Revista de Ingenierías Interfaces, Vol 8 (2) Julio-Diciembre 2025. ISSN 2619-4473 E-ISSN 2619-4465, pp 1-22.

Introducción a los biorreactores: Un análisis cienciométrico*

Introduction to Bioreactors: A Scientometric Analysis

Yoiner Barbosa–Quintero**
Victor Manuel Cantillo–Suarez ***

Recibido: junio 19 de 2025 - Evaluado: julio 28 de 2025 - Aceptado: Agosto 30 de 2025

Para citar este artículo / To cite this Article
Y. Barbosa-Quintero, V. M. Cantillo-Suarez, "Introduction to Bioreactors: A Scientometric Analysis", Revista de Ingenierías Interfaces, vol. 8, no.2, pp.1-22, 2025.

Abstract

Bioreactors play a crucial role in biotechnological production by directly influencing the metabolic regulation of fermentative processes. The optimization of parameters such as pH and oxygen transfer allows for improved efficiency and performance of bioprocesses, highlighting the importance of developing advanced planning in the design and operation of bioreactors to optimize product synthesis [1]. Over time, innovation in the field of bioreactors has been widely explored, yet a comprehensive chronological review has not been conducted. This article seeks to address that gap through an analysis of the evolution of bioreactor-focused technologies, using the framework of the tree of science. To this end, the study is based on systematic searches in the Web of Science and Scopus databases, accessed through the university libraries. These findings provide a foundation for new researchers and developers to design high-performance systems with practical and meaningful impact, supported by accurate information.

Keywords: Bioreactor, automated, biotechnology, systems, bioprocess, monitoring, optimization, production, cultivation, fermentation, solid, design, modeling.

---

*Artículo inédito: "Introduction to Bioreactors: A Scientometric Analysis".

** Ingeniero Mecatrónico, Universidad Nacional de Colombia sede de La Paz, email: vcantillo@unal.edu.co ORCID https://orcid.org/my-orcid?orcid=0000-0003-2589-3741, Cesar-Colombia.
*** Ingeniero Mecatrónico, Universidad Nacional de Colombia sede de La Paz, email: ybarbosa@unal.edu.co ORCID https://orcid.org/0009-0000-3122-9287, Cesar-Colombia.

Resumen

Los biorreactores desempeñan un papel crucial en la producción biotecnológica al influir directamente en la regulación metabólica de los procesos fermentativos. La optimización de parámetros como el pH y la transferencia de oxígeno permite mejorar la eficiencia y el rendimiento de los bioprocesos, lo que resalta la importancia de desarrollar una planificación avanzada en el diseño y la operación de biorreactores para optimizar la síntesis de productos [1]. A lo largo del tiempo, la innovación en el campo de los biorreactores se ha explorado ampliamente, pero no se ha realizado una revisión cronológica exhaustiva. Este artículo busca abordar esa brecha mediante un análisis de la evolución de las tecnologías centradas en biorreactores, utilizando el marco del árbol de la ciencia. Para ello, el estudio se basa en búsquedas sistemáticas en las bases de datos Web of Science y Scopus, a las que se accede a través de las bibliotecas universitarias. Estos hallazgos proporcionan una base para que nuevos investigadores y desarrolladores diseñen sistemas de alto rendimiento con un impacto práctico y significativo, respaldados por información precisa.

Palabras clave: Biorreactor, automatizado, biotecnología, sistemas, bioproceso, monitoreo, optimización, producción, cultivo, fermentación, sólido, diseño, modelado.

