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Research Article

Global Research Trends in Cultured Meat and Halal Biotechnology: a Bibliometric Analysis

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Abstract

Biotechnology has rapidly emerged as a key driver of innovation in the food and industrial sectors, emphasizing efficiency, sustainability, and halal compliance. However, research addressing halal biotechnology remains limited and fragmented. This study aims to analyze research trends in cultured meat, cellular agriculture, and halal biotechnology with a particular focus on halal enzyme production and cultured meat, using a bibliometric approach. Data were collected from the Scopus database using the keywords ("halal biotechnology" OR "halal enzyme" OR "cultured meat" OR "lab-grown meat" OR "cellular agriculture") within the article title field, covering publications from 2020 to 2025. The data were analyzed using VOSviewer and Biblioshiny to map publication growth, author collaboration, institutional affiliations, and keyword co-occurrences. A total of 987 documents were identified, showing fluctuating yet steadily increasing trends over the years. The literature is heavily dominated by cultured meat research, whereas halal biotechnology remains underrepresented, forming the central node in the cultured meat and cellular agriculture research network. Conversely, the keyword "halal" appeared only 11 times, mostly related to halal enzymes, halal awareness, and halal ingredients, indicating limited integration of halal perspectives in current biotechnology research. China, the United States, and South Korea emerged as the most productive countries, while Nanjing Agricultural University, Jiangnan University, and Chung-Ang University were identified as the top contributing institutions. These findings highlight a significant research gap in halal biotechnology, underscoring the need for greater scientific exploration of halal enzymes and halal-certified cultured meat production.

Keywords: cellular agriculture; cultured meat; food biotechnology; halal biotechnology; VOSviewer

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INTRODUCTION

The rapid advancement of modern biotechnology over the past two decades has had a profound impact on various sectors, particularly health, food, and the environment. In the context of food biotechnology, innovations such as cultured meat, precision fermentation, and genetic manipulation have become key milestones in enhancing efficiency, sustainability, and global food security. Cultured meat, for instance, offers an environmentally friendly protein alternative compared to conventional animal-based products by significantly reducing land and water use—two critical resources for maintaining global food resilience [1]. Similarly, precision fermentation demonstrates great potential in improving the diversity and nutritional quality of food products without causing the environmental degradation typically associated with traditional agricultural practices [2]. Meanwhile, genetic manipulation contributes to increased crop productivity, pest and disease resistance, and animal welfare [3], [4]. The relevance of food biotechnology is becoming increasingly prominent amid global challenges such as rapid population growth and the climate crisis, which demand sustainable food systems. These technologies not only enhance productivity but also offer solutions to the ecological consequences of intensive food production [5], [6]. With growing public acceptance of innovations such as cultured meat and other alternative food products, alongside the successful application of biotechnology across sectors, there is a substantial opportunity to drive fundamental transformations in global agricultural and food distribution systems toward greater sustainability [7], [8].

Despite the promising potential of modern biotechnology, it also presents emerging challenges concerning the halal status of biotechnological products, particularly cultured meat and other food items produced through advanced biotechnological processes. The concept of halal extends beyond ritual or Islamic legal dimensions; it also encompasses scientific ethics, safety, and transparency in production chains [9]. The production of cultured meat, for example, involves the use of growth media, enzymes, and additives that may not necessarily be derived from halal sources [10]. This situation has sparked global debate regarding the halal status of cultured meat and underscores the need for an interdisciplinary scientific approach that integrates biotechnology, Islamic jurisprudence, and halal assurance systems [11]. The diversity of interpretations of Islamic law and halal principles may also lead to confusion among producers and consumers [12]. In this context, multidisciplinary collaboration is essential, for instance through chromatographic metabolomic analysis to identify non-halal components in food products [13]. Furthermore, variations in halal regulations among countries affect market access and the global distribution of cultured meat, emphasizing the importance of developing an integrated international standard [14]. Cross-disciplinary research involving biotechnologists, Islamic scholars, regulators, and industry experts indicates that a comprehensive and collaborative approach is necessary to ensure halal assurance for Muslim consumers [15]. Therefore, halal issues in biotechnology-based food products must not be viewed solely from an economic or market perspective but also through the lens of Sharia law and religious ethics, in order to align technological innovation with Islamic values [16]. The discourse on the halal status of cultured meat ultimately highlights the urgency of clear and transparent regulations to ensure that every stage of production adheres to halal principles, enabling consumers to make informed and ethical decisions [17].

Attention to halal issues in biotechnology has risen rapidly in line with the growth of the global halal industry, which is now valued at more than USD 2 trillion annually [18]. Countries with large Muslim populations, such as Indonesia, Malaysia, and Saudi Arabia, have begun to invest heavily in halal biotechnology research to ensure that innovations in the food and

pharmaceutical sectors remain aligned with Islamic Sharia principles [19], [20]. These efforts are not only driven by ethical and religious considerations but also reflect scientific and economic strategies to meet the global demand for halal technology-based products [21]. Consequently, halal biotechnology has emerged as a rapidly growing research field, although its global direction, collaborations, and research focus have not yet been comprehensively mapped [22]. One of the key challenges lies in integrating Sharia principles into biotechnological innovation, particularly in the areas of legal interpretation, ethics, and product certification and validation processes [23], [24]. In this regard, addressing risk, safety, and management strategies becomes crucial to ensure product compliance with halal standards [25]. Concurrently, cross-sectoral collaboration among academics, industry, and regulatory bodies is essential to establish a strong research foundation, develop science-based halal validation methodologies, and strengthen the position of halal biotechnology within the global innovation ecosystem [26], [27] . Such synergy is expected to foster internationally competitive innovations that not only meet domestic market needs but also possess significant export potential, contributing to the growth of the global halal economy.

