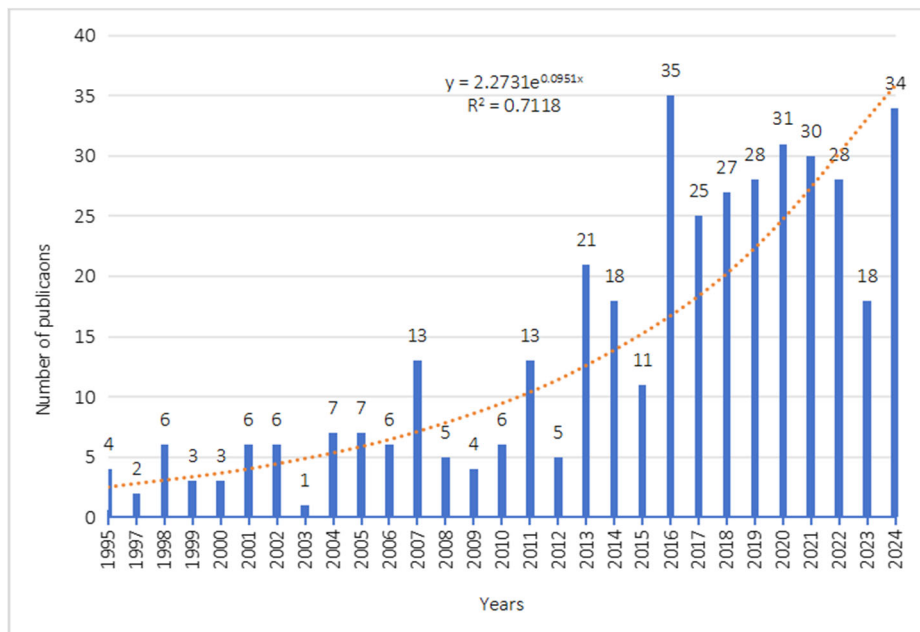


Figure 1. The Combination Chart of the Number of Annual Publications.

(3) Analysis of Countries and Regions

A total of 56 countries worldwide have participated in research on the effects of cold exposure on human metabolism. CiteSpace and VOSviewer were used to visualize the international cooperation network and publication distribution among different regions (Figure 2). As shown in Table 2, the United States leads with 112 publications, followed by the Netherlands (48), Canada (47), Japan (43), and the United Kingdom (32). Additionally, Germany (30),

Spain (29), Finland (24), China (20), and Australia (19) have also made significant academic contributions to this field.

The collaboration network analysis reveals that the United States, the Netherlands, Canada, and Japan maintain close cooperative relationships, forming multiple core research clusters. These collaborations indicate that research in this field is driven by international partnerships, with several leading institutions actively engaging in cross-border scientific exchanges.