1. Introduction

Bioreactors play a crucial role in optimizing biochemical processes, as demonstrated by the study of Oliveira [2], where the bioreactor design significantly affected lipase production in solid-state fermentation, resulting in improvements in yield and control of critical parameters. These systems are designed to optimize microbial growth and facilitate processes such as fermentation or compound synthesis. In this context, the metabolism of certain sugars, such as D-galacturonic acid, represents a key pathway for the generation of value-added products. According to Richard and Hilditch [3], this compound—found in the pectin of agro-industrial waste—can be utilized through bioreactors by means of microbial metabolic pathways for its conversion into biofuels or chemical compounds of biotechnological interest. In its most basic configuration, a bioreactor allows the control of several critical conditions for biological development, such as temperature, pH, agitation, dissolved oxygen, and foam formation. This precise control of environmental parameters facilitates the optimization of biological processes, maximizing production and ensuring the quality of the final product. Within bioreactor design, there are specialized approaches for regulating environmental parameters. For example, in solid-state fermentation processes, the work of Durand [4] has developed laboratory-scale fermenters with precise control of temperature and humidity through thermostated airflow, representing an alternative for cultures that do not require agitation.[5]

In the field of biomedical research, micro and small-scale bioreactors play a crucial role in understanding normal and pathological physiology. To effectively simulate the in vivo cellular niche, it is essential to consider heat and mass transport phenomena, which determine the stability and functionality of cellular systems. According to Teixeira [5] , the analysis of particulate systems in multiphase reactors allows for the optimization of these parameters, facilitating the development of cell cultures under controlled conditions. However, the effective implementation of these systems requires rigorous modeling and scaling studies. In

this regard, Carboué [6] highlights how predicting residence time in plug-flow bioreactors through mathematical models such as PLS regression enables the optimization of solid-state fermentation and the analysis of metabolite production changes at different scales. Given the growing relevance of bioreactors across multiple sectors, it is essential to analyze the evolution of research surrounding this technology. Scientometric studies make it possible to identify trends, key actors, emerging areas, and knowledge gaps, thereby facilitating a comprehensive understanding of the academic and technological development of the topic. Through the analysis of bibliometric indicators and scientific output, patterns can be established regarding international collaboration, thematic evolution, the most influential journals, and the impact of bioreactor-related research.

This article aims to conduct a comprehensive scientometric analysis of the scientific literature related to bioreactors, covering a twenty-year period from 2004 to 2024. To achieve this, internationally recognized databases such as Scopus and Web of Science are used, providing access to a large volume of peer-reviewed scientific publications. This methodological approach facilitates the systematic collection and analysis of bibliographic data, including the number of publications, citations received, collaboration between authors and institutions, as well as the temporal evolution of scientific output in the field of bioreactors. Based on this analysis, the objective is to provide a panoramic and detailed view of the global research dynamics surrounding this technology, identifying emerging trends and shifts in scientific focus over time. In addition, the study seeks to highlight the most productive and influential countries, institutions, and authors in bioreactor research, contributing to a better understanding of the geographical and academic distribution of knowledge in this area.

Likewise, the study reveals the most frequently addressed topics and subtopics, allowing for the identification of priority areas of interest, research gaps, and potential future lines of technological and scientific development. Taken together, this scientometric analysis provides a comprehensive framework for researchers, managers, and decision-makers interested in the advancement and application of bioreactors in various fields, such as biotechnology, energy production, and waste valorization.

2. Methodology

For the development of this scientometric study, a quantitative methodology was employed based on the bibliometric analysis of scientific publications indexed in the Scopus database, which is recognized for its broad international and multidisciplinary coverage [7]. The search was conducted using the keyword “bioreactor” within the Title, Abstract, and Keywords fields, limiting the results to the period between 2004 and 2024, with the aim of capturing the most recent and relevant trends in research on this technology. Table I below presents the number of articles or studies on bioreactors worldwide.

Table I. Search parameter used in both databases.