Meanwhile, bibliometric analysis has proven to be an effective method for systematically assessing the development of a particular field of study. Utilizing global scientific databases such as Scopus or Web of Science, bibliometric analysis enables researchers to identify research trends, author productivity, collaboration networks, dominant keywords, and future research directions. Although numerous bibliometric studies have been conducted in the field of biotechnology in general, Previous bibliometric studies have primarily focused on cultured meat or alternative proteins independently, while the intersection between halal biotechnology and cultured meat research remains largely unexplored. Therefore, This study aims to analyze research trends in cultured meat, cellular agriculture, and halal biotechnology with a particular focus on halal enzyme production and cultured meat, using a bibliometric approach. The findings of this mapping are expected to provide strategic insights for policymakers, academics, and the halal industry, as well as contribute to the development of an ethical and sustainable global biotechnology research framework.

METHODS

Research Design

This study adopted a descriptive–analytical bibliometric design with a quantitative approach to comprehensively map global research trends in Biotechnology with a Focus on Halal, Cultured Meat, and Production from 2020 to 2025. The data search was conducted in September 2025. The bibliometric method was chosen for its ability to identify publication growth patterns, scientific collaboration, and conceptual structures in a systematic and reproducible manner. This design integrates both performance analysis—to assess productivity and citation impact—and science mapping, to visualize the intellectual and collaborative networks among authors, countries, and institutions. The Scopus database was selected as the primary data source due to its extensive multidisciplinary coverage and high indexing quality, ensuring the accuracy and comprehensiveness of bibliometric data.

Data Collection Procedure

Data were collected through an advanced search in the Scopus database using the Boolean query: TITLE-ABS-KEY ("halal biotechnology" OR "halal enzyme" OR "cultured meat" OR "lab-grown meat" OR "cellular agriculture") . These keywords were selected because they adequately represent the main research domain, while the halal aspect is already covered by "halal

biotechnology" and "halal enzyme." Expanding the scope too broadly or making it too nonspecific could potentially reduce the accuracy of the mapping results (high noise). The search covered documents published 2020 - 2025, encompassing all related subject areas. The inclusion criteria: Scopus-indexed journal articles, conference papers, and reviews published between 2020 and 2025, with complete metadata and relevance to keywords.

Table 1. Search Strategy and Data Retrieval Criteria for Bibliometric Analysis

Criteria	Description
Source Database	Scopus
Search within	Article, abstract, keyword
Search Document	TITLE-ABS-KEY ("halal biotechnology" OR "halal enzyme" OR "cultured meat" OR "lab-grown meat" OR "cellular agriculture"). AND PUBYEAR > 2019
Data Year	2020-2025
Subject	Agricultural and Biological Sciences, Biochemistry, Genetics and Molecular Biology, Chemical Engineering, and Engineering
Documents found	1.436
Publication Language	English, Spanish, Chinese and other related matters
Documents Type	Journal articles, conference papers, and reviews
Documents Final	987

Data Analysis Procedure

The bibliometric data were exported in BibTeX format and analyzed using two primary software tools—R Studio (Biblioshiny for Bibliometrix) and VOSviewer (version 1.6.20)—to provide a comprehensive quantitative and visual interpretation of global research trends in halal biotechnology and cultured meat. R Studio, through the Biblioshiny application, was employed to conduct descriptive and performance analyses, including the assessment of annual publication growth, citation metrics, authorship patterns, the most productive authors, leading countries and institutions, and thematic evolution of research. This analytical framework enabled a systematic understanding of scientific growth dynamics, facilitating the identification of dominant topics and emerging research directions within the field. Such methodological capabilities have been previously highlighted in bibliometric studies on halal research [28], emphasizing their effectiveness in detecting significant thematic clusters and research trends.

Meanwhile, VOSviewer was utilized for network analysis and visualization, focusing on keyword co-occurrence, co-authorship networks, and international collaboration mapping. The full counting method was applied to ensure equal analytical weight for each occurrence or collaborative link. Minimum thresholds were set to maintain analytical rigor: 15 occurrences for keyword inclusion, two documents for co-authorship, and 36 documents per country for country collaboration analysis. This approach identified ten countries meeting the criteria, with China, the United States, and the United Kingdom emerging as the most productive contributors to the field—consistent with findings from prior bibliometric investigations on halal innovation and food biotechnology [29], [30] [29]. These findings echo earlier studies that have successfully used bibliometric mapping to reveal networks of influence and collaboration in halal-related domains [28], [31].

The integration of both R Studio and VOSviewer ensured a robust statistical foundation and clear network visualization, yielding results that were comprehensive, valid, and visually informative. Moreover, this dual-tool approach aligns with established bibliometric methodologies that bridge quantitative analysis and qualitative interpretation, thereby enhancing understanding of thematic evolution, collaboration networks, and citation structures in the global discourse of halal biotechnology and cultured meat. Ultimately, this methodological integration provides a strong basis for evaluating scientific progress, research influence, and future directions in this emerging and interdisciplinary field [32]–[35].

RESULT AND DISCUSSIONS

Annual Scientific Production

The annual trend of scientific publications provides an overview of the growing research interest and the level of scholarly attention devoted to a specific field over time. In the context of halal biotechnology and cultured meat, analyzing publication growth helps identify the momentum of scientific development, emerging research priorities, and global engagement in this interdisciplinary domain. The annual distribution of research output from 2020 to 2025, as illustrated in Figure 1, demonstrates a consistent increase in the number of scientific publications. This upward trajectory indicates an expanding academic focus on sustainable food innovation, bio technology applications, and ethical considerations within the halal framework. The distribution of the number of scientific publications from 2022 to 2025 can be seen in Figure 1.

