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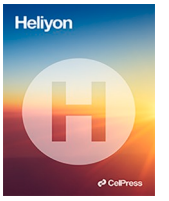

# Global scientific trends in healthy aging in the early 21st century: A data-driven scientometric and visualized analysis

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ABSTRACT

*Background:* According to the World Health Organization (WHO), healthy aging is the process of developing and maintaining the functional capacity for health in old age. A rapidly growing number of research studies on healthy aging have been conducted worldwide. The purpose of this research work is to explore global scientific landscape of healthy aging research over the last 22 years.

*Methods:* Scientific publications on healthy aging from January 1, 2000 to October 11, 2022 were retrieved from the Web of Science Core Collection (WoSCC) on October 11, 2022. A total of 6420 publications were included in the scientometric analysis. VOSviewer (1.6.18) was used to conduct scientometric and visualized analysis.

*Results:* The publication growth rate was 35.68 from 2000 to 2021. The United States of America (USA) led in both productivity and citations. *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA* was prominent in terms of both the highest citation count and the highest average citation count. The National Institute on Aging (NIA) and Evans, Michele K. were the most influential organization and author, respectively. Research hotspots in healthy aging were identified based on the co-occurrence analysis of keywords: (1) physical activity and mental health of older adults; (2) diseases impacting the health and lifespan of older adults; and (3) neuroscience. Our analysis indicates that gut microbiota, loneliness, frailty, mitochondria and resilience were the emerging themes in healthy aging research.

*Conclusions:* The quantity of annual publications on healthy aging has rapidly increased over the past 22 years, especially during 2018–2021. This analysis identified the status, trends, hot topics, and frontiers of healthy aging research. These findings will help researchers quickly understand the global representation of healthy aging research, influence resource dissemination, promote international collaborations, guide policy formulation, and improve health services for older adults.

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## 1. Introduction

Currently, over 962 million people, or 13 % of the world's population, are aged 60 and up [1]. This demographic is growing at a faster rate than any of the younger age groups due to decreased fertility and increased life expectancy, and this estimate is anticipated to quadruple by 2050 [2]. By 2070, people aged 65 and above are projected to comprise 45 % of the European population [3]. These unprecedented changes affect persons, families, governments, and private enterprises as they need to be prepared to deal with issues pertain to housing, job and retirement, social security, health care, caregiving, and the burden of disability and disease. Aging is responsible for the majority of the global healthcare burden [4] and is the main factor contributing to considerable increases in the prevalence of chronic illnesses, including diabetes, chronic obstructive pulmonary disease, stroke and dementia [5]. Diseases affecting older adults are becoming a serious global public health concern.

The World Health Organization (WHO) defines healthy aging as "the process of developing and maintaining functional capacity for health in old age", this functional capacity is determined by the individual's physical and psychological conditions (including social psychology, etc.), the environments around them (including social environment, policy environment, etc.), and their interaction [1]. WHO has prioritized healthy aging to make sure high-quality life for older adults [6]. There is an urgent need to promote global research on aging populations because the higher rates of population aging and a greater proportion of older adults in the coming decades will occur in low- and middle-income countries [7]. Literature on healthy aging plays a pivotal role in developing geriatric healthcare systems and improving geriatric health services [8]. Evaluating published literature in respect of the volume, journals, authors and topical trends will provide insights and references on the progress, challenges, and future research orientations in the area for geriatric healthcare organizations, healthy aging researchers, and funding agencies [9]. Previous studies have focused on two main areas: one, the analysis of the content of research on healthy aging, including disciplinary classifications, research themes and fields, research trends and frontiers [1]; and two, the analysis of scientometric indicators in the literature on healthy aging, selected for a short time span (10 years), and the analysis of indicators such as productivity and cooperation [10]. However, there is no systematic multi-perspective analysis of the global scientific trends in healthy aging to date. Our study filled this gap with a more comprehensive analytical perspective. Not only were scientometric indicators selected to explore overall trends in healthy aging research, but scientometric methods were applied to categorize and analyze research content. The international collaboration was further analyzed in terms of the institutions and authors, and the literature data was cleaned and integrated for literature network analysis, making the clustering results clearer and more accurate.

The aim of this scientometric analysis is to uncover the rich research components within the field and the scientometric structure illustrating the network between these components as well as the knowledge structure of relevant thematic clusters. The method can be employed in a replicable and transparent manner with minimal bias using new and powerful software programs [11]. Furthermore, scientometric analysis serves a crucial role in informing government policy formulation, with a specific focus on identifying funding guidelines [12], and, notably, in shaping public health guidelines [13]. The present study has undertaken a comprehensive scientometric analysis to delve into the global scientific landscape of healthy aging research in the early 21st century. Our investigation encompasses a wide array of facets, including publications, countries, journals, institutions, authors, and keywords. In addition, we provide data visualization to assist in locating research hotspots and emerging topics. In summary, the exploration of the world scientific landscape of healthy aging research holds significant practical implications. It contributes to the improvement of the quality of life for older adults, informs research priorities and policy formulation, and fosters international collaboration to effectively tackle the distinctive challenges arising from an aging population.

## 2. Methods

In the Web of Science database, we assessed the research outputs of healthy aging studies. This database is the world's biggest and most comprehensive scholarly information resource, encompassing a broad spectrum of disciplines and containing core academic journals across various research areas [14]. Fig. 1 presents the research framework of healthy aging. We utilized a set of synonymous phrases in the Web of Science Core Collection (WoSCC) to conduct our search. The language variant issue was addressed using a finite truncation operator ("$"). The following were search terms: TS= ("Healthy Ag$ing" or "Ag$ing Well" or "Well Ag$ing") AND Language = English. The document type was limited to articles. In total, 6420 scientific publications from January 1, 2000 to October 11, 2022, were retrieved from WoSCC. The complete records and cited references of the articles were downloaded in plain text format. The search and download were completed in one day on October 11, 2022, to minimize daily update bias. It was carried out on a publicly available database and did not necessitate institutional review board approval, as it was deemed non-human subject research).

