Ind. J. Pharm. Edu. Res., 2026; 60(4s):s1374-s1382.
https://www.ijper.org

Review Article

Natural Products and Cellular Senescence Research: A Scientometric Analysis of Global Trends, Thematic Clusters, and Emerging Frontiers (2016-25)

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ABSTRACT

Background: Interest in natural products-polyphenols, flavonoids, terpenoids, and related phytochemicals-as candidate senotherapeutic and geroprotective agents has expanded rapidly over the past decade, yet the literature spans pharmacology, cosmetic science, food chemistry, and model-organism biology in ways that are difficult to map through narrative review alone. This study provides a scientometric analysis of the global research landscape connecting natural products to cellular senescence and aging-related outcomes between 2016 and 2025. **Methodology:** Bibliographic records were retrieved from Scopus using a title-abstract-keyword boolean query combining natural-product/phytochemical terms with senescence/aging terms, restricted to English-language articles and reviews published between 2016 and 2025, yielding 7255 documents. A Python-based co-occurrence network analysis (NetworkX, Louvain community detection, scikit-learn TF-IDF cluster labeling, and Matplotlib visualization-conceptually equivalent to the coword mapping performed by VOSviewer or CiteSpace) was applied to the documents' author keywords to identify thematic clusters, detect keyword bursts, and rank the most prolific authors and affiliations. **Results:** Publication output grew from 311 documents in 2016 to 1407 in 2025, an overall increase of more than 350% across the window. The keyword co-occurrence network (n=150 nodes, E=3234 edges) resolved into four clusters with a modularity of Q=0.246 and a weighted mean silhouette of S=0.328, identifying distinct research streams centered on antioxidant phytochemistry, skin-aging cosmeceuticals, model-organism longevity (*Caenorhabditis elegans* and *Drosophila)*, and the cellular-senescence/oxidative-stress mechanistic core. Keyword bursts in "skincare," "collagen synthesis," and "glycation" point to a recent shift toward translational, application-oriented framing. Author and institutional productivity is concentrated in China and Thailand. The mapped structure can help funders, journal editors, and early-career researchers identify which subthemes are mature versus emergent, and where translational gaps (for example, bioavailability and clinical validation of senolytic phytochemicals) remain underexplored relative to preclinical output. **Conclusion:** This is, to the authors' knowledge, the first scientometric mapping of the natural-product–cellular-senescence literature specifically, as distinct from the broader and more heavily studied natural-products-and-aging or polyphenol-and-health literatures.

Keywords: Aging, Phytochemicals, Bibliometric analysis, Cellular senescence, Co-occurrence network, Natural products, Scientometric analysis, Senotherapeutics.

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Received: 13-04-2026;
Revised: 04-06-2026;
Accepted: 29-08-2026.

INTRODUCTION

The global anti-aging products market was valued at roughly USD 48-78 billion in 2024-25 and is forecast to continue growing at a compound annual rate of 6%-7% through the early 2030s, with the natural-ingredients segment of that market projected to grow even faster, at close to 15% annually, as consumers and formulators alike turn toward plant-derived alternatives to synthetic actives. This commercial pull sits alongside a parallel and more fundamental scientific shift: the recognition that cellular senescence-the irreversible, secretory growth arrest first described decades ago-is not merely a marker of aging but an active driver of tissue dysfunction and age-related disease, and that pharmacologically clearing or modulating senescent cells ("senolysis" and "senomorphism," respectively) is a viable therapeutic strategy.[1] Natural products-polyphenols, flavonoids, terpenoids, and other plant- or fungus-derived secondary

DOI: 10.5530/ijper.20265864

metabolites-sit at the intersection of both trends: they are simultaneously marketed cosmeceutical ingredients and leading experimental senotherapeutic candidates.

A substantial and rapidly growing body of work has accumulated on this intersection. Reviews have cataloged the senolytic and senomorphic activity of plant polyphenols, such as fisetin, quercetin, and resveratrol,[2] assessed natural antioxidants against synthetic comparators for mitigating senescence-associated oxidative stress,[3] and synthesized the broader senolytic/senomorphic pharmacology of which natural compounds form a major subset (Targeting cellular Senescence for Healthy Aging, 2025; Heterogeneity of cellular Senescence, 2025). In parallel, the model-organism literature has used *Caenorhabditis elegans* and *Drosophila melanogaster* as rapid screening platforms for life span-extending phytochemicals and crude extracts, identifying numerous geroprotective candidates through pathways, such as DAF-16/FoxO signaling.[4-6] A third, more applied stream has examined the same compound classes as cosmeceutical actives for photoaging and skin senescence, with several recent systematic reviews and meta-analyses evaluating the clinical evidence for plant-extract-based anti-aging skincare.[7,8]

What is missing from this picture is a quantitative, corpus-wide view of how these strands relate to one another, how the field's emphasis has shifted over the past decade, and which subthemes represent mature versus emergent research fronts. Prior reviews in this space are narrative and necessarily selective: each surveys a sub-literature the authors judged relevant, but none maps the full citation/keyword structure of the field empirically. Scientometric or bibliometric mapping-quantitatively describing a corpus through co-occurrence networks, cluster detection, and burst analysis-has been applied productively to adjacent topics, including natural products in cognitive-disability research and advanced glycation end-products in obesity, but, to the authors' knowledge, has not yet been applied specifically to the natural-product–cellular-senescence literature as a defined field.