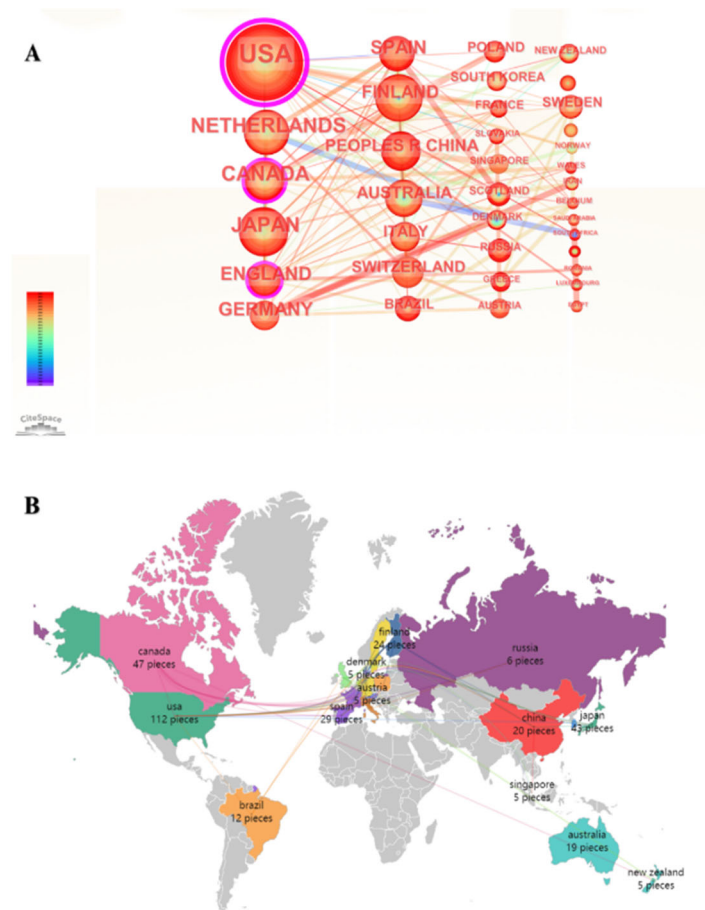


Figure 2. (A) Global Collaboration Network in Cold Exposure Research (CiteSpace); (B) Global Distribution of Publications on Cold Exposure Research (SCImago Graphica).

Table 3. Top 10 Most Productive Institutions in Cold Exposure Research.

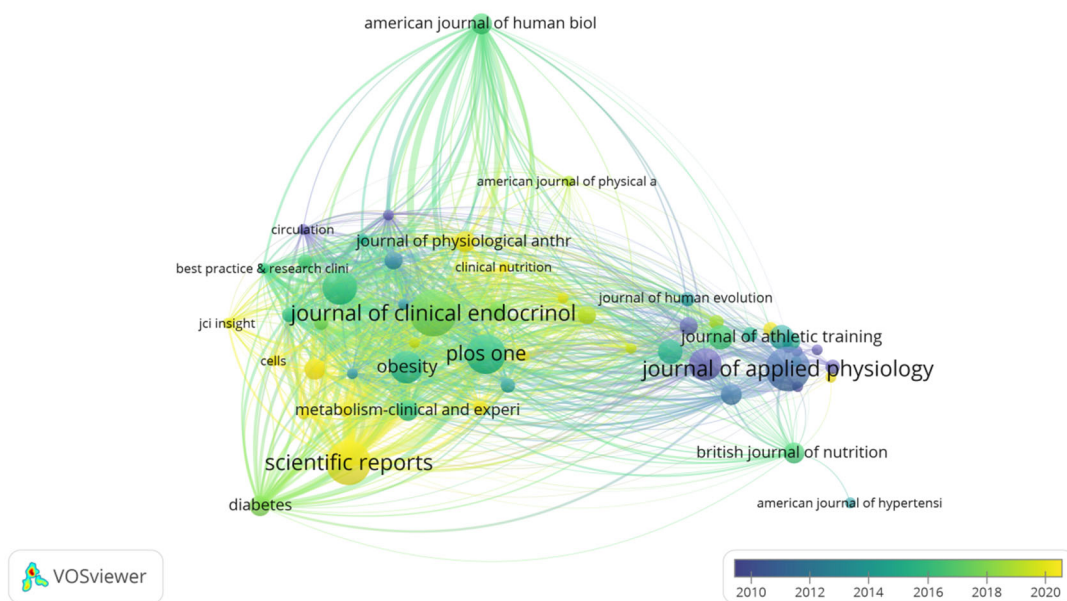
Rank	Institutions	Publication/Documents	Total citations	Average citation
1	University of Ottawa (Canada)	23	1227	53.3
2	Maastricht University (Netherlands)	19	1173	61.7
3	Tenshi College (Japan)	18	1800	100
4	Leiden University (Netherlands)	17	280	16.5
5	University of Turku (Finland)	17	620	36.5
6	Turku University Hospital (Finland)	16	613	38.3
7	University of Granada (Spain)	15	142	9.5
8	Hokkaido University (Japan)	15	1378	91.9
9	Pennington Biomedical Research Center (USA)	12	228	19
10	LSI Sapporo Clinic (Japan)	9	1514	168.2

(5) Analysis of Journals

In the field of cold exposure research, a total of 221 journals have published relevant studies. Figure 4 shows the visualization network of core journals, illustrating their interconnections and academic influence, and Table 4 lists the top ten journals with the most publications in this field. These include Journal of Clinical Endocrinology & Metabolism, Scientific Reports, PLOS One, Journal of Applied Physiology,

etc.

It is worth noting that Journal of Clinical Endocrinology & Metabolism and Journal of Applied Physiology occupy a prominent position in terms of the number of publications, influence, and citation frequency Table 4, with 806 and 411 citations respectively. In addition, journals such as Obesity and International Journal of Obesity have also exerted considerable influence in this research field.