A classic software application named VOSviewer for constructing and visualizing scientometric networks, is commonly used in literature analysis and research to conduct data mining, mapping and clustering on retrieved literature [15]. Compared to other scientometric tools (e.g. CiteSpace [16]), VOSviewer is more ideal for handling large-scale data, with stronger graphical visualization capabilities for certain analytical content. The free JAVA-based application was designed by Van Eck and Waltman from the Centre for Science and Technology Studies (CWTS) at Leiden University in the Netherlands in 2009 [17]. It is primarily oriented toward literature data and adapts to the analysis of one-mode undirected networks, focusing on scientific knowledge visualization. The key idea behind VOSviewer is co-occurrence clustering, in which the simultaneous appearance of two objects indicates that they are connected. The connections vary in strength and direction. It uses a similarity measure called association strength to normalize co-occurrence data [17]. The association strength and its direction were used by the clustering algorithm to identify groups consisting of closely related nodes [17]. Three major functions of VOSviewer are Network visualization, Overlay visualization and Density visualization, based on

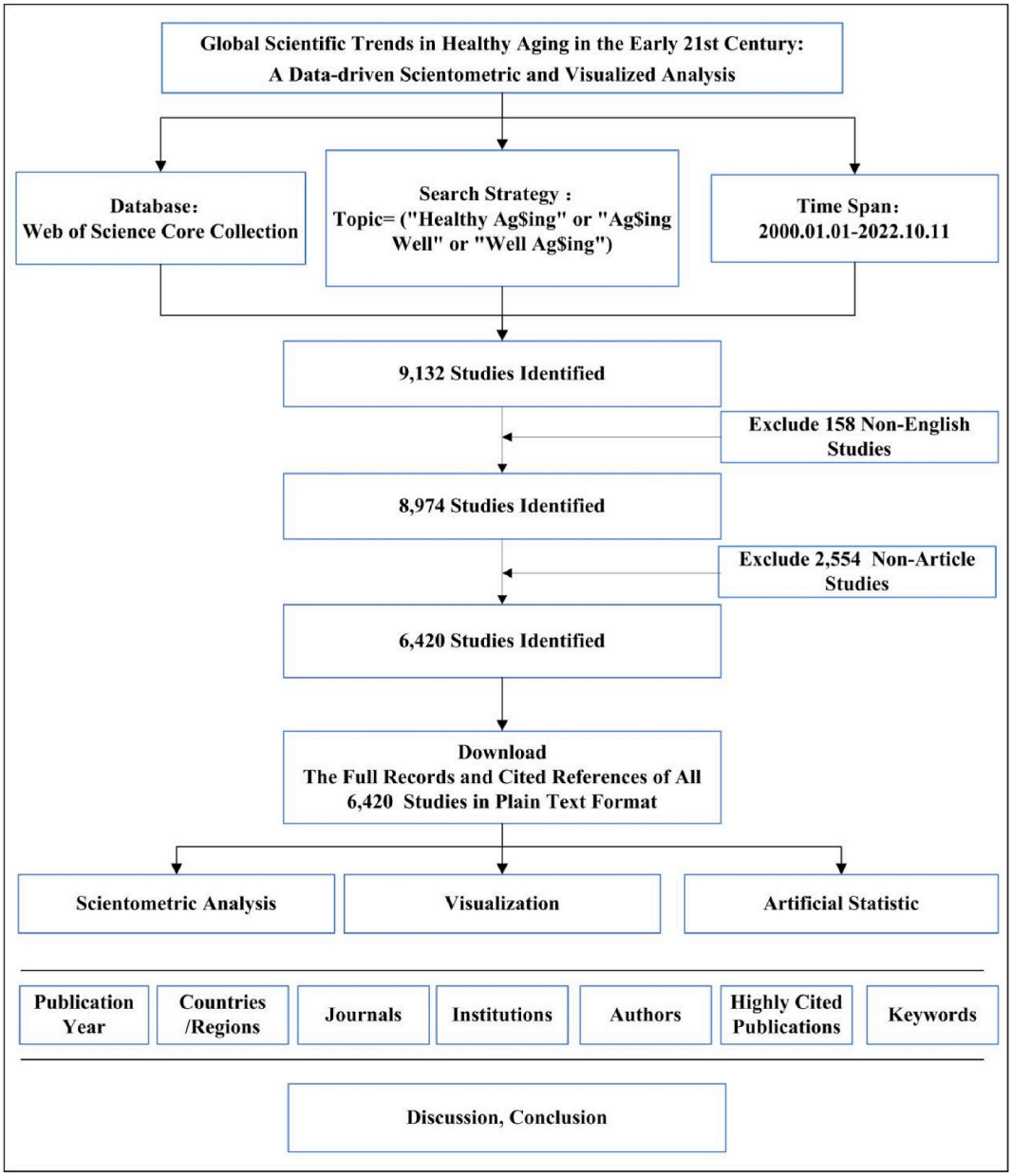


**Fig. 1.** The research framework of healthy aging.

the analysis units of co-occurrence clustering and clustering visualization impact. In addition to knowledge graph visualization, it also offers data cleaning and vocabulary filtering. From VOSviewer (1.6.18), we extracted scientometric index data, including publishing sources, institutions, authors, citations and keywords. Not only the top ten countries, journals, institutions, and authors were examined, but the number of annual publications and the total number of citations. The 2021 impact factor (IF) for each journal was also included in the results. Finally, a visual analysis of institutions, authors, and keywords was carried out. To evaluate collaborative relationships among institutions and authors, network visualization maps were generated using the VOSviewer program [18]. Co-author collaborations might be either intra-institutional (within the same institution but in separate research fields) or inter-institutional (i.e. different national or international institutions) [19]. Using item correlations based on the volume of co-authored literature and the institution/author as the unit of analysis, the network for this analysis was created [20]. To further categorize the primary themes or issues in the available publications on healthy aging, we plotted the relatedness of high-frequency keywords utilizing a term co-occurrence analysis [21]. The association strength was used to standardize the links between the keywords for this analysis [22].

## 3. Results

### 3.1. Number of global publications

The annual number of publications on healthy aging from 2000 to 2021 is shown in Fig. 2. The global annual publications witnessed a remarkable increase of 3568 %, rising from 25 in 2000 to 917 in 2021. Only 8.3 % (482/5794) of the total between 2000 and 2008, with no more than 100 papers published in any single year during this period. During the years 2009–2015, the annual number of publications grew from 128 to 343. From 2016 to 2021, the annual number of publications exceeded 400 in 2016 and peaked at 917 in 2021, with a median of 573. The total number of publications from 2018 to October 2022 amounted to 3,855, representing 53.3 % of the total (3425/6420).

### 3.2. Contributions of countries/regions

Publications on healthy aging originated from authors representing 110 countries/regions. Among the 110 countries/regions identified, 51 (46.4 %) have 10 or more publications. The global distribution of these leading countries/regions (at least 10 publications) on healthy aging is shown in Fig. 3. The top 10 productive countries/regions as shown in Table 1. Regarding publications that highlighted a specific country/region, the United States of America (USA) garnered the most attention with 2313 (36.0 %) publications, followed by United Kingdom (UK) (913 publications, 14.2 %), Australia (608 publications, 9.5 %), Canada (589 publications, 9.2 %) and Germany (575 publications, 9.0 %). The USA held the highest number of citations (73,694 citations), followed by UK (26,086 citations) and Germany (16,398 citations).

### 3.3. Contributions of journals

Publications on healthy aging were published in 1471 unique journals, of which 18.0 % (1155/6420) were published in the top 10 journals by number of publications, as presented in Table 2. *INTERNATIONAL JOURNAL OF ENVIRONMENTAL RESEARCH AND PUBLIC HEALTH* (IF 2021: 4.614, 800 citations) with 165/6420 (2.6 %) publications was the top journal by count, followed by *FRONTIERS IN AGING NEUROSCIENCE* (153 publications, IF 2021: 5.702, 2489 citations) and *PLOS ONE* (139 publications, IF 2021: 3.752, 3156 citations). Out of the top 10 productive journals, *NEUROBIOLOGY OF AGING* was the most cited journal with 4932 citations.