Parameter	Web of Science	Scopus
Range	2004 – 2024	
Date	January 19, 2024	
Document Type	Paper, book, chapter, conference proceedings	
Words	(TITLE (“bioreactor”) AND TITLE (“fermentation”)) AND PUBYEAR > 2003 AND PUBYEAR < 2026 AND (LIMIT-TO (DOCTYPE , “ar”)) AND (LIMIT-TO (LANGUAGE , “English”))	
Results	327	383
Total (Wos+Scopus)		427

Inclusion criteria were applied, considering only research articles and excluding reviews, editorials, and other types of documents, to ensure a representative sample of high relevance and international visibility. This rigorous selection allowed the analysis to focus on original contributions that provide empirical data and concrete scientific advances in the field of bioreactors. The results obtained were exported in CSV format for further analysis and processing using specialized tools. Additionally, Microsoft Excel was used for basic statistical processing and the creation of charts illustrating annual publication trends, thematic area distribution, and citation-based impact analysis.

This comprehensive methodological approach enabled the identification of scientific production dynamics, emerging topics, and collaboration networks that characterize bioreactor research, thus providing a solid foundation for evaluating the field’s development and making strategic decisions in research and technological development. The combination of quantitative analysis and data visualization facilitated the detection of growth patterns, key actors, and areas with potential for future research, contributing to a better understanding of the global landscape in this discipline.

Figure 1 presents a PRISMA-type flow diagram that illustrates the methodological process followed to conduct the scientometric analysis of the study topic. In the identification phase, a total of 710 scientific records were collected from the Web of Science (n=327) and Scopus (n=383) databases. Subsequently, during the screening phase, 283 duplicate records were removed, resulting in a set of 427 unique entries. These were subjected to a preprocessing stage that included text mining and web scraping techniques, with the aim of organizing the information into an Excel file composed of 22 sheets. Finally, the scientometric analysis was carried out, focusing on three main aspects of scientific production: analysis by country, by journal, and by author. This approach provided a structured and detailed overview of the current state of knowledge in the field of bioreactors.

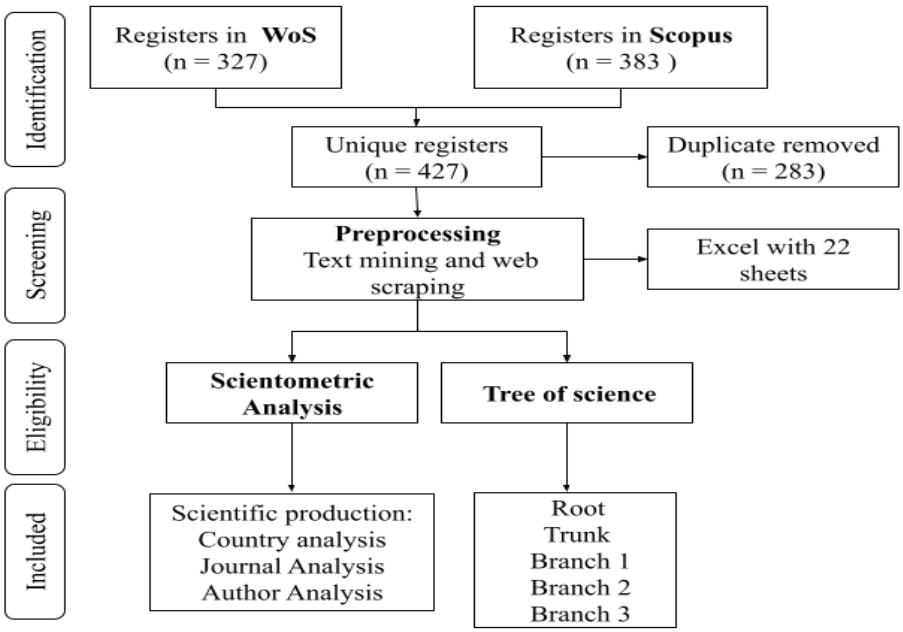

Figure 1. PRISMA Methodology

Regarding the types of documents analyzed, there was a clear predominance of original research articles, which accounted for 94.66% of the total (n = 408). These were followed by conference abstracts or meeting abstracts, representing 1.86% (n = 8). Editorial corrections made up 0.93% (n = 4), while review articles and proceedings papers each represented 0.70% (n = 3). Editorial materials and letters to the editor each accounted for 0.46% (n = 2), and finally, one book chapter was identified, corresponding to 0.23% of the total documents analyzed.