This study addresses that gap by asking: how has research connecting natural products to cellular senescence and aging evolved between 2016 and 2025, and what does the keyword co-occurrence structure of this literature reveal about its principal thematic clusters, their relative maturity, and the field's most recent research frontiers? To answer this, 7255 Scopus-indexed articles and reviews published over this 10-year window were retrieved and subjected to a Python-based co-occurrence network analysis-conceptually equivalent to the co-word mapping performed by VOSviewer or CiteSpace-that detects thematic clusters via Louvain community detection, labels them via TF-IDF term extraction, and flags keywords undergoing a sudden, sustained surge in attention ("bursts").

LITERATURE CONTEXT

Rather than a separate systematic review, this section briefly situates the present analysis against the dataset's own most heavily cited works, which collectively illustrate why a corpus-wide mapping is useful. The single most-cited document in the dataset, a 2023 Archives of Toxicology review on reactive oxygen species, toxicity, and antioxidants in chronic disease.[9] (2184 citations), exemplifies the mechanistic oxidative-stress literature that underlies much of the field's antioxidant-cluster output. A second highly cited document, a 2022 Signal Transduction and Targeted Therapy review of aging and aging-related diseases.[10] (1417 citations), bridges the mechanistic and translational strands by surveying molecular interventions, including phytochemical ones, against age-related pathology.

Within the model-organism stream, Ryu *et al.*'s[11] Nature Medicine paper showing that urolithin A-a gut-microbial metabolite of ellagitannins found in pomegranates and walnuts-induces mitophagy and extends life span in *C. elegans* while improving muscle function in rodents (961 citations) remains a touchstone reference, as does Yousefzadeh *et al.*'s[12] EBioMedicine demonstration that the flavonoid fisetin acts as a senotherapeutic that extends health span and life span (872 citations). A related 2021 Nature Metabolism paper identified procyanidin C1, a grape-seed-derived flavonoid, as having senotherapeutic activity with life span-extending effects in mice.[13] (286 citations). On the cosmeceutical side, a 2020 Journal of Cosmetic Dermatology review of polyphenols as natural antioxidants in cosmetics applications.[14] (307 citations) and a 2021 Biomedicine and Pharmacotherapy review and "call for further research" on resveratrol pharmacology.[15] (499 citations) typify the translational-application literature. Together, these works span the four thematic regions that the cluster analysis recovers directly from the data, providing an external check on the network's substantive coherence.

METHODOLOGY

Rationale for a scientometric approach

The natural-product–senescence literature spans pharmacology, food and cosmetic science, gerontology, and model-organism biology, and has grown to a scale (over 1400 documents in 2025 alone) that exceeds what a manual narrative review can comprehensively synthesize. A quantitative, corpus-wide co-occurrence mapping is therefore well suited to surfacing the field's principal thematic structure, its relative balance across subthemes, and its temporal evolution, in a way that is reproducible and not dependent on which subset of papers a reviewer happens to select.

Data source and search strategy

Bibliographic records were retrieved from the Scopus database. The search was restricted to the title, abstract, and keyword fields using the following Boolean query:

TITLE-ABS-KEY (("natural product*" OR "natural compound*" OR phytochemical* OR "secondary metabolite*" OR "bioactive compound*" OR "plant-derived compound*" OR "marine natural product*" OR "medicinal plant*" OR polyphenol* OR flavonoid* OR terpenoid* OR alkaloid* OR phytomedicine OR "herbal medicine" OR "plant extract*") AND (senescence OR "cellular senescence" OR senolytic* OR senomorphic* OR senotherapeutic* OR "anti-aging" OR "anti-ageing" OR antiaging OR "healthy aging" OR "healthspan" OR longevity OR geroprotector* OR "senescence-associated secretory phenotype")) AND PUBYEAR > 2015 AND PUBYEAR < 2026 AND DOCTYPE (ar OR re) AND LANGUAGE (English).

Inclusion was limited to documents published between 2016 and 2025 inclusive, to articles and reviews (excluding conference papers, book chapters, notes, and editorials), and to documents in English. The query returned 7255 records after these filters; no further manual screening was applied beyond Scopus's own database-level deduplication, since the analysis is corpus-descriptive rather than a systematic review requiring item-level eligibility judgments. Of the retrieved set, 5231 (72.1%) were classified as articles and 2024 (27.9%) as reviews.