**Figure 4.** Journal Co-Citation Network in Cold Exposure Research.**Table 4.** Top Journals in Cold Exposure Research Based on Publications and Citations.

Rank	Journal	Documents	Citations	Centrality
1	Journal of Clinical Endocrinology & Metabolism	15	806	0.037
2	Scientific Reports	14	343	0.034
3	Journal of Applied Physiology	14	411	0.034
4	Plos One	12	664	0.029
5	International Journal of Obesity	10	558	0.025
6	Obesity	9	597	0.022
7	European Journal of Applied Physiology	9	222	0.022

Table 5. (Continued).

Rank	Journal	Documents	Citations	Centrality
8	Experimental Physiology	6	135	0.015
9	Journal of Thermal Biology	6	155	0.015
10	Journal of Athletic Training	6	184	0.015

(6) Analysis of Authors

Since 1995, a total of 2046 researchers have published papers in the field of cold exposure research. The visual network diagram (Figure 5) illustrates the collaboration between scholars in this field. The analysis shows that a close academic collaboration network has not yet been formed, and most research is conducted by independent scholars or small research teams. However, some well-known collaborative groups have emerged, including those led by Acosta

Francisco M, Martinez-Tellez Borja, and Lichtenbelt Wouter D. van Marken.

Table 6 lists the top 9 scholars by number of published papers. Acosta Francisco M ranks first with 14 publications, followed by Martinez-Tellez Borja and Ruiz Jonatan R, each with 12 publications. In addition, co-citation analysis shows that Yoneshiro T, Cypess AM, and Lichtenbelt WDV are the most cited scholars, reflecting their high academic influence in the field (Table 7).

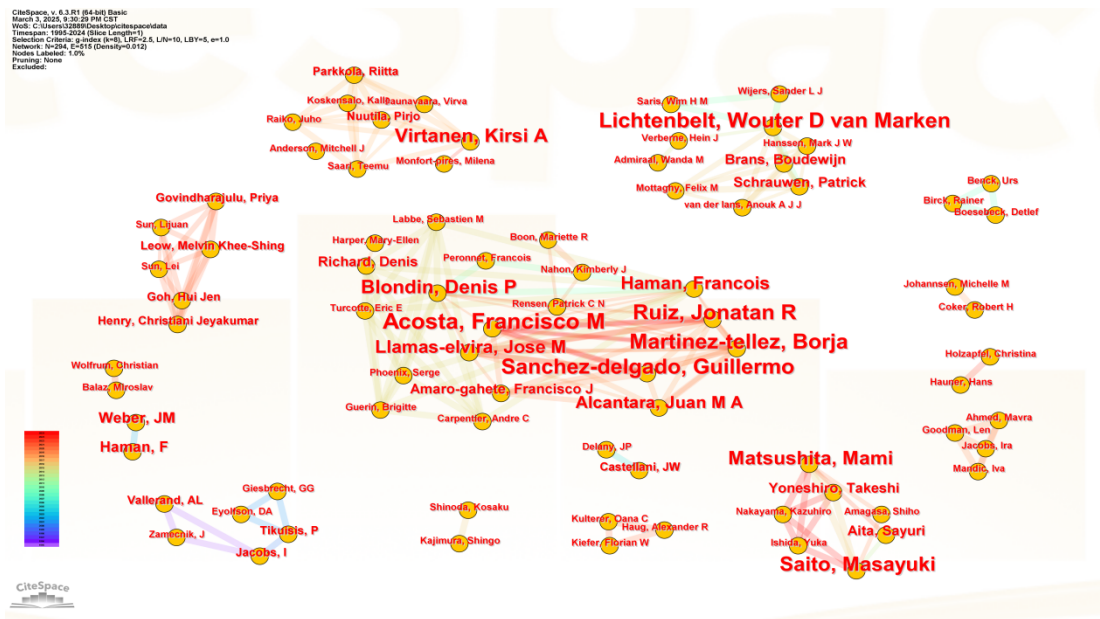


Figure 5. Collaboration Network of Authors in Cold Exposure Research.

Table 6. Top Authors by Publication Volume in Cold Exposure Research.

Rank	Author	Documents
1	Acosta, Francisco M	14
2	Martinez-tellez, Borja	12
3	Ruiz, Jonatan R	12
4	Lichtenbelt, Wouter D van Marken	11
5	Sanchez-delgado, Guillermo	11
6	Saito, Masayuki	10
7	Virtanen, Kirsi A	9
8	Blondin, Denis P	8
9	Matsushita, Mami	8

Table 7. Most Co-Cited Authors in Cold Exposure Research.