3. Results

Scientometric Analysis

Scientific Annual Production

The analysis of scientific production is a key tool for identifying research trends, technological advancements, and emerging areas within a specific field—in this case, bioreactors applied to cocoa fermentation and other biotechnological uses. This type of analysis makes it possible to understand how scientific knowledge has evolved over time, what topics are priorities for the research community, and what technological innovations are being developed. Furthermore, it helps to detect research gaps and opportunities for new studies, thus contributing to the direction of future research lines and the optimization of resources in scientific and technological projects.

In particular, Figure 2 presents a statistical summary based on data extracted from the Scopus and Web of Science (WoS) databases, two of the most well-known and comprehensive sources for collecting scientific literature. This figure illustrates the evolution in the number of publications and citations related to bioreactors from 2004 to 2024. The data show an average annual growth rate of 6.82% in the number of publications, demonstrating a growing and sustained interest in this area of study.

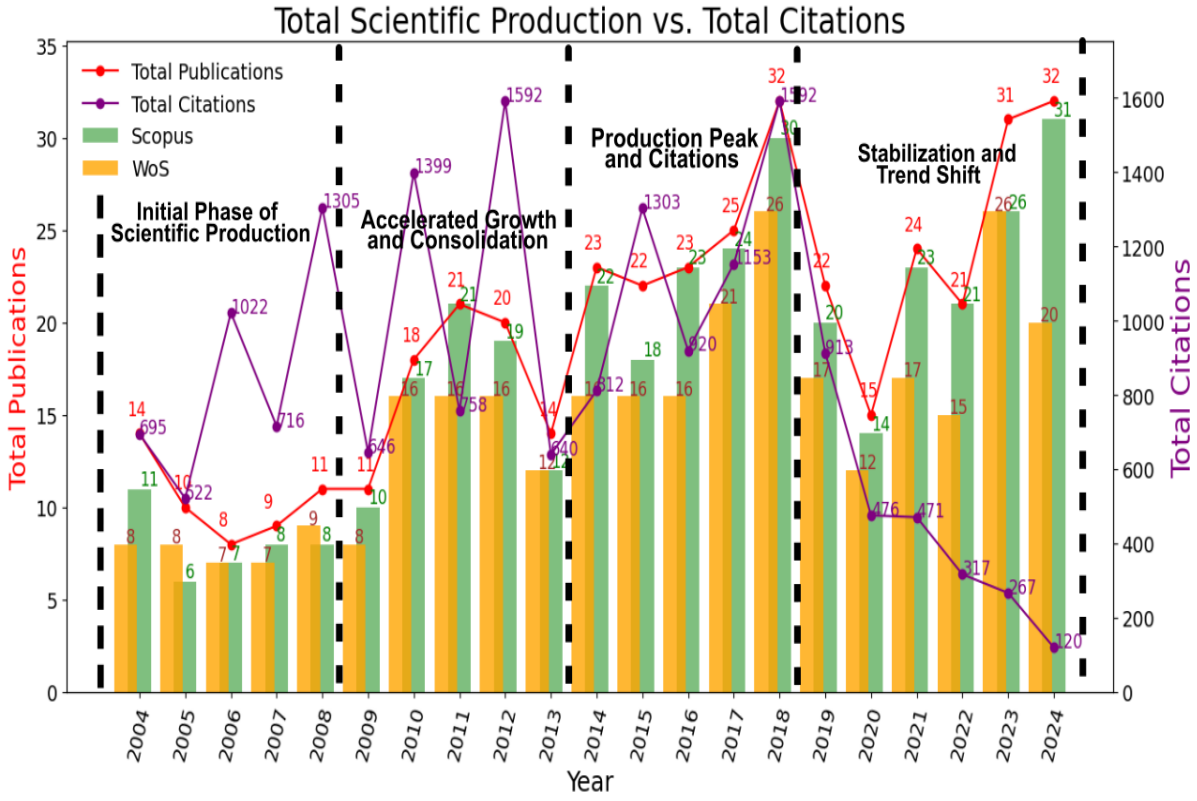

Figure 2. Total scientific output

The increase in citations also indicates that published works are being referenced more frequently, suggesting greater scientific relevance and impact of research on bioreactors. This sustained growth in publications and citations is a clear indicator of the field's consolidation and maturity, as well as its strategic importance for sectors such as biotechnology, agro-industry, sustainable production, and the valorization of agricultural waste [8]. Taken together, these results allow for the visualization of not only the quantitative but also the qualitative progress of research on bioreactors, providing a solid foundation for decision-making in scientific policy, investment in innovation, and technological development.

A more detailed analysis of Figure 2 reveals three distinct periods in the evolution of scientific production.

Period 1 – Initial Phase of Scientific Production (2004–2008):

Characterized by a moderate number of publications and citations, with an initial upward trend in citations. However, there is an observed annual decrease rate of -5.8% in the total number of unique publications—that is, those not duplicated across the databases consulted.

Period 2 – Accelerated Growth and Consolidation (2009–2013):

There was sustained growth in both publications and citations, reflecting academic consolidation. The annual growth rate reached 6.21%, suggesting a temporal trend in the generation of research on the topic.