Analysis tools and metrics

The exported records were processed with a Python-based co-occurrence network analysis script using NetworkX for graph construction and Louvain community detection, scikit-learn for TF-IDF-based cluster labeling, and Matplotlib for visualization. This pipeline is conceptually equivalent to the coword mapping performed by dedicated bibliometric software, such as VOSviewer or CiteSpace, though the actual network construction, clustering, and figures reported here were produced by this script rather than by either of those packages.

The export's Authors, Affiliations, Cited by, Year, and Document Type fields were populated for nearly all records (Authors: 7253/7255; Affiliations: 7251/7255; Cited by and Year: 7255/7255), supporting reliable publication-trend and author/affiliation productivity statistics. However, the export did not include a parseable References or Cited References field, which is required to construct a reference cocitation network (the CiteSpace-style "what foundational works" map). Co-citation analysis was therefore not possible for this dataset, and the analysis instead used keyword co-occurrence (the VOSviewer-style "what topics" map), which the export supported well: Author Keywords were populated for 6644 of 7255 records (91.6%) and Index Keywords for 5733 (79.0%).

A preliminary run of the network on the combined Author Keywords and Index Keywords fields produced clusters dominated by generic controlled-vocabulary terms (eg, "human," "article," "controlled study," "nonhuman") rather than substantive topical terms-a known artifact of Scopus's Index Keywords field, which draws on the Emtree/MEDLINE controlled vocabulary and tags methodological and demographic descriptors alongside topical ones. To avoid this boilerplate dominance, the reported network was instead built using Author Keywords only, which authors assign freely to describe a paper's substantive content and which produced markedly more interpretable clusters (modularity Q=0.246 versus Q=0.079 for the combined-field run).

Given the corpus size (n=7255), a minimum co-occurrence frequency threshold of 10 was applied (terms appearing in fewer than 10 documents were excluded from the network) and the network was capped at the 150 most frequent remaining terms, following the skill's guidance to raise the frequency threshold for large corpora to keep the resulting network legible. Within the retained network, Louvain community detection partitioned nodes into clusters, and modularity (Q)-the standard measure of how cleanly a network divides into distinct communities relative to a random null model, ranging in practice from 0 to just under 1-and a silhouette-style mean coherence score (S)-measuring how tightly each cluster's members group together relative to their separation from other clusters, ranging from −1 to 1-were computed for the resulting partition. Each cluster was automatically labeled using a combination of its most frequent member keywords and TF-IDF term extraction over the titles, abstracts, and keywords of its member documents, with a boilerplate stop word filter applied to suppress generic scientific-writing terms.

Keyword burst detection was applied to identify terms whose year-by-year frequency surged sharply within a specific window rather than growing steadily, using a simplified Kleinberg-style burst-scoring approach; bursts are reported with their begin year, end year, peak year, total frequency, and a burst strength score. Because bursts here are detected over keywords rather than over cited references, each burst item is a term (not a previously published work), so no separate "publication year of the cited item" applies; the peak year reported is the year within the burst window with the highest observed frequency for that term.

RESULTS

Overview and descriptive trends

The final corpus comprised 7255 documents published between 2016 and 2025, accumulating 234 437 citations in total as of the retrieval date. Publication output grew almost every year across the window: from 311 documents in 2016 to 348 in 2017 (+ 11.9%), 424 in 2018 (+ 21.8%), 500 in 2019 (+ 17.9%), 612 in 2020 (+ 22.4%), 766 in 2021 (+ 25.2%), and 912 in 2022 (+ 19.1%). Output dipped slightly to 896 documents in 2023 (−1.8%) before resuming growth to 1079 in 2024 (+ 20.4%) and 1407 in 2025 (+ 30.4%), the single largest year-over-year increase in the series. Because 2025 was the most recent complete calendar year captured at retrieval, this final-year count is not a partial-year artifact in the way an in-progress current year would be, and the 2025 peak is interpreted here as a genuine continuation of the field's accelerating growth rather than a retrieval-boundary effect.

Citations followed a related but distinct pattern (Figure 1): annual citation counts rose from 19 862 in 2016 to a peak of 33 596 in 2022, before declining to 23 520 (2023), 15 512 (2024), and 6782 (2025). This decline in recent-year citation counts is expected and reflects citation-accumulation lag-a paper published in 2025 has had only months, rather than years, to accumulate citations-rather than a genuine drop in the field's relevance; it should not be read alongside the publication-count trend as if the two measured the same underlying quantity.

Most prolific authors and affiliations

The most prolific author in the dataset is Wang Y, with 175 documents and 5199 total citations, followed closely by Zhang (157 documents, 5409 citations) and Liu (154 documents, 5432 citations). Table 1 lists the ten most prolific authors. Because Scopus author names are frequently shared across multiple distinct individuals with common East Asian surnames and initials, these counts likely aggregate the output of several different researchers under each name rather than reflecting a single author's true productivity, and should be read as name-level rather than individual-level statistics.