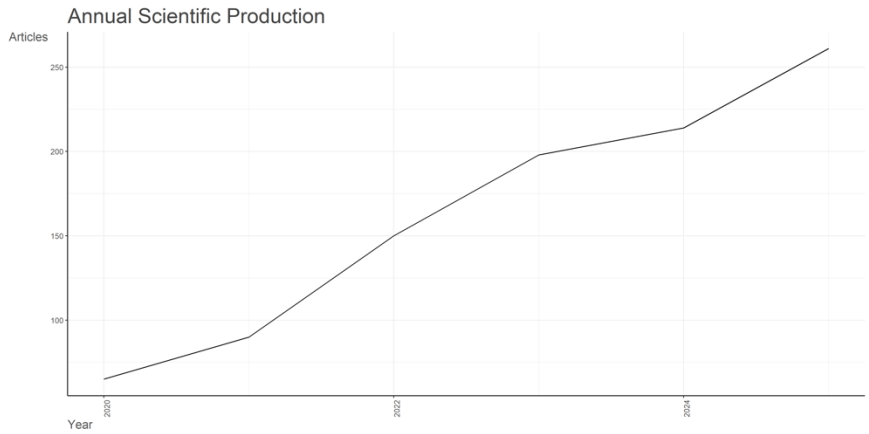

Figure 1. Distribution of the number of scientific publications from 2020 to 2025

Figure 1 shows that the annual trend of scientific publications increased consistently from 2020 to 2025. Overall, the graph illustrates a steady upward pattern, reflecting the growing global academic interest and research intensity in this rapidly expanding interdisciplinary field. The number of publications rose significantly—from 65 articles in 2020 to 261 articles in 2025—indicating a sustained increase in scholarly attention and the continuous advancement of research related to biotechnology, halal innovation, and cultured meat.

Co-Occurence Analysis

The keyword co-occurrence analysis provides a comprehensive overview of the conceptual structure and thematic relationships within the field of halal biotechnology and cultured meat, highlighting how frequently specific keywords appear together in scientific publications. This approach enables the identification of core research themes, interdisciplinary linkages, and emerging topics that shape the intellectual landscape of the field. Consistent with the findings of

Halmi and Khalli (2025), this method has proven effective in mapping global trends and research trajectories in halal meat studies. Similarly, Pareti et al. (2025) emphasized the relevance of the relationship between cultured meat and consumer response, reflecting the growing market interest in biotechnology-based food innovations. Nordin et al. (2025) further supported this by demonstrating that keyword co-occurrence analysis not only helps in mapping dominant research areas but also reveals new opportunities for innovation and future exploration. Figure 2 illustrates the keyword co-occurrence network, showcasing the interconnections among key concepts in halal biotechnology and cultured meat research, thereby providing a strong conceptual foundation for scholars to direct their studies toward the most promising and relevant research areas.

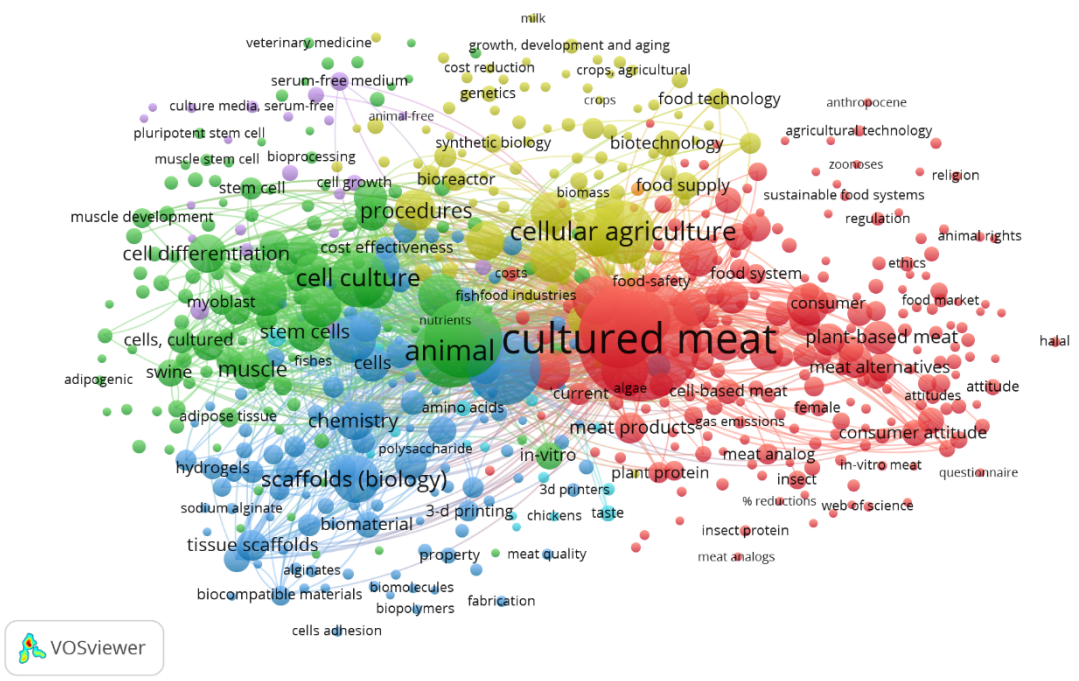

Figure 2. Co-occurrence network visualization of keywords related to halal biotechnology and cultured meat (2020–2025)

Based on Figure 2, the unit of analysis was set to include all keywords using the full counting method, whereby each keyword occurrence was assigned equal weight. The minimum occurrence threshold was set at four, resulting in a total of 4,868 keywords, with 579 keywords meeting the threshold criteria for visualization. The generated map, as illustrated in Figure 2, reveals several clusters representing interconnected research areas. The visualization indicates that the keyword "cultured meat" serves as the dominant node, closely associated with terms such as "cellular agriculture," "cell culture," and "animal." This suggests that the primary focus of the scientific discourse lies in the production aspects, biological mechanisms, and ethical implications of cultured meat. Other clusters highlight supporting themes, including biomaterial scaffolds (blue cluster), bioprocessing and food biotechnology (yellow cluster), and consumer attitudes and sustainability (red cluster).