Rank	Cited Author	Co-citations
1	yoneshiro, t	205
2	cypess, am	197
3	lichtenbelt, wdv	196
4	blondin, dp	163
5	saito, m	138
6	ouellet, v	122
7	lee, p	119
8	virtanen, ka	114
9	haman, f	108
10	cannon, b	107

(7) Analysis of References

In the citation co-citation network analysis, as shown in Figure 6, the studies by Lichtenbelt WDV (2009), Ouellet V

(2012), and Cypess AM (2015) stand out as fundamental contributions.

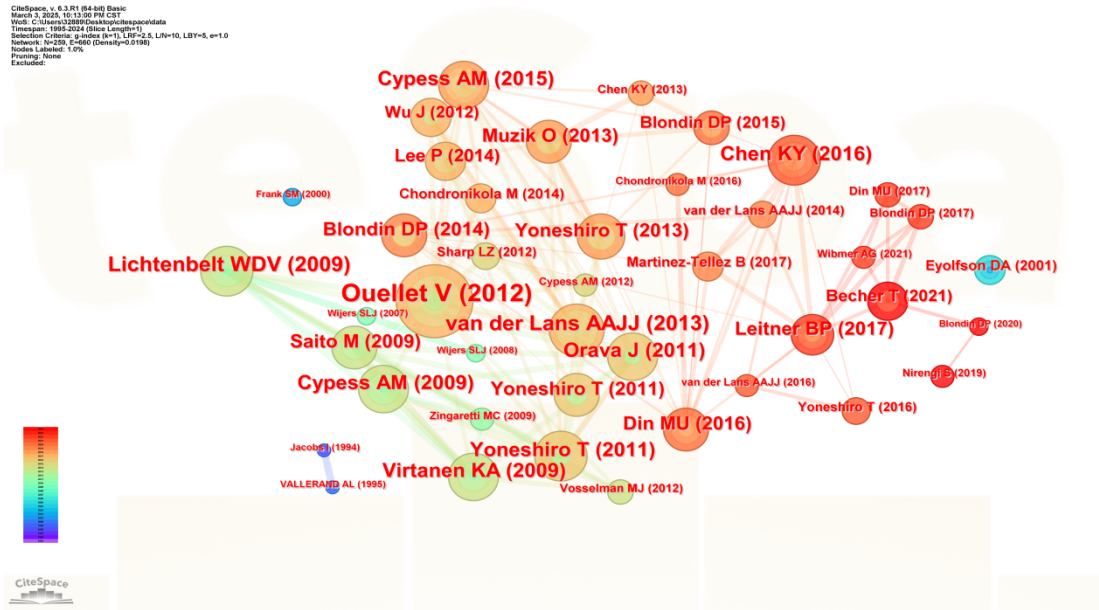


Figure 6. Co-Citation Network of Key References in Cold Exposure Research.

(8) Analysis of Keywords

Figure 7A and Figure 7B in the keyword co-occurrence analysis illustrate the density distribution and clustering of keywords and the top 10 co-occurrence times of keywords are listed in Table 8. among which "energy expenditure" (99 occurrences, centrality 0.34, first published in 1995), "brown adipose tissue" (93 occurrences, centrality 0.09, first published in 2005), and "cold exposure" (90 occurrences, centrality 0.12, first published in 2007) are the most frequently occurring terms. Other high-frequency keywords include "fat" (59 occurrences), "exposure" (58 occurrences), "thermogenesis" (55 occurrences), and "human" (51 occurrences).

In the co-occurrence network (Figure 7C), "thermogenesis",

"cold exposure", and "energy expenditure" show the strongest connection strength, confirming their central role in cold-induced metabolic adaptation. "activation" (39 occurrences, first published in 2011), "metabolism" (36 occurrences, first published in 2010), and "exercise" (36 occurrences, first published in 1995).

Figure 7D shows the 17 most cited keywords, with "cold-induced thermogenesis," "insulin sensitivity," and "temperature" increasing significantly from 2019 to 2024. The concentration of high-impact keywords in recent years suggests that research is shifting toward clinical and translational research applications, positioning cold exposure as a potential intervention strategy for metabolic health and chronic disease management.