At the institutional level, the Department of Pharmaceutical Sciences at Chiang Mai University, Thailand, leads with 28 documents and 418 citations, followed by the University of Chinese Academy of Sciences, China (26 documents, 779 citations) and the School of Cosmetic Science at Mae Fah Luang University, Thailand (18 documents, 422 citations). Table 2 lists the top ten affiliations. Eight of the ten most productive affiliations are based in Thailand or China, indicating that institutional productivity in this field is geographically concentrated in East and Southeast Asia rather than dispersed broadly across regions; this pattern is consistent with the prominence of traditional-medicine-informed natural-product research programs at several of the listed institutions.

Table 1: Ten most prolific authors by document count, with total citations, name-level.

Rank	Author	Documents	Total Citations
1	Wang Y.	175	5199
2	Zhang Y.	157	5409
3	Liu Y.	154	5432
4	Wang J.	142	3733
5	Li Y.	135	4965
6	Zhang X.	131	3903
7	Wang X.	127	3252
8	Li J.	121	4778
9	Li X.	114	5120
10	Wang L.	99	2318

Network structure

The Author Keyword co-occurrence network built from the corpus comprised n=150 nodes (the 150 most frequent keywords appearing in at least ten documents) and E=3234 edges, yielding a network density of 0.289. As is typical for co-occurrence networks of this kind, this density is far below the theoretical maximum of 1.0 (which would indicate every keyword pair co-occurring), but a moderate level of interconnectivity is expected at this node-count and frequency threshold and does not by itself indicate anything about clustering quality; only Q and S speak to that.

Louvain community detection partitioned the network into four clusters with a modularity of Q=0.246 and a weighted mean silhouette of S=0.328. A modularity at this level sits below the conventional Q=0.3 minimum threshold for a network to be considered clearly and robustly modular, and is best described as a relatively diffuse network structure: while four substantively coherent and separately interpretable thematic groupings did emerge (Figure 2, Table 3), the boundaries between them are not sharp, and a number of keywords bridge more than one cluster, which is unsurprising given how tightly the antioxidant-mechanism, model-organism, and cosmeceutical literatures are intertwined at the level of shared vocabulary ("antioxidant," "oxidative stress," and "natural products" each appear as connective tissue across clusters). The weighted mean silhouette of S=0.328 likewise falls in the "homogeneous clustering" range-acceptable but modest internal consistency-rather than indicating a highly cohesive partition. Both values should accordingly be read as indicating a real but moderate degree of thematic structure, not a sharply delineated field.

Cluster-by-cluster discussion

Cluster No. 3.- aging/cellular senescence (n=54, mean year 2021.9)

The largest cluster, with 54 member keywords, is anchored on aging, oxidative stress, senescence, polyphenols, resveratrol, and inflammation. This is the field's mechanistic core: the conceptual vocabulary connecting oxidative damage, the senescence-associated secretory phenotype, and inflammatory signaling to the polyphenolic compounds proposed to intervene in these pathways. Its mean publication year of 2021.[9] Essentially identical to the corpus-wide midpoint-marks it as a long-running, foundational stream rather than either an early-legacy or a brand-new theme; it has been continuously active across the full window rather than concentrated at either end. The dataset's most-cited document overall, a 2023 Archives of Toxicology synthesis of reactive oxygen species, toxicity, oxidative stress, and antioxidants in chronic disease.[9] (2184 citations), and a 2018 Frontiers in Pharmacology review on the mutual interplay between antioxidants and oxidative stress in age-related disease.[16] (1011 citations) both sit squarely within this cluster's vocabulary, illustrating its role as the mechanistic substrate that the more applied clusters (#0, #1, #2) draw upon.

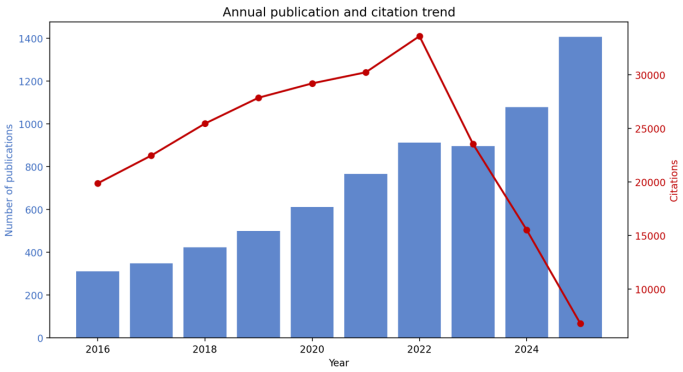

Figure 1: Annual number of publications (bars, left axis) and citations (line, right axis), 2016-25.