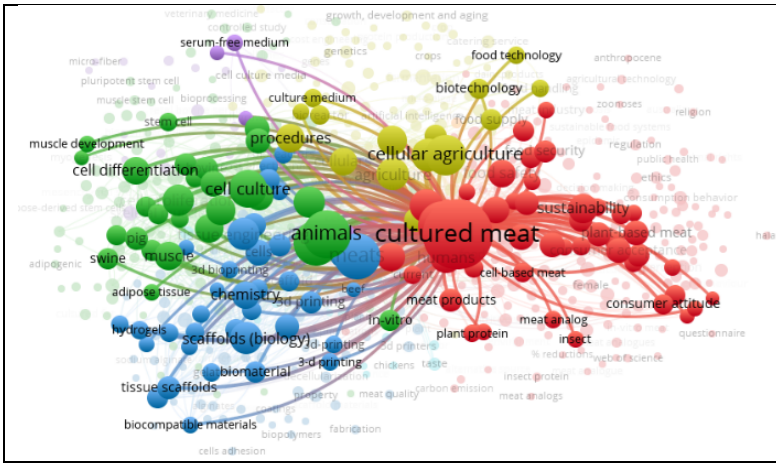

Figure 3. Keyword Co-occurrence network of global research on cultured meat and halal biotechnology (2020–2025)

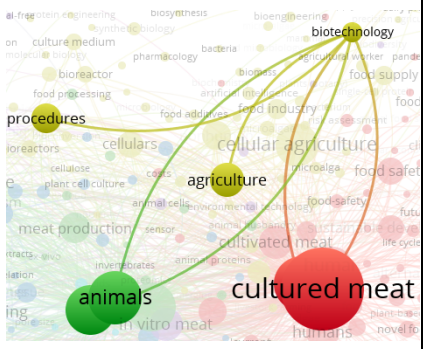

Figure 4. Link strength visualization between core keywords in cultured meat and biotechnology research (2020–2025)

Figure 3 presents the visualization of the keyword co-occurrence network generated using VOSviewer, illustrating the conceptual structure and thematic relationships within global research on halal biotechnology and cultured meat. The visualization reveals several interconnected colored clusters, highlighting the interdisciplinary nature of this field. The red cluster, centered on the term "cultured meat", encompasses themes such as consumer perception, ethics, sustainability, and plant-based alternatives, indicating growing scholarly attention toward social acceptance, religious values, and environmental impacts [36], [37]. The green cluster includes terms like "cell culture," "stem cells," "scaffolds," and "biomaterials," which emphasize the biological and material aspects of cultured meat production, particularly in tissue engineering and scaffold design to enhance technical efficiency and product quality [38]. Meanwhile, the yellow cluster, composed of terms such as "biotechnology," "food technology," "cellular agriculture," and "bioreactor," reflects engineering innovations and process optimization, demonstrating progress in biotechnology and sustainable food systems [36]. Additionally, the blue cluster, containing keywords like "tissue scaffolds," "hydrogels," "biocompatible materials," and "3D printing," focuses on applied material science, particularly the development of biocompatible materials and 3D printing technologies to reproduce realistic meat textures [39]. Lastly, the purple cluster, characterized by the terms "pluripotent stem cell" and "serum-free medium," represents the latest innovations in serum-free cell culture, which are crucial to ensuring halal compliance and ethical production [37].

Figure 4 illustrates the keyword linkage network, displaying the conceptual relationships among key terms in publications related to cultured meat and biotechnology. The visualization shows that "cultured meat" serves as the core node within the network, underscoring its strategic role in connecting multiple disciplines such as biology, agriculture, and technology [40]–[42]. The strong association between "cultured meat," "biotechnology," "agriculture," and "animals" suggests that research in cultured meat is deeply rooted in agricultural biotechnology and cellular biology, utilizing scientific approaches to replicate animal muscle tissue formation while reducing reliance on conventional livestock systems [3], [42]. The yellow cluster, which links "biotechnology" and "agriculture," represents the technical and industrial framework underlying cultured meat development. The presence of terms such as "procedures" and "cellular agriculture" indicates research focused on optimizing biotechnological processes, including cell culture techniques, bioreactor design, and growth media formulation, which form the foundation for

large-scale, efficient, and ethical production [42], [43]. Meanwhile, the "animals" node (green) highlights the biological foundation of cultured meat studies, emphasizing cellular mechanisms, stem cell differentiation, and tissue engineering aimed at replicating the texture and nutritional quality of conventional meat [3].

Table 2. Documents with the highest citation

Authors	Title	Journal	Year	Cited
Onwezen, M.C.; Bouwman, E.P.; Reinders, M.J.; Dagevos, H.	A systematic review on consumer acceptance of alternative p vroteins: Pulses, algae, insects, plant-based meat alternatives, and cultured meat	Appetite	2021	725
Siegrist, M.; Hartmann, C.	Consumer acceptance of novel food technologies	Nat Food	2020	534
Post, M.J.; Levenberg, S.; Kaplan, D.L.; Genovese, N.; Fu, J.; Bryant, C.; Negowetti, N.; Verzijden, K.E.; Moutsatsou, P.	Scientific, sustainability and regulatory challenges of cultured meat	Nat Food	2020	523
Klerkx, L.; Rose, D.C.	Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways?	Global Food Security	2020	455
Rubio, N.; Xiang, N.; Kaplan, D.L.	Plant-based and cell-based approaches to meat production	Nat Commun	2020	451
Kyriakopoulou, K.; Keppler, J.K.; Van der Goot, A.J.	Functionality of ingredients and additives in plant-based meat analogues	Foods	2021	448
Galanakis, C.M.; Rizou, M.; Dawoud, T.M.S.; Uçak, I.; Rowan, N.J.	Innovations and technology disruptions in the food sector within the COVID-19 pandemic and post-lockdown era	Trends In Food Science and Technology	2021	385
Chriki, S.; Hocquette, J.-F.	The Myth of Cultured Meat: A Review	Frontiers In Nutrition	2020	383
Van Loo, E.; Caputo, V.; Lusk, J.L.	Consumer preferences for farm-raised meat, lab-grown meat, and plant-based meat alternatives: Does information or brand matter?	Food Policy	2020	355