Setting the minimum number of articles published by journals to 10 resulted in 121 minimally productive journals, which contributed to 57.8 % (3712/6420) of the publications. Citation analysis of these journals revealed an overlay visualization of them (Fig. 4). In the visualized network, each journal is symbolized by a node. The size of a node corresponds to the number of publications related to that node, while the distance between two nodes indicates their relatedness as defined by the number of times they cite each other [23]. The color gradient represents the average number of citations within each node, and a shift from blue to red denotes that the journal is being cited more frequently. Of the 121 productive journals, *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA* had both the highest number of citations (5134 citations) and the highest average number of citations (257 average citations per publication).

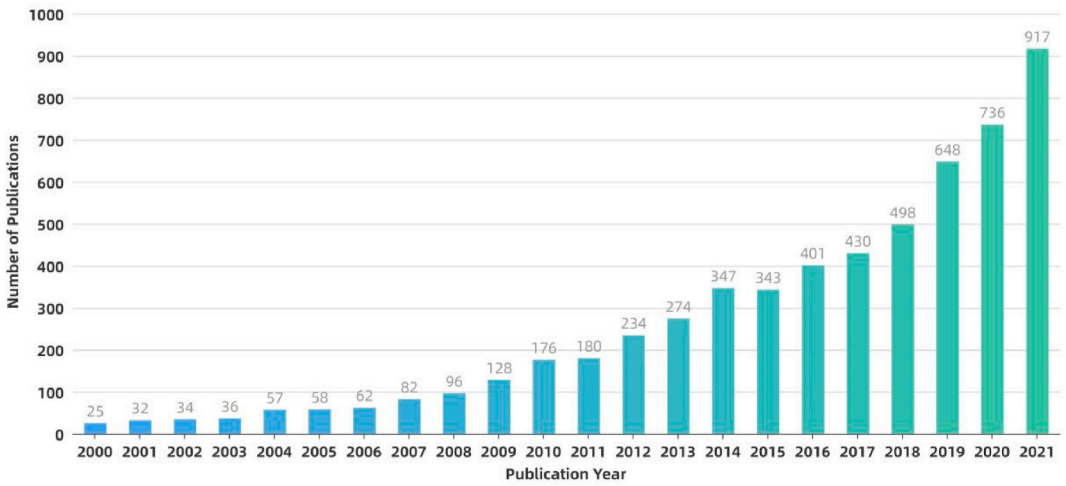


**Fig. 2.** The annual number of publications on healthy aging from 2000 to 2021.

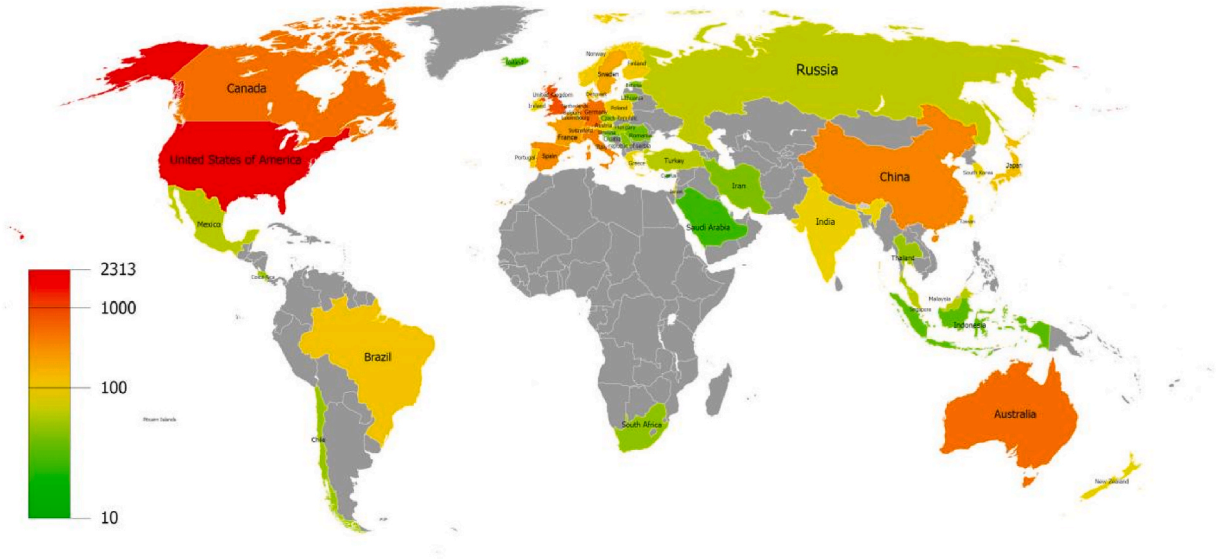


**Fig. 3.** The global distribution of leading countries/regions (at least 10 publications) on healthy aging.

**Table 1**
The top 10 productive countries/regions on healthy aging.

| Rank | Countries/regions | Counts | Citations | Avg. Citations | Avg. Pub. Year |
|---|---|---|---|---|---|
| 1 | United States of America | 2313 | 73694 | 32 | 2015.96 |
| 2 | United Kingdom | 913 | 26086 | 29 | 2016.62 |
| 3 | Australia | 608 | 14544 | 24 | 2016.10 |
| 4 | Canada | 589 | 16148 | 27 | 2016.10 |
| 5 | Germany | 575 | 16398 | 29 | 2016.88 |
| 6 | Italy | 444 | 13826 | 31 | 2016.77 |
| 7 | China | 431 | 5650 | 13 | 2019.15 |
| 8 | Netherlands | 427 | 15165 | 36 | 2016.06 |
| 9 | Spain | 399 | 9136 | 23 | 2018.19 |
| 10 | France | 285 | 8003 | 28 | 2016.27 |

**Table 2**
The top 10 productive journals on healthy aging.

| Rank | Journal Title | Country | Count | Citations | Avg. Citations | IF (2021) | H-index |
|---|---|---|---|---|---|---|---|
| 1 | INTERNATIONAL JOURNAL OF ENVIRONMENTAL RESEARCH AND PUBLIC HEALTH | Switzerland | 165 | 800 | 5 | 4.614 | 67 |
| 2 | FRONTIERS IN AGING NEUROSCIENCE | Switzerland | 153 | 2489 | 16 | 5.702 | 55 |
| 3 | PLOS ONE | USA | 139 | 3156 | 23 | 3.752 | 268 |
| 4 | JOURNALS OF GERONTOLOGY SERIES A-BIOLOGICAL SCIENCES AND MEDICAL SCIENCES | USA | 130 | 3576 | 28 | 6.591 | 168 |
| 5 | NEUROBIOLOGY OF AGING | England | 129 | 4932 | 38 | 5.133 | 168 |
| 6 | BMC GERIATRICS | England | 102 | 930 | 9 | 4.070 | 56 |
| 7 | NEUROIMAGE | USA | 100 | 4554 | 46 | 7.400 | 320 |
| 8 | EXPERIMENTAL GERONTOLOGY | England | 81 | 1602 | 20 | 4.253 | 124 |
| 9 | NUTRIENTS | Switzerland | 81 | 789 | 10 | 6.706 | 75 |
| 10 | AGING-US | USA | 75 | 1504 | 20 | 5.955 | 73 |