Cluster No. 1. - antioxidant/skin aging (*n*=43, mean year 2022.1)

The second-largest cluster centers on antioxidant, anti-aging, skin aging, anti-inflammatory, and cosmetics, marking the translational cosmeceutical application of natural antioxidants. Its mean year of 2022.1 is marginally later than Cluster No. 3's, consistent with a downstream, application-focused literature that builds on the upstream mechanistic work once it has accumulated. The dataset's 2020 Journal of Cosmetic Dermatology review on polyphenols as natural antioxidants in cosmetics applications.[14] (307 citations) is a representative document from this cluster, as is the 2021 Biomedicine and Pharmacotherapy review and "call for further research" on resveratrol's pharmacology and applications, including dermatologic ones.[15] (499 citations). This cluster's recency relative to Cluster No. 3, combined with the "skincare" burst discussed in results section, suggests that cosmeceutical application is one of the field's more actively expanding fronts rather than a settled subtheme.[16]

Cluster No. 0. - antioxidant phytochemistry (*n*=42, mean year 2022.1)

Closely related to, but distinguishable from, Cluster No. 1, this cluster groups antioxidants, flavonoids, bioactive compounds, antioxidant activity, phytochemicals, and reactive oxygen species-the vocabulary of natural-product chemistry and assay-based antioxidant characterization rather than of clinical or cosmetic application specifically. Its low silhouette score (0.098, by far the lowest of the four clusters) indicates that this cluster's members are the most loosely bound and most likely to bridge into neighboring clusters, which is consistent with its content: terms like "antioxidants" and "flavonoids" are generic enough to co-occur broadly across the whole corpus rather than marking a tightly bounded sub-topic. The dataset's 2017 International Journal of Molecular Sciences review on natural antioxidants in foods and medicinal plants.[17] (1116 citations) and the 2018 Asian Journal of Pharmaceutical Sciences review of bioactive flavonoids in medicinal plants.[18] (962 citations) exemplify this cluster's characterization-and-cataloging emphasis, as distinct from the senescence-mechanism focus of Cluster No. 3 or the applied cosmeceutical focus of Cluster No. 1.

Cluster No. 2. - model-organism longevity (*n*=11, mean year 2021.8)

The smallest cluster by member-keyword count, but the most internally coherent (silhouette=0.610, the highest of the four), groups *Caenorhabditis elegans*, longevity, life span, natural products, *C. elegans*, and *Drosophila melanogaster*. This is the field's invertebrate-model screening literature: studies using short-lived model organisms to rapidly test whether a natural compound or extract extends life span or healthspan, often as a precursor step before more expensive mammalian validation. Its small-size relative to the other three clusters reflects that this is a more specialized methodological niche than a broad thematic area, but its high silhouette indicates that the niche is tightly and consistently defined in the keyword vocabulary, with relatively little bleed into neighboring clusters. The dataset's 2016 Nature Medicine paper showing that urolithin A induces mitophagy and extends *C. elegans* life span while improving rodent muscle function.[11] (961 citations) is the most-cited document associated with this cluster's vocabulary, alongside the 2018 EBioMedicine paper identifying fisetin as a life span-extending senotherapeutic.[12] (872 citations) and the 2021 Nature Metabolism identification of procyanidin C1 as a senotherapeutic flavonoid with life span-extending activity in mice.[13] 286 citations-work that, while validated in mammalian models, originates from the same natural-product-screening logic this cluster represents.

Burst analysis

Table 4 reports the ten strongest keyword bursts detected in the corpus-keywords whose frequency surged sharply within a specific window rather than growing steadily across the full 10-year period. Because bursts are detected over keywords (terms) rather than over cited references in this analysis, each burst item is identified by the keyword itself together with the window (Begin–End) during which its use surged and the year within that window in which its frequency peaked; there is no separate "publication year of a cited work" to report for keyword bursts, unlike for a reference cocitation burst table. Cluster membership is reported only where a burst keyword appears among each cluster's top labeled member terms (Table 3); most burst keywords are more specific or more recent terms that fall outside that shortlist, and are reported as not attributable to a specific labeled cluster rather than guessed, consistent with this study's data-integrity standard of not inferring information the underlying analysis did not actually produce.

The strongest burst, "*Tricholoma matsutake*" (the *matsutake* mushroom, Strength 6.00, 2024-25), and the closely related "postharvest preservation" burst (Strength 5.83, 2025) both point to a narrow but sharply emerging interest in fungal and postharvest-biology natural products-a small but real signal worth monitoring as a potential frontier rather than a broad established

theme, given their low total frequencies (five and six documents respectively).

The third-strongest and substantively most important burst is "skincare" (Strength 5.67, total Frequency 30, active 2024-25, peaking in 2024). Unlike the *matsutake* and postharvest bursts, this term's total frequency of 30 documents reflects a genuinely broad surge rather than a handful of papers, and corroborates the recency pattern already visible in Cluster No. 1's mean year (2022.1, the latest of the four): cosmeceutical and skincare application is not just a sizeable cluster but an actively accelerating one. "Skin diseases" (Strength 5.40, 2024) reinforces the same dermatologic-application signal from a clinical rather than cosmetic angle. "Physical activity" (Strength 5.14, 2023-25) is a smaller but multi-year burst suggesting growing interest in how natural-product interventions interact with exercise-related aging outcomes, a combination largely absent from the field's earlier literature. The remaining bursts- "sublethal effects," "iron," "drug repurposing," "behavior," and "Aloe vera"- are each lower-frequency (5-6 documents) and most likely reflect localized surges of attention around specific studies or sub-topics rather than corpus-wide shifts, and are reported for completeness rather than as major thematic signals.