Table 2 presents the nine most-cited publications in the field of food biotechnology, cultured meat, and alternative proteins during the period 2020–2021. Overall, the citation patterns indicate that research on consumer acceptance of novel and sustainable foods dominates global academic attention. The article by Onwezen et al. (2021) in Appetite received the highest number of citations (725), followed by Siegrist and Hartmann (2020) in Nature Food (534 citations), both emphasizing the importance of public perception and acceptance of innovative food products such as cultured meat, plant-based proteins, insects, and microalgae. Beyond the social and behavioral aspects of consumer studies, Post et al. (2020) in Nature Food highlighted the scientific and regulatory challenges in cultured meat development, underscoring the urgency of integrating sustainability principles, food safety, and ethical production within modern food biotechnology. Similarly, Klerk and Rose (2020) in Global Food Security and Rubio et al. (2020) in Nature Communications emphasized the technological transformation of agriculture toward biotechnology-based modern farming systems, often referred to as Agriculture 4.0. Meanwhile, studies such as Kyriakopoulou et al. (2021) in Foods and Galanakis et al. (2021) in Trends in Food Science and Technology focused on the functional properties of ingredients and additives in plant-

based food products, demonstrating growing interest in material engineering and process efficiency. On the other hand, the reflective article by Chriki and Hocquette (2020) in Frontiers in Nutrition provided a critical perspective on the myths and realities surrounding cultured meat, revealing that the topic remains scientifically and socially debated among scholars regarding its technical feasibility and ethical implications.

To further understand the collaborative relationships among researchers contributing to the field of halal biotechnology and cultured meat, an author collaboration network analysis was conducted using global publication data. This analysis aimed to identify key researchers with central roles in international collaborations and to map the most active research groups producing scientific publications. Figure 5 illustrates the structure of the author collaboration network, depicting the intensity of relationships and interconnections among researchers in this domain.

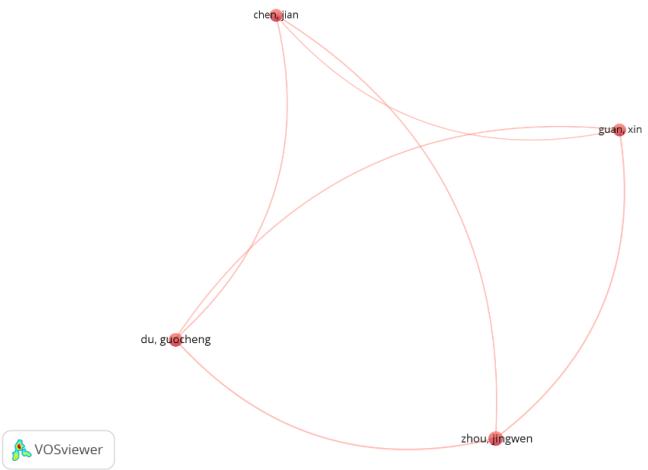

Figure 5. Author collaboration network in global research

The visualization in Figure 5 shows that Jingwen Zhou, Guocheng Du, Xin Guan, and Jian Chen form a strong collaborative research cluster. These four researchers actively co-author scientific publications within the same field, demonstrating a cohesive and productive research partnership. Among them, Jingwen Zhou exhibits the widest collaborative network, with a total of 43 connections, positioning him as the central node in the collaboration network and the key contributor driving international research cooperation in halal biotechnology and cultured meat studies.

Table 3. Authors with the highest number of publications and citations

Author	Total Link Strength	Total Citations	Affiliation
Kaplan, D.L.	10	978	Tuts School Of Enginering, Medford, United States
Bryant, C.	8	523	University of bath, departement of psychology
FU, J.	8	523	PAN-Biotech GmbH, Aidenbach Germany
Genovese, N.	8	523	Line Development Memphis meats, Barkeley, United States
Levenberg, S.	8	523	Techhnion-Israel Institute of technology, Haifa, Israel

Table 3 presents a list of authors with the highest number of publications and citations in the field of halal biotechnology and cultured meat research during the period 2020–2025. The

analysis identifies D.L. Kaplan from the Tufts School of Engineering, Medford, United States, as the leading researcher, with a total of 978 citations and 10 collaborative connections, highlighting his role as the most influential scholar within the global publication network on cell-based meat and biomaterial scaffolds. Following closely, C. Bryant, J. Fu, N. Genovese, and S. Levenberg each recorded 523 citations with a collaborative strength of eight connections, underscoring their substantial contributions to advancing the scientific foundation and fostering international collaboration in the domain of sustainable food biotechnology. These researchers are affiliated with prominent institutions such as the University of Bath (United Kingdom), PAN-Biotech GmbH (Germany), Line Development Memphis (United States), and the Technion–Israel Institute of Technology (Israel). The strong collaboration among these authors illustrates that the development of halal biotechnology and cultured meat extends beyond cellular biology and bioprocess engineering. It also encompasses social sciences, ethics, regulatory frameworks, and sustainability considerations, reflecting the interdisciplinary and global nature of innovation in modern food biotechnology.