Table 8. Keyword Analysis of Cold Exposure Research.

Rank	Keyword	Counts	Centrality	First Publication Year
1	energy-expenditure	99	0.34	1995
2	brown adipose tissue	93	0.09	2005
3	cold exposure	90	0.12	2007
4	fat	59	0.03	2013

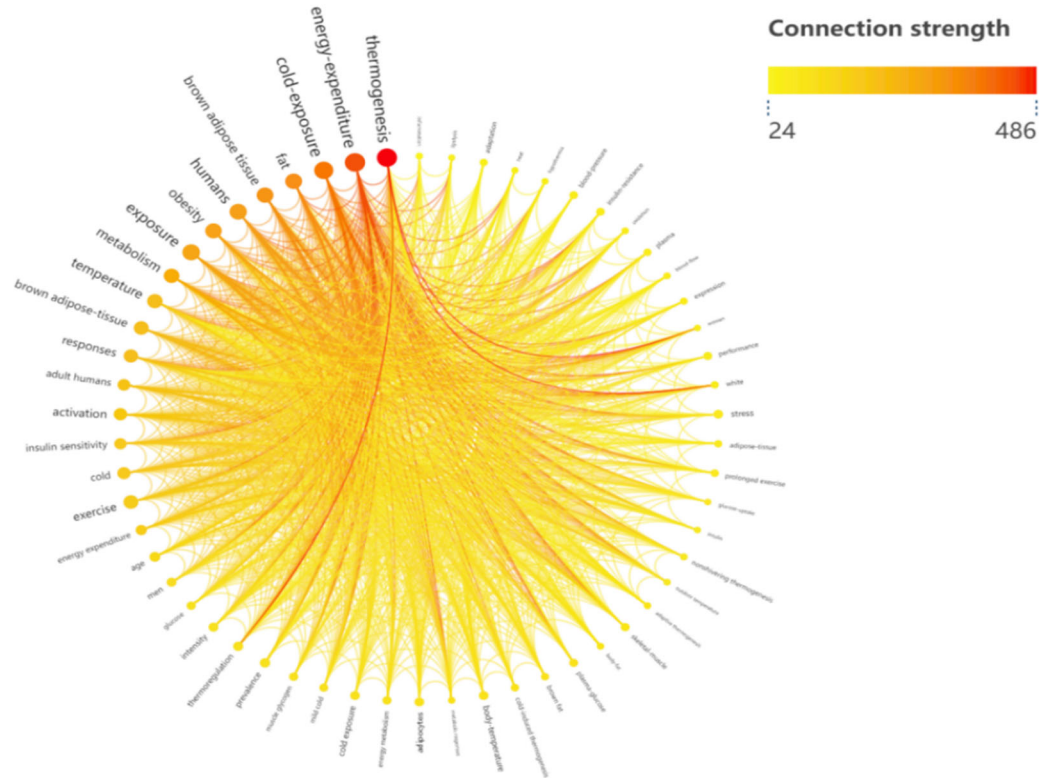
Table 9. (Continued).

Rank	Keyword	Counts	Centrality	First Publication Year
5	exposure	58	0.20	1995
6	thermogenesis	55	0.03	2013
7	humans	51	0.15	1998
8	temperature	40	0.09	1995
9	activation	39	0.06	2011
10	metabolism	36	0.04	2010
10	exercise	36	0.08	1995

of brown adipose tissue (BAT) in thermogenesis (25), For example, cold exposure regulates mitochondrial biogenesis and lipid metabolism by activating the PPAR α /PGC-1 α signaling pathway. As a key factor of nuclear receptors, PPAR α promotes the decomposition and utilization of fatty acids by transcriptionally activating the gene expression of

key enzymes of fatty acid oxidation (such as CPT1 α and ACOX1), thereby improving overall energy consumption and lipid metabolism efficiency (26). This shift highlights the growing interest in alternative, noninvasive metabolic interventions.