DISCUSSION

The field's developmental trajectory

Read together, the cluster mean years, sizes, and burst timings sketch a field that has not so much passed through sharply delineated phases as broadened outward from a stable mechanistic core. Cluster No. 3 (aging/cellular senescence, mean year 2021.9, the corpus midpoint) functions as that core: the oxidative-stress and senescence-signaling vocabulary that has been continuously productive across the full window rather than concentrated early or late. Clusters No. 0 and No. 1 (antioxidant phytochemistry and antioxidant/skin-aging application, both mean year 2022.1) represent a slightly later, more applied layer built on that mechanistic foundation-one orientated toward compound characterization, the other toward cosmeceutical translation. Cluster No. 2 (model-organism longevity, mean year 2021.8, but the smallest and most specialized cluster) represents a persistent methodological niche rather than a phase the field has moved through. The keyword bursts add a further, more recent layer on top of this structure: "skincare," "skin diseases," and "physical activity" bursting in 2023-25 indicate that the field's newest growth is concentrated in translational and application-oriented territory-moving compounds already characterized mechanistically toward consumer-facing or lifestyle-integrated contexts-rather than in further elaboration of the underlying senescence biology itself.

Connecting the frontier to current developments outside the dataset

Several features of the cluster and burst structure align closely with what recent literature outside this dataset is independently reporting, lending external credibility to the patterns the network analysis surfaced. First, the prominence and continued centrality of Cluster No. 3's senescence-mechanism vocabulary is consistent with a wave of 2025-26 reviews explicitly framing senolytics and senomorphics as a maturing but still rapidly developing therapeutic category, several of which explicitly foreground natural-product senolytics, such as fisetin, quercetin, and resveratrol as the most clinically advanced examples-directly mirroring this corpus's own most-cited documents in Cluster No. 2 and No. 3.

Second, the skincare-application burst (Cluster No. 1) is corroborated by a cluster of 2024-25 systematic reviews and meta-analyses specifically evaluating clinical-trial evidence for plant-extract-based topical anti-aging products[7,8] and by broader reviews of cosmeceutical mechanisms and regulatory considerations (Cosmeceuticals for Anti-Aging, 2025[19] aromatic

Table 2: Ten most productive affiliations by document count, with total citations.

Rank	Affiliation	Documents	Total Citations
1	Dept of Pharmaceutical Sciences, Faculty of Pharmacy, Chiang Mai University	28	418
2	University of Chinese Academy of Sciences, Beijing, China	26	779
3	School of Cosmetic Science, Mae Fah Luang University	18	422
4	Dept of Pharmaceutical Botany, Faculty of Pharmacy, Mahidol University, Thailand	13	477
5	College of Food Science and Nutritional Engineering, China Agricultural University, China	12	818
6	Innovation Center for Holistic Health, Nutraceuticals & Cosmeceuticals, Chiang Mai University	10	205
7	AcSIR, Ghaziabad, India	10	95
8	Dept of Biotechnology, Quaid-I-Azam University, Pakistan	9	529
9	College of Food Science, Fujian Agriculture and Forestry University, China	9	299
10	Dept of Cell Biology and Biophysics, National and Kapodistrian University of Athens, Greece	9	224

Abbreviations: AcSIR: Academy of Scientific and Innovative Research.

Table 3: Cluster summary, sorted by size (descending). Mean Year is the mean publication year of each cluster's member keywords' associated documents.

Cluster ID	Size	Silhouette	Mean Year	Label (Top Terms)
3	54	0.376	2021.9	Aging/cellular senescence (aging, oxidative stress, senescence, polyphenols, resveratrol, inflammation).
1	43	0.421	2022.1	Antioxidant/skin aging (antioxidant, anti-aging, skin aging, anti-inflammatory, cosmetics).
0	42	0.098	2022.1	Antioxidant phytochemistry (antioxidants, flavonoids, bioactive compounds, phytochemicals, reactive oxygen species).
2	11	0.610	2021.8	Model-organism longevity (*Caenorhabditis elegans*, longevity, life span, natural products, *Drosophila melanogaster*).

plants as cosmeceuticals, 2024). These external sources echo this study's own finding that cosmeceutical translation is one of the field's most actively expanding fronts rather than a marginal application.

Third, the model-organism cluster's continued relevance is reinforced by very recent *C. elegans* geroprotector-screening work appearing after this dataset's own most recent year, including a 2025 report on *Caryota maxima* leaf extract extending *C. elegans* life span via DAF-2 signaling[5] and a 2024 demonstration that *Anoectochilus roxburghii* extract extends *C. elegans* life span through the daf-16/FoxO pathway[4]-both of which mirror the specific DAF-16/FoxO and insulin-signaling vocabulary that recurs throughout Cluster No. 2's member literature. A 2025 AI-driven screen for polypharmacological life span-extending compounds in *C. elegans*[20] further suggests that this methodological niche, while small in this dataset, is beginning to intersect with the computational drug-discovery methods discussed next.