Most Cites Countries

Figure 6 presents the results of the international co-authorship network analysis based on authors' countries of origin, illustrating the global patterns of scientific collaboration in the field of halal biotechnology and cultured meat. This analysis aims to identify countries that serve as major collaboration hubs and to examine interregional relationships among those with high research productivity. Out of a total of 72 countries involved in related publications, only 10 countries met the threshold of at least 36 documents. The visualization reveals that the United States, China, and the United Kingdom represent the three most productive and collaborative nations [44], [45]. The United States functions as the central hub of global collaboration (red node), maintaining strong connections with European countries such as Germany, the Netherlands, and Canada. Meanwhile, China (green node) exhibits close partnerships with Asian countries including South Korea, India, and Singapore, while the United Kingdom (blue node) acts as a strategic bridge connecting the Asian and European clusters [9], [28].

This pattern of collaboration underscores the multinational and interdisciplinary nature of research on cultured meat and halal biotechnology, encompassing the exchange of expertise, technology, and resources between developed and developing nations. Consistent with Fernandes et al. (2019), such international research networks not only strengthen cross-country cooperation but also foster knowledge transfer and global capacity building in food biotechnology. Hence, these scientific collaborations play a pivotal role in promoting innovation, ethics, and food sustainability, while expanding the broader impact of research on global food security [46], [47].

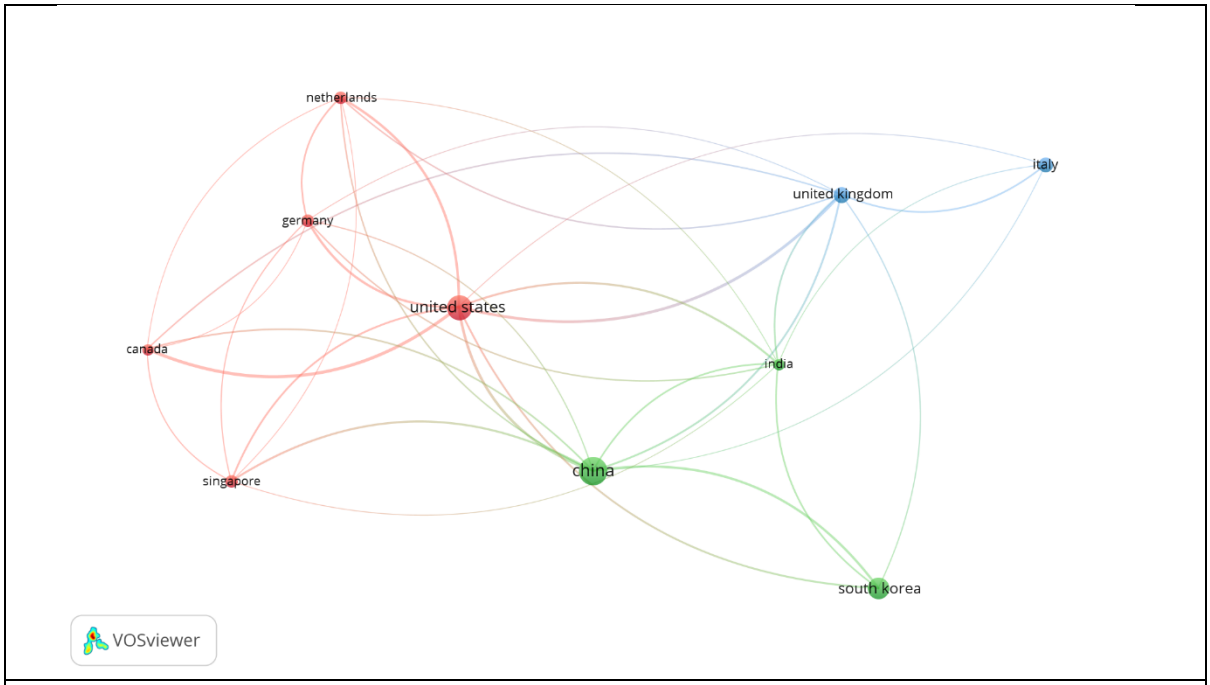

Figure 6. International Co-authorship network of the most cited countries

Distribution of research documents by country

The geographical distribution of research in halal biotechnology, enzymes, and cultured meat was analyzed based on the country of publication. This analysis aims to identify the most active countries contributing to scientific output related to modern biotechnology and its integration with halal principles. The data provide insight into global research centers that play a pivotal role in advancing innovation and sustainable food biotechnology. Figure 7 illustrates the proportion of each country's contribution to the total number of publications indexed in the Scopus database during the 2020–2025 period.

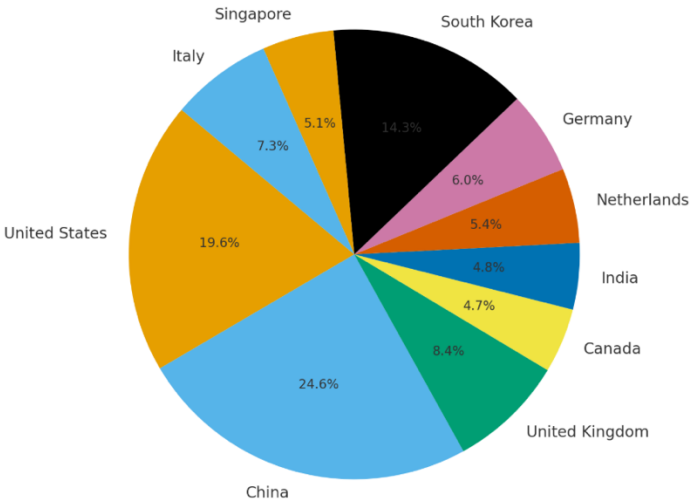

Figure 7. Distribution of research documents by country

As shown in Figure 7, the distribution of research publications indicates that the field is dominated by three leading countries: China (24.6%), the United States (19.6%), and South Korea (14.3%). These nations serve as primary research hubs, driving advancements in science and innovation within biotechnology-based food systems. China demonstrates the highest