C



D

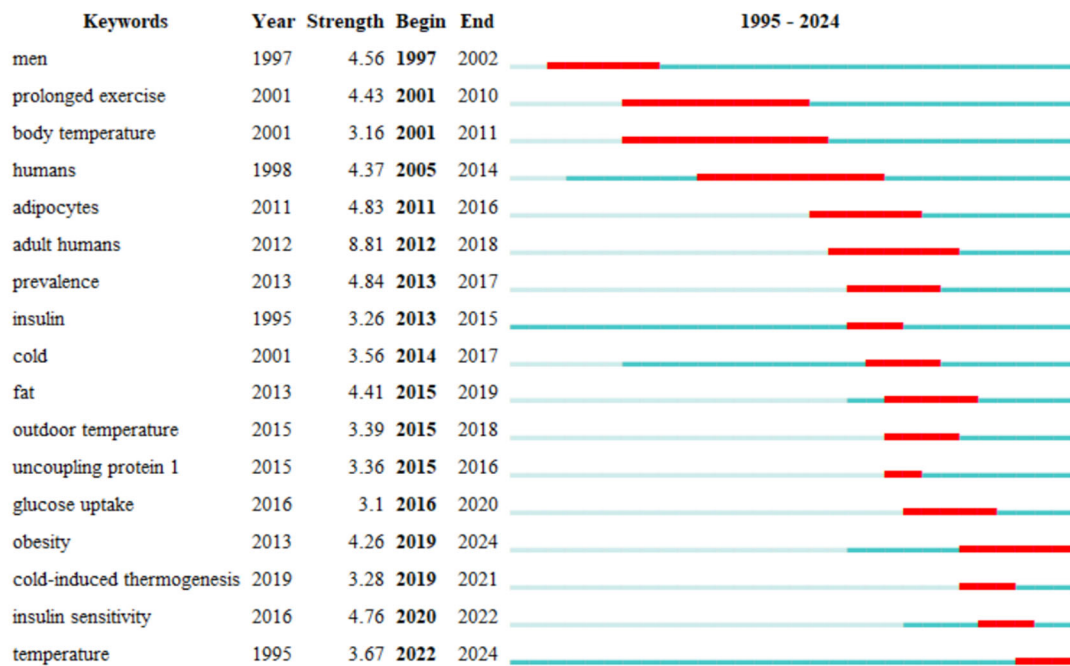


Figure 8. (Continued).

As illustrated in the Table 10, cold exposure research demonstrates a multidisciplinary convergence spanning endocrinology, physiology, exercise science, thermoregulation, and environmental health, bridging

fundamental metabolic investigations with clinical and public health applications. This transdisciplinary integration suggests that cold exposure is not merely a metabolic phenomenon but a complex physiological adaptation

involving neuroendocrine regulation, energy homeostasis, and environmental interactions (27).

Geographic analysis of scholarly output reveals predominant contributions from North America and Europe (Figure 2), with the United States (n=112), the Netherlands (n=48), and Canada (n=47) constituting the primary knowledge hubs. This geoscientific prominence may be attributed to advanced research infrastructure, sustained governmental funding, prioritization of metabolic disorder investigations, and latitude-specific climatic conditions (28). Notably, China has emerged as an ascending contributor (n=20 publications), though current efforts remain geographically constrained with limited international synergy (total link strength=35). This stands in contrast to the robust collaborative frameworks observed among U.S., Dutch, and Japanese institutions, where multicenter data harmonization and shared experimental protocols have accelerated field advancement (Figure 2). These findings emphasize the imperative of establishing strategic international partnerships and implementing knowledge-sharing platforms.

The institutional contribution analysis identifies the University of Ottawa (23 publications) and Maastricht University (19 publications) as the leading research centers in cold exposure research (Figure 3). However, the institutional collaboration network reveals a fragmented research landscape, where inter-institutional cooperation remains limited. This lack of collaboration may restrict the cross-validation of findings and hinder large-scale data integration (29). Strengthening international research partnerships through data sharing, joint funding programs, and standardized methodologies could significantly enhance the scientific rigor and reproducibility of research outcomes, accelerating advancements in this field (30).

The Journal of Clinical Endocrinology & Metabolism ranks highest in both publication volume (15 articles) and total citations (806) within cold exposure research (Table 4), highlighting its key role in disseminating influential studies on metabolic and endocrine responses to cold exposure. Close behind, Scientific Reports and the Journal of Applied Physiology, each with 14 publications, emphasize the interdisciplinary integration among clinical endocrinology, metabolic science, and exercise physiology. The significant presence of PLOS One (12 publications, 664 citations) indicates an increasing preference toward open-access journals, enhancing the accessibility and interdisciplinary dissemination of cold exposure findings. Furthermore, journals specifically focused on obesity and metabolism research, including the International Journal of Obesity and Obesity, underline the growing clinical relevance of cold exposure interventions for metabolic health and weight management. Meanwhile, journals such as Experimental Physiology, Journal of Thermal Biology, and Journal of Athletic Training provide complementary perspectives by emphasizing cold exposure's applications in exercise science and environmental physiology, further showcasing the field's broad applicability. Collectively, these publication patterns highlight a distinct interdisciplinary trend within cold exposure research, bridging clinical endocrinology, metabolism, exercise physiology, and environmental science. To maximize future research impact, researchers are encouraged to target high-quality, specialized journals and strengthen collaborative networks across highly productive research groups, thereby accelerating knowledge transfer and facilitating the clinical translation of cold exposure