### *3.4. Contributions of institutions*

In total, 6167 institutions contributed to research on healthy aging. Table 3 presents the top 10 most prolific institutions by publication amounts. During this period, the National Institute on Aging (NIA) (193 publications, 6268 citations) was the institution that contributed the most to literature, followed by University of Washington (185 publications, 8763 citations) and Harvard University (164 publications, 6863 citations). Among the top 10 productive institutions, University of California, San Diego (50 average citations) and University of Washington (47 average citations) had the highest average citations, and University College London (UCL)

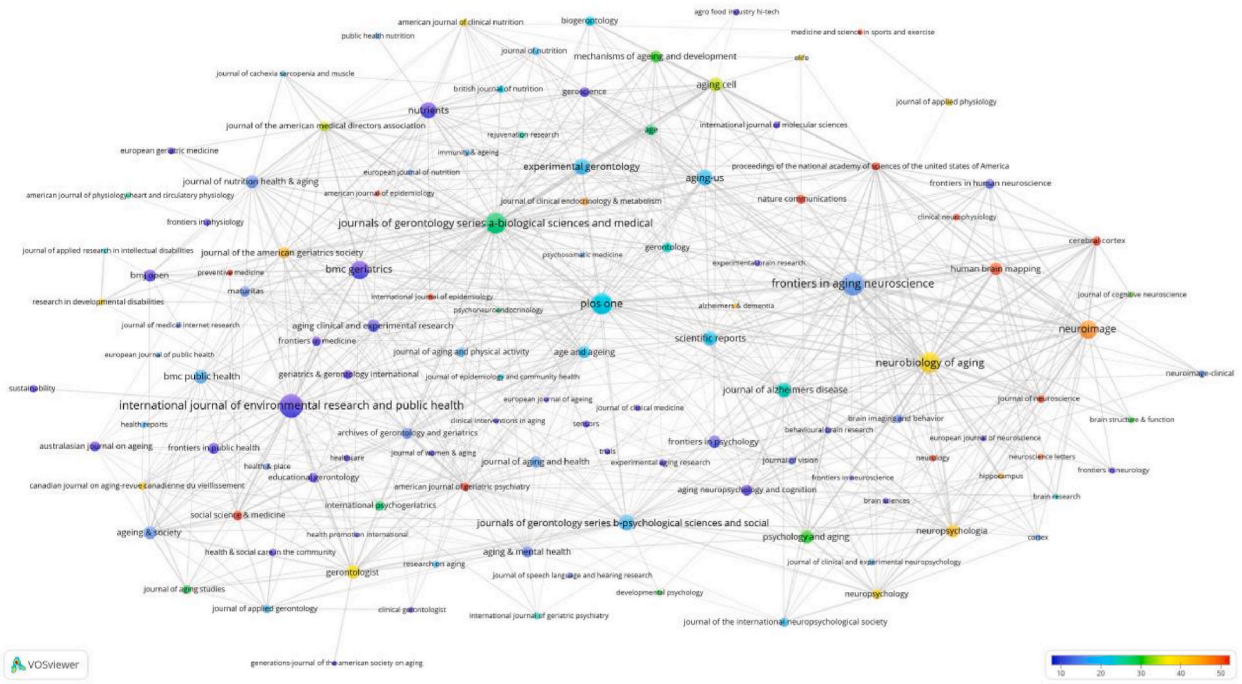


**Fig. 4.** The overlay visualization map of leading research journals on healthy aging.

**Table 3**
The top 10 productive institutions on healthy aging.

| Rank | Institution | Country | Counts | Citations | Avg. Citations | Avg. Pub. Year |
|---|---|---|---|---|---|---|
| 1 | National Institute on Aging | USA | 193 | 6268 | 32 | 2016.18 |
| 2 | University of Washington | USA | 185 | 8763 | 47 | 2015.43 |
| 3 | Harvard University | USA | 164 | 6863 | 42 | 2016.22 |
| 4 | University College London | England | 134 | 5251 | 39 | 2016.92 |
| 5 | University of Pittsburgh | USA | 113 | 4102 | 36 | 2015.46 |
| 6 | Johns Hopkins University | USA | 108 | 4044 | 37 | 2015.57 |
| 7 | University of Melbourne | Australia | 101 | 2423 | 24 | 2015.58 |
| 8 | University of Toronto | Canada | 98 | 2235 | 23 | 2016.36 |
| 9 | University of California, San Diego | USA | 96 | 4757 | 50 | 2016.16 |
| 10 | University of Sydney | Australia | 94 | 3499 | 37 | 2014.58 |

(Avg. Pub. Year: 2016.92) had the latest average publication year. The University of Washington (8763 citations) ranked first in terms of the amount of citations.

A co-authorship analysis of 171 institutions with at least 20 publications yielded 7 clusters represented by various colors. Fig. 5 depicts the co-authorship network of institutions. The largest cluster, represented in red, comprised 55 institutions centered on NIA, University of Washington and Harvard University. The Harvard University had the largest number of cooperating partners (n = 100), followed by UCL (n = 77) and University of Washington (n = 70).

### 3.5. Contributions of authors

There were 28,719 authors appeared 39,057 times in 6420 publications, resulting in an average of 6 co-authors per publication. The 10 most prolific authors who collectively contributed 487 publications (7.6 %) to the field of healthy aging are listed in Table 4. Evans, Michele K. (113 publications, 2596 citations) and Zonderman, Alan B. (109 publications, 2514 citations) from the NIA were the most productive authors, followed by Rodriguez-Manas, Leocadio from the Getafe University Hospital (47 publications, 1562 citations). It is noteworthy that Evans, Michele K. held the distinction of being both the most prolific author and the most cited, with 2596 citations, signifying great academic influence in the field. Among the top 10 prolific authors, Franceschi, Claudio (42 average citations) and Rodriguez-Manas, Leocadio (33 average citations) had the greatest average citations. On the other hand, the average publication year for authors reveals that Beydoun, Hind A. (Avg. Pub. Year: 2018.57), Beydoun, May A. (Avg. Pub. Year: 2018.14) and Rodriguez-Manas, Leocadio (Avg. Pub. Year: 2018.00) have been active more recently.