contribution, reflecting its strong commitment to food biotechnology research and the development of alternative proteins as part of sustainable food strategies. The United States, in contrast, leads in technological innovation, regulatory frameworks, and interdisciplinary integration that bridges biotechnology with the social and economic sciences. Meanwhile, South Korea ranks third, contributing significantly to the development of cell culture and biomaterial technologies, which form the scientific foundation for cultured meat production. European countries such as the United Kingdom (8.4%), Italy (7.3%), and Germany (6.0%) also demonstrate notable contributions, particularly in ethics, food safety, and public policy research. Additionally, Singapore (5.1%), despite its small size, stands out for its applied research and policy innovation in future food development. Overall, this distribution pattern confirms that research on cultured meat and halal biotechnology is globally dispersed rather than regionally concentrated, characterized by active interregional collaboration among Asia, Europe, and North America.

China's dominance in publications on cultured meat and halal biotechnology indicates that research developments in this field are largely driven by biotechnology capabilities, investment in future food research, and policy support for food security. China has a strong research ecosystem, a large number of researchers, and a strong focus on innovation in alternative protein sources. Therefore, China's significant contribution reflects not only academic interest but also a national strategy to address long-term food needs. In contrast, Muslim-majority countries such as Indonesia, Malaysia, and Saudi Arabia have not yet demonstrated dominance in publications despite having a strong interest in halal issues. This may be because research in these countries still focuses more on the legal aspects of halal, certification, and consumer acceptance. Meanwhile, cultured meat research requires complex biotechnology infrastructure, such as cell culture, growth media, scaffolds, and bioprocesses. These findings indicate a gap between halal market needs and technical research capacity in Muslim countries. Thus, the global publication landscape does not yet fully reflect the needs of Muslim consumers worldwide. Muslim countries need to strengthen collaboration among halal institutions, universities, the biotechnology industry, and governments so that research on halal cultured meat does not stop at normative studies but evolves into competitive technological innovations.

Most Relevant Affiliations

To identify the most influential and productive institutions in the field of halal biotechnology and cultured meat, an analysis of researchers' institutional affiliations was conducted based on the number of scientific publications produced. This analysis aims to determine which universities and research institutions serve as global research hubs and to assess how each institution contributes to the advancement of modern food biotechnology. Figure 8 presents the ten institutions with the highest publication output, which play a si. gnificant role in shaping the international research network in this field.

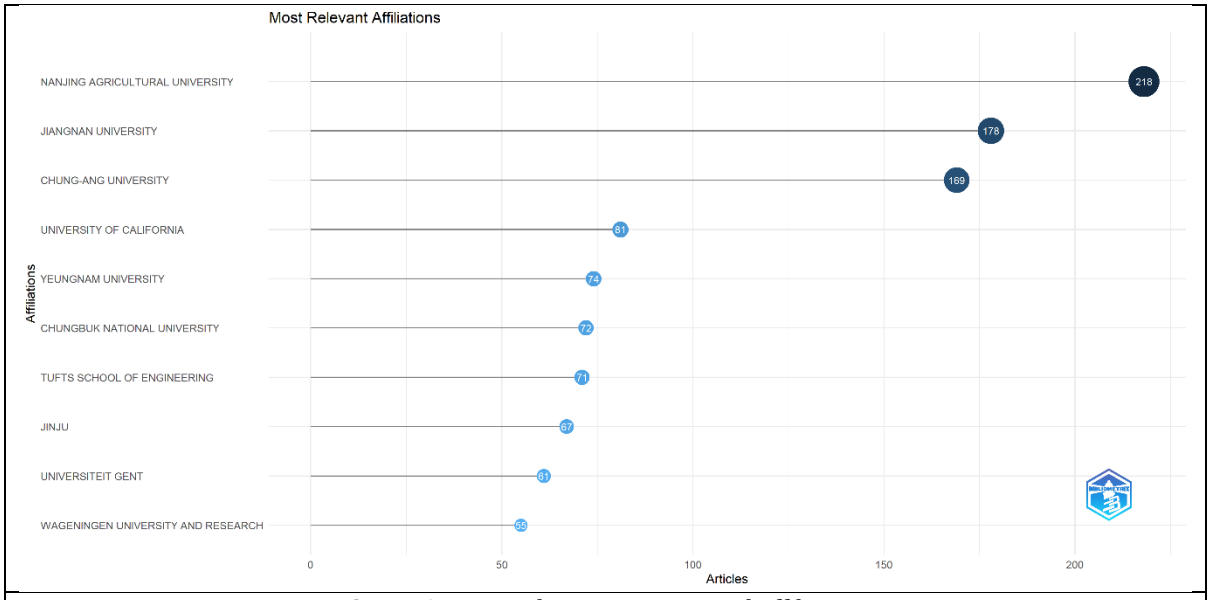

Figure 8. Most relevant institutional affiliations

The results of the affiliation analysis in halal biotechnology and cultured meat research indicate that leading research centers are predominantly located in East Asia, particularly in China and South Korea. According to bibliometric data and the visualization shown in Figure 8, Nanjing Agricultural University ranks first with 218 articles, followed by Jiangnan University with 178 articles, and Chung-Ang University with 169 articles. This dominance underscores East Asia's position as the primary hub for global research and development in cultured meat, focusing on technological innovation in sustainable food production [48]–[50]. Significant contributions also come from institutions such as the University of California, Yeungnam University, and Chungbuk National University, reflecting strong research synergy between the United States and South Korea in advancing food biotechnology and developing alternative protein technologies [36], [51]. In Europe, Universiteit Gent (Belgium) and Wageningen University and Research (the Netherlands) emerge as leading research centers in food science and agricultural biotechnology, contributing to technological advancement and sustainability in cultured meat research [52]. These findings reveal the existence of a robust cross-regional collaboration among Asia, America, and Europe, which serves as a key driver of innovation in halal biotechnology and future food systems. Such collaborative patterns illustrate the global trend of knowledge, resource, and expertise sharing among universities—forming an essential foundation for scientific progress and the long-term sustainability of research in alternative protein development [53], [54].