interventions for metabolic disorders.

In the co-citation network analysis (Figure 6), several foundational studies emerged as central nodes with high citation frequencies, notably those by Cypess AM (2009, 2015) (31,32), Lichtenbelt WDV (2009) (33), and Ouellet V (2012) (34), which provided critical insights into brown adipose tissue (BAT) activation, thermogenesis, and metabolic regulation. Other influential authors, such as Yoneshiro T (2011, 2013) (35,36) and van der Lans AAJJ (2013, 2014) (37,38), further advanced the field by examining individual variability in metabolic adaptations to repeated cold exposure, highlighting the importance of factors like age, sex, and genetic predisposition, and underscoring the need for personalized cold-induced metabolic interventions. Co-citation analysis revealed distinct yet interconnected research clusters, including BAT thermogenesis and metabolic health, explored through core studies by Cypess, Lichtenbelt, and Blondin, which positioned cold exposure as a promising approach for obesity and diabetes management; human physiological adaptation, investigated by Virtanen KA (2009) (39), Saito M (2009) (40), and Din MU (2016) (41), emphasizing mechanisms such as non-shivering thermogenesis and substrate utilization; and clinical applications and intervention studies, as demonstrated by Leitner BP (2017) (42) and Becher T (2021) (43), which have begun translating experimental insights into potential clinical interventions. Taken together, these findings illustrate a clear shift toward translational and clinical research, bridging basic physiological studies and practical metabolic interventions.

Keyword network analysis has identified three major themes in cold acclimation research. First, thermogenesis includes BAT activation, mitochondrial biogenesis, and non-shivering thermogenesis. Seminal studies by Lichtenbelt et al (44). (2009) and Cypess et al. (2009) established BAT as a key regulator of human energy homeostasis, with significant findings emerging by 2015 (45). Second, substrate utilization is another key aspect of cold exposure research (46). It is associated with increased lipolysis, fatty acid oxidation, and glucose uptake, such as acute cold exposure has been shown to increase energy expenditure (35). Third, systemic regulation involves the sympathetic nervous system, hormonal pathways (e.g., leptin, adiponectin), and inflammatory mediators, emphasizing the role of cold exposure in systemic metabolic adaptation (47,48).

5. Limitations

This study has several limitations that should be acknowledged. First, the data were exclusively retrieved from the Web of Science® Core Collection, which may have led to the omission of relevant literature from other databases such as PubMed, Scopus, or Google Scholar. As a result, some influential studies might not have been included in the analysis.

Second, this study focused solely on human research, excluding animal studies, which have played a crucial role in elucidating the molecular mechanisms of brown adipose tissue (BAT) activation and gene regulation. Integrating findings from both human and animal studies could provide a more comprehensive understanding of the physiological and metabolic effects of cold exposure.

Finally, the predictive analysis remains uncertain, as rapid advancements in biotechnology and metabolic research could significantly alter the trajectory of this field (49). The emergence of new experimental techniques and genetic

interventions may introduce novel insights that could reshape current research directions on cold exposure and metabolic health (50).

6. Conclusion

This bibliometric analysis evaluated global research trends on cold exposure and fat metabolism from 1995 to 2025, highlighting an exponential rise in studies after 2015. Early research focused on acute physiological responses, shifting recently toward molecular mechanisms, clinical applications, and metabolic disorder management. The United States, the Netherlands, and Canada dominate contributions, whereas China's growing output lacks extensive international collaboration. Keyword analyses identified thermogenesis, substrate utilization, and systemic metabolic regulation as primary research themes. However, gaps remain regarding long-term metabolic adaptations, individual variability, and fragmented research collaboration. Strengthening global partnerships and standardizing methodologies are essential to advance cold exposure interventions for metabolic health.

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