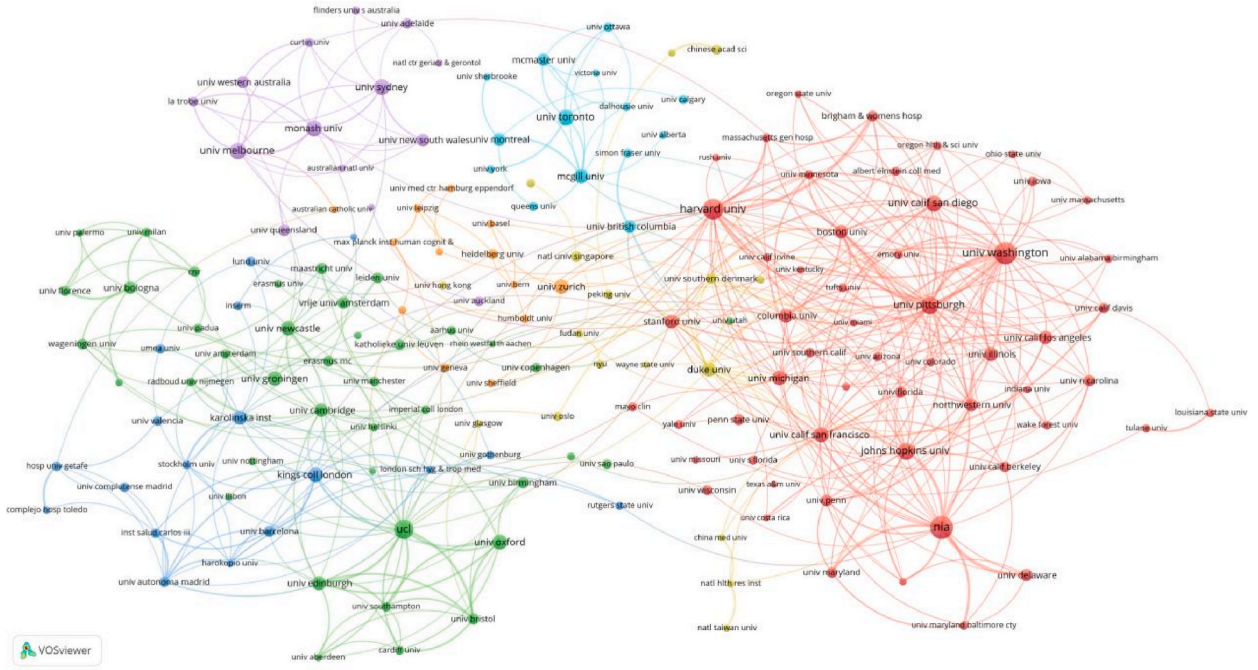


**Fig. 5.** The co-authorship network map of leading research institutions on healthy aging.

**Table 4**
The top 10 productive authors on healthy aging.

| Rank | Author | Country | Institution | Counts | Citations | Avg. Citations | Avg. Pub. Year |
|---|---|---|---|---|---|---|---|
| 1 | Evans, Michele K. | USA | National Institute on Aging | 113 | 2596 | 23 | 2017.37 |
| 2 | Zonderman, Alan B. | USA | National Institute on Aging | 109 | 2514 | 23 | 2017.39 |
| 3 | Rodriguez-Manas, Leocadio | Spain | Getafe University Hospital | 47 | 1562 | 33 | 2018.00 |
| 4 | Beydoun, May A. | USA | National Institute on Aging | 43 | 506 | 12 | 2018.14 |
| 5 | Newman, Anne B. | USA | University of Pittsburgh | 37 | 987 | 27 | 2016.14 |
| 6 | Franceschi, Claudio | Italy | University of Bologna | 32 | 1336 | 42 | 2017.25 |
| 7 | Beydoun, Hind A. | USA | Ft Belvoir Community Hospital | 28 | 319 | 11 | 2018.57 |
| 8 | Christensen, Kaare | Denmark | University of Southern Denmark | 26 | 650 | 25 | 2016.46 |
| 9 | Deary, Ian J. | England | University of Edinburgh | 26 | 844 | 32 | 2014.19 |
| 10 | Kuczmarski, Marie Fanelli | USA | University of Delaware | 26 | 633 | 24 | 2016.23 |

Applying a minimum 5-publication threshold, 595 authors were included in the co-authorship network analysis. The largest co-authorship network among authors, consisting of 371 of the 595 prolific authors, was divided into 18 major clusters, each denoted by distinct colors, as illustrated in Fig. 6. The biggest cluster (colored red) is composed of 45 co-authors, with Newman, Anne B., Christensen, Kaare, and Ferrucci, Luigi at its core. Evans, Michele K. and Zonderman, Alan B. had a combined total of 31 cooperating partners each, making them the two most active co-authors.

### *3.6. Highly cited publications*

Citations in the scientific literature were analyzed to determine the most influential articles on each topic [24]. In order to trace thematic trajectories, we identified the prominent literature on healthy aging according to citation counts. Among the 6420 retrieved publications, 278 have received over 100 citations. Table 5 shows the top 10 most cited publications, with citations counts ranging from 688 to 2648. The most cited publication was titled "Default-mode network activity distinguishes Alzheimer's disease from healthy aging: Evidence from functional MRI" with 2648 citations. It was published in *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA* in 2004. Notably, *NATURE* was the only journal that published two of the most cited publications.