Trend Topics

To understand the direction and focus of global research in halal biotechnology and cultured meat, a keyword frequency analysis was conducted to track the evolution of the most frequently used terms from 2020 to 2025. This analysis is essential for identifying emerging topics that are gaining scholarly attention and for tracing the dynamic shifts in research focus over time. Figure 9 presents the cumulative trend of key term occurrences, reflecting each term's relative contribution to the development of modern food biotechnology research.

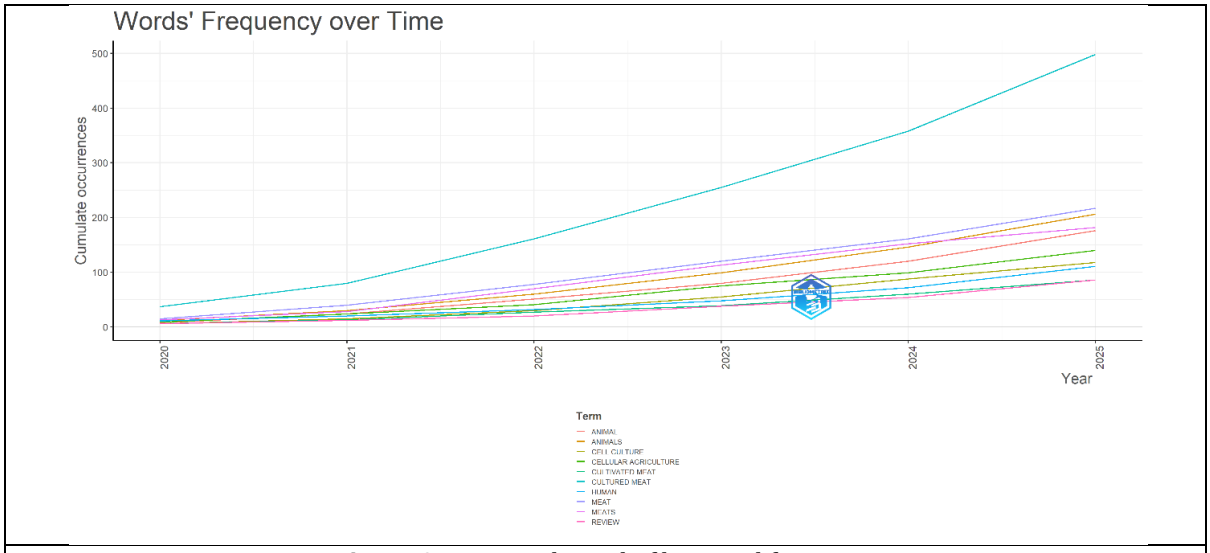

Figure 9. Temporal trend of keyword frequency

As shown in Figure 9, there is a consistent upward trend in keyword frequency within global research on halal biotechnology and cultured meat during the 2020–2025 period, indicating sustained scientific interest in the field. The term "cultured meat" exhibits a pronounced dominance, with a sharp rise beginning in 2022 and continuing through 2025, suggesting that this topic has become the central focus of biotechnology-based food innovation [44]. Similar increases are observed in keywords such as "cellular agriculture," "cell culture," and "animals," highlighting the close connection between cultured meat research, cellular biotechnology, and sustainable agriculture [55]. In contrast, the keywords "halal" and "enzyme" appear far less frequently, indicating that the halal dimension and halal enzyme development have received comparatively limited scholarly attention [28], [56]. This imbalance reflects a research gap, where global efforts remain primarily focused on technological and production efficiency, while ethical, regulatory, and Shariah-compliance aspects remain underexplored. Consistent with Boereboom et al. (2022), the acceptance of cultured meat within Muslim communities is heavily dependent on adherence to halal principles, which are still insufficiently integrated into modern biotechnological discourse. Therefore, although food biotechnology research continues to advance rapidly in the context of innovation and sustainability, halal and ethical considerations require greater academic attention to ensure that emerging technologies achieve broad acceptance—both scientifically and religiously.

CONCLUSION

This study mapped the global research landscape of halal biotechnology, cultured meat, and biotechnology-based food innovation through a bibliometric analysis of 987 Scopus-indexed publications from 2020 to 2025. The findings reveal that cultured meat research dominates the scientific discourse, with themes such as cellular agriculture, cell culture, and biomaterial scaffolds emerging as the most influential topics. In contrast, halal-related research, including halal enzymes and halal certification, remains limited and underrepresented, indicating a significant gap in the integration of halal perspectives within modern biotechnology. China, the United States, and South Korea emerged as the leading contributors in terms of publication output and international collaboration, while institutions such as Nanjing Agricultural University, Jiangnan University, and Chung-Ang University played central roles in advancing research in this

field. The increasing frequency of keywords related to cultured meat since 2022 reflects growing global attention toward sustainable food technologies. Overall, the study highlights a substantial imbalance between technological advancement in cultured meat and the development of halal biotechnology, positioning halal biotechnology as an emerging research frontier. Future progress in this area will require stronger interdisciplinary collaboration among biotechnology researchers, halal certification bodies, policymakers, and Islamic scholars to support the development of halal-compliant cultured meat systems and promote broader acceptance of future food innovations within Muslim communities worldwide.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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