Fourth, and most forward-looking, a small but growing body of 2023-25 work is applying machine learning directly to natural-product senolytic discovery: Smer-Barreto *et al.*[21] used machine-learning models trained on published screening data to identify three new senolytic compounds (ginkgetin, periplocin, and oleandrin) with potency comparable to established senolytics, and a 2025 senolytic predictor explicitly screened the TCMbank traditional-Chinese-medicine compound database to infer which medicinal herbs might harbor undiscovered senolytic activity, while a broader 2025 review surveys AI/ML-driven strategies across senotherapeutic discovery generally (Next-gen senotherapeutics, 2025). None of these AI-driven discovery keywords appear among this corpus's strongest bursts, which suggests that, as of the 2025 retrieval window, computational natural-product senolytic discovery remains a nascent rather than an established subtheme-a genuine frontier the keyword network has not yet had enough documents to register as its own cluster, but one that recent literature outside the dataset suggests is likely to grow.

LIMITATIONS

Several limitations bear on how these results should be interpreted. First, the analysis draws on a single database (Scopus); coverage differences relative to Web of Science, PubMed, or other databases could shift the precise document count and, to a lesser extent, the keyword frequencies underlying the network, though the scale of this corpus (7255 documents) makes large qualitative shifts from a different database unlikely. Second, the search and inclusion criteria were restricted to English-language articles and reviews, which will under-represent non-English natural-product research, including some traditional-medicine literature published in Chinese, Korean, or other languages that may be substantively relevant to several of the identified clusters. Third, and most consequentially for the network analysis itself, the export lacked a usable References field, which made reference cocitation analysis-the complementary "foundational works" view that a fuller scientometric treatment would normally pair with the keyword co-occurrence map-impossible for this dataset; the results reported here describe topical structure only, not citation-based intellectual lineage.

Fourth, the modularity (Q=0.246) and mean silhouette (S=0.328) both fall below the thresholds conventionally associated with a sharply distinct cluster structure, and this should be read as an honest property of the field's keyword vocabulary-the antioxidant-mechanism, cosmeceutical, and natural-product-chemistry literatures are genuinely intertwined at the level of shared terminology-rather than as a methodological shortcoming to be explained away. The four clusters reported here are real and substantively interpretable, but their boundaries are softer than in a more sharply modular network, and Cluster No. 0 in particular (silhouette=0.098) should be read as a loosely bound, bridging grouping rather than a tightly bounded sub-topic. Fifth, the top-authors table is reported at the name-string level as Scopus exports it; common East Asian surname-plus-initial combinations (eg, "Wang Y.," "Zhang Y.") are highly likely to aggregate multiple distinct individuals under a single name, and the productivity figures in Table 1 should not be read as describing single researchers' true output without further author-disambiguation work beyond the scope of this analysis. Sixth, the burst-to-cluster mapping in Table 4 is necessarily incomplete: because each cluster's reported label terms represent only its most frequent members rather than its full membership, most detected bursts could not be confidently attributed to one of the four labeled clusters, and are reported as such rather than assigned by inference.

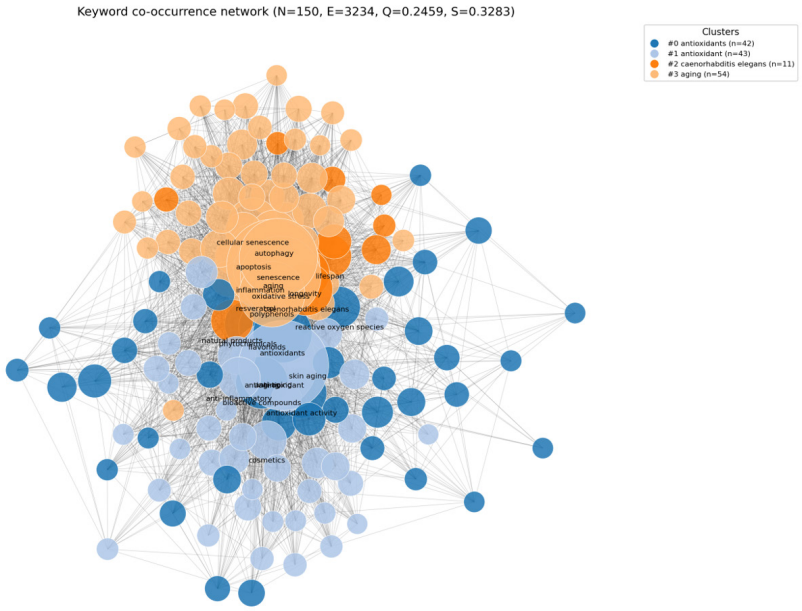

Figure 2: Author Keyword co-occurrence network (2016-25). Node size is proportional to keyword frequency; color denotes cluster membership. n=150, E=3234, density=0.289, Q=0.246, S=0.328.