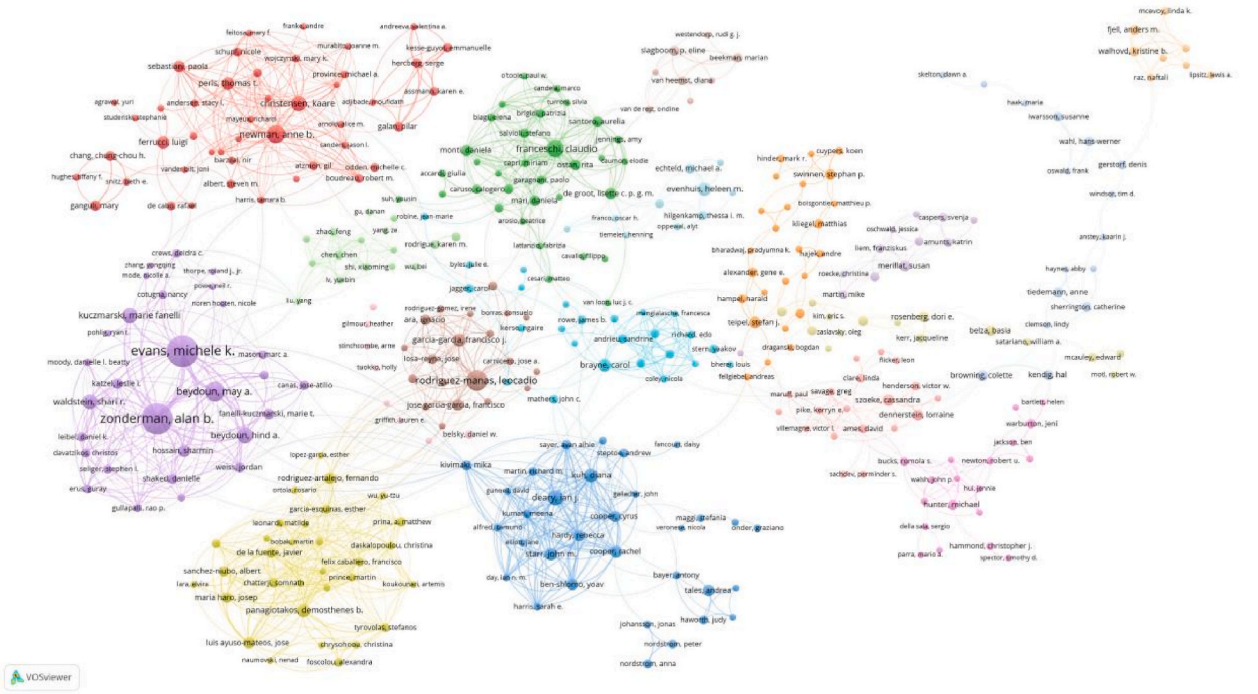


**Fig. 6.** The co-authorship network map of leading research authors on healthy aging.

**Table 5**
The top 10 most cited publications on healthy aging.

| Rank | Title | First Author | Year | Journal | Citations |
|---|---|---|---|---|---|
| 1 | Default-mode network activity distinguishes Alzheimer's disease from healthy aging: Evidence from functional MRI | Greicius, MD | 2004 | PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA | 2648 |
| 2 | Mediterranean diet, lifestyle factors, and 10-year mortality in elderly European men and women - The HALE project | Knoops, KTB | 2004 | JAMA-JOURNAL OF THE AMERICAN MEDICAL ASSOCIATION | 1077 |
| 3 | The ageing systemic milieu negatively regulates neurogenesis and cognitive function | Villeda, SA | 2011 | NATURE | 1077 |
| 4 | The World report on ageing and health: a policy framework for healthy ageing | Beard, JR | 2016 | LANCET | 840 |
| 5 | Automatic classification of MR scans in Alzheimers disease | Kloppel, S | 2008 | BRAIN | 791 |
| 6 | Network analysis of intrinsic functional brain connectivity in Alzheimer's disease | Supekar, K | 2008 | PLOS COMPUTATIONAL BIOLOGY | 786 |
| 7 | Metformin improves healthspan and lifespan in mice | Martin-Montalvo, A | 2013 | NATURE COMMUNICATIONS | 781 |
| 8 | Definitions and predictors of successful aging: A comprehensive review of larger quantitative studies | Depp, CA | 2006 | AMERICAN JOURNAL OF GERIATRIC PSYCHIATRY | 751 |
| 9 | Vitamin D-Binding Protein and Vitamin D Status of Black Americans and White Americans | Powe, CE | 2013 | NEW ENGLAND JOURNAL OF MEDICINE | 738 |
| 10 | The sirtuin SIRT6 regulates lifespan in male mice | Kanfi, Y | 2012 | NATURE | 688 |

### *3.7. Co-occurrence analysis of keywords*

The significance of keyword co-occurrence analysis lies in the fact that words inherently convey information, ideas and scientific concepts [25]. When more keywords appear together, it indicates a higher degree of similarity among publications [25]. Insights into the main study themes are given by keyword co-occurrence networks, which help discover significant keywords used in publications within the knowledge field [26]. Approximately 20,567 keywords were identified in the 6420 articles. Fig. 7 depicts a keyword co-occurrence network map featuring 192 keywords with a minimum of 40 co-occurrences that consists of three clusters displayed in three different colors. As shown in Supplementary Table 1, the most popular keywords enabled us to identify the most common researched topics. The largest cluster, which is made up of 65 keywords, is seen in both the green (centered on healthy aging,

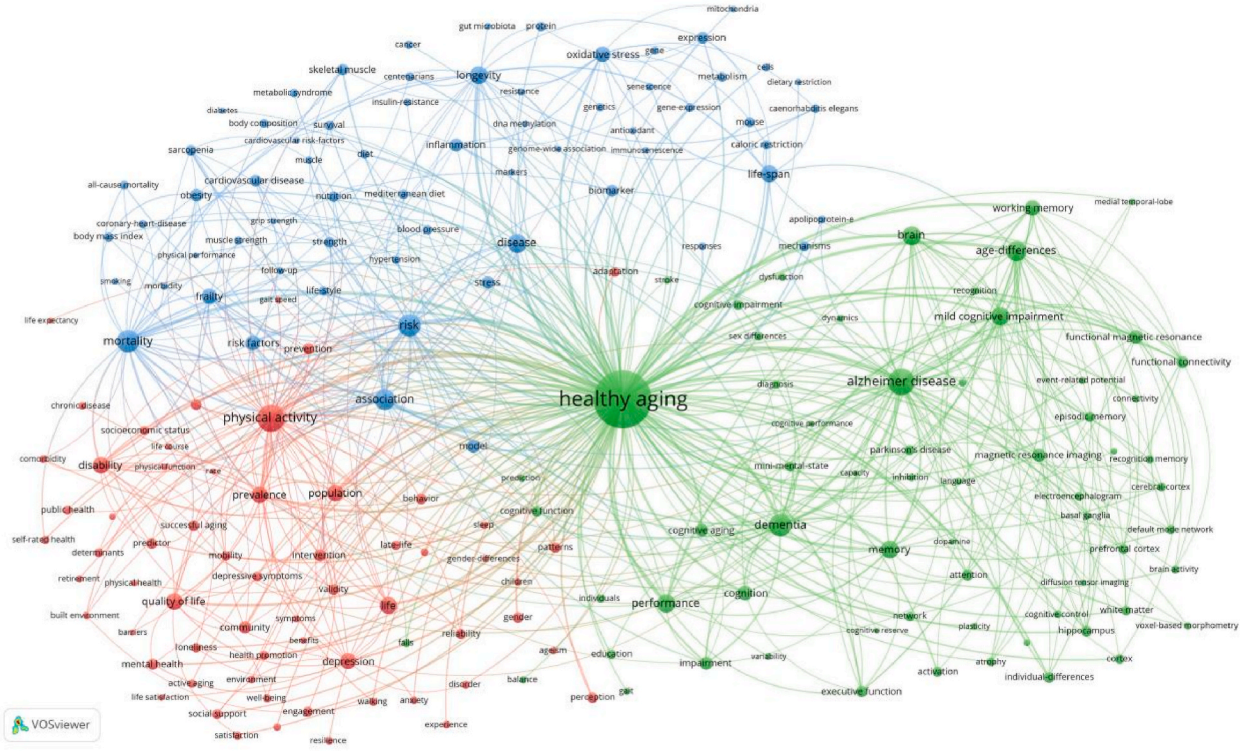


**Fig. 7.** The co-occurrence network map of keywords on healthy aging.


**Fig. 8.** The overlay visualization map of keywords on healthy aging.

Alzheimer disease and dementia) and blue (centered on mortality, risk and association) clusters. The distance between keywords denotes their relatedness, the size of the circles denotes their frequency of usage, while the fluctuation of the lines denotes the frequency of co-occurrences or link strengths [22]. Terms for retrieval and generic keywords were excluded. The most frequently appearing keywords were physical activity (n = 763), alzheimer disease (n = 706), mortality (n = 519), risk (n = 515) and dementia (n = 511).

Keywordsemployed in publications can deduce the footprint of scientific development. Keywords that exhibit transitional phenomena reveal the research's forward-thinking and exploratory nature [ [27]]. Throughout various periods of healthy aging research, the analysis of keywords co-occurrence can reflect the frontiers and hotspots in the evolution of research, hence shifts in the popularity of specific research subjects are shown [ [28]]. To gauge the novelty of a keyword in the overlay visualization map, VOSviewer defines the concept of the average appearing year (AAY) [ [12]]. VOSviewer colored it according to the various AAY of the keywords. As shown in Fig. 8, the AAY value range is represented by the color gradient, and those closest to red signify terms that have appeared more recently. The latest keywords with average appearing year were gut microbiota (AAY: 2019.61), loneliness (AAY: 2018.99), frailty (AAY: 2018.68), mitochondria (AAY: 2018.57), resilience (AAY: 2018.57) and gait speed (AAY: 2018.45).

## 4. Discussion

### 4.1. Global trend of publications

The scientometric analysis of the 6420 retrieved publications reveals publication trends of healthy aging. This yielded six main results that contribute to knowledge of research in this area.

(1) Interest in healthy aging research has surged over the last 22 years based on the substantial growth in publication counts, especially during 2018–2021. As shown in Fig. 2, it is clear that the quantity of annual publications dramatically increased from around 2018.
(2) Table 1 reveals that the USA and the UK contributed to at least half of the publications. Simultaneously, they were the two most cited countries. Additionally, as shown in Fig. 3, European countries displayed significant enthusiasm and participation in healthy aging research, making Europe the leading continent in this field among the world's six continents (omitting Antarctica).
(3) Interestingly, Table 2 highlights that Switzerland, while not among the top 10 countries/regions for productivity, had three of the top 10 productive journals. Fig. 4 reveals twelve journals marked in red, signifying an average of over 50 citations. *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA* stands out as it ranked first in both total and average citation frequency, underscoring its significance and reference value in health aging research.
(4) As shown in Table 3, UCL ranked first in terms of average publication years, signifying its status as an emerging institution in this field. In Table 4, it's noteworthy that Beydoun, Hind A., Beydoun, May A., and Rodriguez-Manas, Leocadio were the three authors with the most recent average years of publication, highlighting their active involvement in recent years as researchers.
(5) We notice that the top 10 prolific authors listed in Table 4 are affiliated with different organizations, with the exception of three jointly from NIA. The NIA (institute of the NIH) is the world's largest research institute on aging and geriatrics, and is also the main federal agency supporting and carrying out research on Alzheimer's disease. Relatedly, the USA emerged as the most prolific nation, while the NIA was the most prolific organization, underlining the substantial contribution made by American scholars. Considering these trends, the USA is projected to maintain its position as a global leader in this field in the future.
(6) Over half of the top ten most prolific authors originate from the USA, while only four are affiliated with the top ten most prolific institutions. This argues that the most engaged academics in the area of healthy aging may not necessarily come from the most engaged research institutions.

### 4.2. International cooperation network

By analyzing the network of collaborations among institutions and authors, we identified the key research institutions and authors that have published a significant amount of publications in healthy aging. From the standpoint of a collaboration network, a greater quantity of links showed a preference for collaboration among research institutions/authors.

Researchers who have a considerable amount of highly cited articles frequently lead in theoretical and methodological trends in their research field, contributing significantly to its advancement [29]. Therefore, identifying those outstanding academics provides insight into who leads the academic discourse [29]. For instance, as shown in Table 4, the top-contributing author, Evans, Michele K., focuses on the clinical therapeutic applications of eukaryotic DNA repair in cancer etiology and aging, as well as conducting epidemiologic research on health disparities [30,31]. Through examining her scholarly publications, we can readily gain insights into the primary research themes and trends in that specific field.

As shown in Fig. 5, we found that the collaboration among institutions within the same nation was closed (i.e., American institutions dominated the red cluster, while British dominated the green cluster). Strong academic cooperation relationships existed between several organizations, particularly those academic groups led by Harvard University, UCL and University of Washington, whereas there were still certain limitations regarding collaboration between individual authors. As shown in Fig. 6, it reflected the fact that these authors actively collaborated, especially those who belonged to the same cluster. However, the co-authorship network comprised only 62.4 % (371/595) productive authors. We hope that collaboration between individual authors across international and

interdisciplinary fields can be strengthened, especially among prolific authors, in order to jointly contribute to the progress of research on healthy aging. Additionally, it was discovered that collaborating institutions/authors as cluster centers were typically among the highest contributing segment, as shown in Figs. 5 and 6. One of the possible explanations may be the fact that a wealth of collaborations have contributed to the flourishing of the scientific field.

### 4.3. Research hotspots of healthy aging

Keywords were identified in the retrieved literature, demonstrating the diversity of the terminology used to express topics relevant to healthy aging. Three major research domains were identified according to the keyword network, as shown in Fig. 7: physical activity and mental health of older adults (presented by the red cluster), diseases on the impact of health and lifespan of older adults (presented by the blue cluster), and healthy aging related research in neuroscience (presented by the green cluster). Academic research work in the area is anticipated to proliferate around these main research issues [32]. The NIA has spent a year proposing broad strategic directions for research in healthy aging for 2020–2025, setting goals and identifying scientific priorities for the next five years [33]. The three primary research hotspots identified through our analysis are well aligned with NIA's strategic goals as explained below.

First, an important priority is comprehending the aging process's dynamics. This involves gaining a deeper understanding of the implications of individual, interpersonal, and sociocultural elements on aging, including the mechanisms through which these elements make a difference. As shown in the red cluster in Fig. 7, some studies focus on older adults' physical activity and mental health. Previous studies into the relationship between exercise and senior health have often been based on the knowledge of what triggers or avoids chronic diseases, instead of what improves health of older adults [34]. It is now apparent that a successful healthy aging pattern encompasses not only physical and cognitive activities but necessitates social participation and support [35]. Scholars have concentrated on depression, depressive symptoms, anxiety and gender-differences when it comes to the mental health of older adults. Unfortunately, the high prevalence of mental health issues among older adults constitutes a major public health concern that requires urgent attention, with men's participation in mental health therapy lagging far behind that of women [36]. Attempts have been made to start from the theory of gerotranscendence [37] and integrate with practicalities, with the expectation of meeting the complex care needs of a rapidly growing and diverse elderly population. The Patient-Centered Outcomes Research Institute (PCORI) [38] centers its focus on different phases of the aging continuum [39], with the goal of optimizing physical and mental performance throughout this continuum [40]. They aim to facilitate chronic disease management, reduce the caregiving burden, and improve quality of life. It is also important to enhance our knowledge of the effects of an aging society to guide the formulation of interventions and policies. Special attention was paid to ageism, a common phenomenon faced by older adults in social life [3]. Indeed, older adults should be given the opportunity to have their goals, passions and valued role in society, which not only enhances their quality of life but ensures the fulfillment of their fundamental needs. We should move beyond a needs-based method and recognize the need for a cultural paradigm change [41].