Table 4: Ten strongest keyword bursts, sorted by strength (descending).

Begin	End	Strength	Peak Year	Keyword	Cluster
2024	2025	6.00	2025	Tricholoma Matsutake	Not Attributable
2025	2025	5.83	2025	Postharvest Preservation	Not Attributable
2024	2025	5.67	2024	Skincare	Not Attributable
2025	2025	5.40	2025	Sublethal Effects	Not Attributable
2021	2021	5.40	2021	Iron	Not Attributable
2016	2016	5.40	2016	Drug Repurposing	Not Attributable
2024	2024	5.40	2024	Skin Diseases	Not Attributable
2023	2025	5.14	2023	Physical Activity	Not Attributable
2016	2017	5.00	2017	Behavior	Not Attributable
2024	2025	5.00	2024	Aloe vera	Not Attributable

CONCLUSION

This scientometric analysis of 7255 Scopus-indexed documents published between 2016 and 2025 shows that research connecting natural products to cellular senescence and aging has grown substantially over the past decade-publication output more than quadrupled, from 311 documents in 2016 to 1407 in 2025-and that its Author Keyword co-occurrence structure resolves into four interpretable, if moderately rather than sharply separated, thematic clusters (Q=0.246, S=0.328): a foundational aging/cellular-senescence mechanistic core, an antioxidant-phytochemistry characterization stream, an antioxidant/skin-aging cosmeceutical-application stream, and a smaller but tightly coherent model-organism (*C. elegans*/*Drosophila*) longevity-screening niche. Recent keyword bursts in "skincare," "skin diseases," and "physical activity" indicate that the field's most active current growth is concentrated in translational, application-oriented territory rather than in further elaboration of senescence mechanism itself, and this pattern is corroborated by a parallel and largely independent wave of 2024-26 reviews and clinical evidence syntheses identified outside the dataset.

Three concrete directions for future research follow directly from gaps this analysis surfaced rather than from generic calls for "more research." First, the absence of a parseable References field in this export prevented reference cocitation analysis; a follow-up study using a Web of Science or a more completely populated Scopus export with cited-reference data could pair the topical map presented here with a genuine intellectual-lineage map of the field's most foundational works, which this analysis could not construct. Second, the loosely bound, low-silhouette antioxidant-phytochemistry cluster (#0, S=0.098) and the absence of any AI/computational-discovery cluster or burst, despite a clear and growing body of external literature applying machine learning to natural-product senolytic screening,[21] together suggest that computational natural-product discovery is a genuine, currently

under-represented frontier within this specific literature, worth deliberately tracking in future bibliometric updates as it matures. Third, the geographic concentration of top-producing institutions in Thailand and China (eight of the top ten affiliations), combined with the field's persistent translational gap between extensive preclinical/model-organism evidence and comparatively sparse clinical validation (most of the dataset's highest-cited works are *in vitro*, animal-model, or narrative-review studies rather than randomized clinical trials), points toward a need for more geographically diverse, clinically rigorous follow-up studies on the natural-product senotherapeutic candidates this field has already identified mechanistically.[22-24]

ACKNOWLEDEGMENT

We are thankful to the Deanship of Scientific Research, Vice Presidency for Graduate Studies and Scientific Research, King Faisal University, Saudi Arabia, for their financial support.

ABBREVIATIONS

AI: Artificial Intelligence; **AcSIR:** Academy of Scientific and Innovative Research; **c:** *Caenorhabditis elegans*; **DAF-2:** Dauer Formation Protein 2; **DAF-16/FoxO:** Dauer Formation Protein 16/Forkhead Box O; **EBioMedicine:** EBioMedicine; **E:** Edges; **ML:** Machine Learning; **NF-κB:** Nuclear Factor Kappa B; **OPG:** Osteoprotegerin; **Q:** Modularity; **RANKL:** Receptor Activator of Nuclear Factor Kappa-B Ligand; **ROS:** Reactive Oxygen Species; **RV:** Resveratrol; **S:** Silhouette Score; **Scopus:** Elsevier Scopus Database; **TF-IDF:** Term Frequency–Inverse Document Frequency; **USD:** United States Dollar.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

FUNDING

This work was funded through the Deanship of Scientific Research, Vice Presidency for Graduate Studies and Scientific Research, King Faisal University, Al-Ahsa, Saudi Arabia [Grant Number KFU263589].

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Cite this article: Almuqbil RM, Aldhubiab B, Ahmed KKM, Sab MC. Natural Products and Cellular Senescence Research: A Scientometric Analysis of Global Trends, Thematic Clusters, and Emerging Frontiers (2016-25). Indian J of Pharmaceutical Education and Research. 2026;60(4s):s1374-s1382.