Second, it is vital to increase our knowledge of the biology of aging and the influence on the prevention, progression, and prognosis of illness and disability. As shown in the blue cluster in Fig. 7, researchers have explored the influence of diseases on the health and longevity of older adults, including cardiovascular disease, diabetes, hypertension, obesity, sarcopenia, and metabolic syndrome [42–45]. According to studies, oxidative stress is a significant risk factor for the progression of aging and diseases [46]. Older adults with chronic illnesses and malnutrition have weakened immune systems and are more vulnerable to health issues like cardiovascular disease. Recent advances in the fundamental biology of aging have suggested that preventive or protective interventions may prolong the healthy lifespan of mammals, including humans. Frailty, in particular, is becoming more widely recognized as a clinically relevant syndrome that can be treated [47]. The exploration of biomarkers concerning aging is a research priority in the field of biology. Another crucial area of research is understanding the relationship between genes and the emergence of age-related illnesses (e.g., Alzheimer's disease) [48], and exploring the correlation between gene expression and healthy aging in humans [49]. One of the essential aims is to improve adults' health, independence and well-being as they age. To preserve health, function, and well-being as well as prevent or lessen the impact of age-related illnesses, disorders, and impairments, effective interventions must be developed.

Third, another priority is to increase our knowledge of dementias like Alzheimer's disease, neurodegenerative diseases and the aging brain. Interventions for Alzheimer's and other age-related neurological diseases are needed. As shown in the green cluster in Fig. 7, research findings related to healthy aging were extremely rich in the field of neuroscience. The level of conceptual cognition and related examination techniques in neuroscience have been consistently improved and developed, especially with the increasing maturity of magnetic resonance imaging techniques [1]. Functional connectivity has developed into a very effective tool for visualizing brain activities as a result of the improvement of neuroimaging techniques [50]. Such as default mode network (DMN), electroencephalogram (EEG), event-related potential (ERP),diffusion tensor imaging (DTI), magnetoencephalography (MEG), magnetic resonance imaging (MRI), functional magnetic resonance imaging (fMRI), and voxel-based morphometry (VBM) were utilized to assess the brain ageing process, as well as to study brain activity and older adults' cognitive function. Apart from considerable research on Alzheimer's disease, one of the most prevalent conditions affecting older adults, studies have increasingly emphasized factors associated with the human brain, including dementia, cognitive aging, cognitive impairment, Parkinson's disease, cerebral-cortex, white matter, hippocampus, etc [51–57]. As shown in Table 5, the most commonly cited article titled "Default-mode network activity distinguishes Alzheimer's disease from healthy aging: Evidence from functional MRI" by Greicius, MD with up to 2648 citations published in 2004 was from this area [58]. Based on the results of a goodness-of-fit analysis conducted at the individual subject level, the paper stated that activity in the default-mode network can eventually serve as a specific and sensitive biomarker for early-stage Alzheimer's disease [58]. Additionally, the aging brain influences overall bodily function, leading to a decline in the mobility of older adults. The study covered objective mobility measures for older adults including gait and balance [59], exercise approaches in early falls prevention [60], health care services for older adults at risk for balance disorders and falls [61], and other aspects.

We are surprised to discover that almost all of the top 10 highly cited publications (Table 5) overlap with priorities of NIA as above mentioned. For the purpose of more effectively guide and lead global research efforts on healthy aging, WHO has developed the plan for the *decade of healthy aging 2020–2030* [62], which is the second action plan of the WHO global strategy on aging and health [63]. The plan emphasizes that the major public health goal is "to live not just long but also healthy lives" and the main instrument for health care success is "healthy life expectancy" [64]. In conclusion, the next research priority will focus on improving the quality of life for older adults and further extending average life expectancy. In addition to aligning with NIA and WHO's strategic priorities, our findings also point to gut microbiota, loneliness, frailty, mitochondria and resilience were gaining prominence in the realm of healthy aging research. We hope that this research will assist researchers and government managers to keep abreast of the latest developments, conduct innovative research in the field, and guide their focus in their work.

The current study has several limitations. First, one limitation lies in the literature sample used, as it only includes English articles and articles in the manuscript kinds. Second, although WoSCC is an authoritative literature retrieval database, there may still be missing relevant publications. Also, some of the publications identified via our search strategy may not directly contribute to health aging research. Finally, we didn't normalize variations of the author and institutional names in the analysis.

## 5. Conclusions

In the current study, we analyzed a great quantity of scientific literature over the past 22 years, and utilized the VOSviewer tool to review the academic accomplishments and development in the area of healthy aging, both quantitatively and visually. Specifically, the most prolific countries/regions, sources, institutions, authors and current research interests were identified, and we created the cooperation network of organizations and authors, as well as conducted the analysis of keywords co-occurrence. Our results showed an increasing growth trend of the annual total quantity of publications in healthy aging over the past 22 years. In addition, the studies relevant to the gut microbiota, loneliness, frailty, mitochondria and resilience show trends for future research directions. We hope these findings will help researchers and policy makers identify the emerging themes and provide them with new insights into the future development of the field of healthy aging. We encourage interdisciplinary collaboration to jointly address the complex challenges of healthy aging. Furthermore, strategies to enhance resilience and psycho-social growth of older adults must be considered when developing public health responses to aging. It is also crucial to challenge the many stereotypes and instances of discrimination associated with old age, as they can adversely affect our efforts.

## Data availability statement

Data included in article/supp. material/referenced in article.

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## CRediT authorship contribution statement

**Ye Zhang:** Methodology, Writing – original draft. **Zhengmin Gu:** Software. **Yingxin Xu:** Data curation. **Miao He:** Investigation. **Ben S. Gerber:** Writing – review & editing. **Zhongqing Wang:** Conceptualization, Supervision, Writing – review & editing. **Feifan Liu:** Visualization, Writing – review & editing. **Cheng Peng:** Conceptualization, Supervision.

## 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.

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None.

## Abbreviations :

| | |
|---|---|
| WHO | World Health Organization |
| WoSCC | Web of Science Core Collection |
| USA | United States of America |
| UK | United Kingdom |
| NIA | National Institute on Aging |
| UCL | University College London |
| NIH | National Institutes of Health |

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e23405.

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