Period 3 – Peak in Production and Citations (2014–2018):

This phase marks the peak in both publications and citations, with a strong presence in both Scopus and WoS. A significant annual growth rate of 8.61% was recorded, indicating renewed interest and a substantial acceleration in studies related to bioreactors. This growth underscores the current relevance and innovation in this line of research, particularly in applications such as cocoa fermentation and other biotechnological processes.

Period 4 – Stabilization and Shift in Trend (2019–2024):

Publications remained high with continued growth, reaching an annual growth rate of 7.78%. However, citations began to decline, suggesting a possible thematic or strategic shift in the field.

Country Analysis

Table II provides a detailed overview of the scientific production on bioreactors from 10 countries, along with impact metrics (measured in citations) and quality (measured by Scimago quartiles). China tops the list with 73 articles (16.94% of the total) and an impressive 24.15% of citations (2664), demonstrating its leadership in both quantity and impact. It surpasses Brazil, which also has high production but falls below China. However, the last three quartiles show similarities, and Brazil has a notable similarity in production and impact with the USA, although they do not share similar quartile rankings. Bioreactors have gradually gained traction in emerging countries such as India, Iran, and Malaysia due to the need for entrepreneurial development among their populations. The United Kingdom leads in total citation percentage after the fourth position, with 4.32%.

Table II. Scientific Production and Impact by Country

Country	Production		Citation		Quality			
	Count	%	Count	%	Q1	Q2	Q3	Q4
China	73	16.94	2664	24.15	51	15	4	1
Brazil	52	12.06	1301	11.79	28	14	5	0
Usa	26	6.03	1163	10.54	10	8	1	1
India	23	5.34	323	2.93	9	11	0	0
Iran	20	4.64	402	3.64	7	7	4	1
Malaysia	19	4.41	323	2.93	3	7	6	2
Germany	14	3.25	350	3.17	6	6	1	1
Turkey	14	3.25	328	2.97	8	3	2	0
United Kingdom	13	3.02	477	4.32	9	4	0	0
Thailand	12	2.78	94	0.85	7	3	1	0

Source: Self-prepared.

One of the most recent articles from China is by Professor Xiao [9], in which they identify how to produce volatile fatty acids from kitchen waste using an anaerobic bioreactor. On Brazil's side, the most recent article has a stronger focus on agronomy, aiming to produce bioherbicides using the fungus *Trichoderma koningiopsis* in an airlift-type bioreactor [10].The most recent study by an author affiliated with the USA presents an analysis of theoretical and experimental shortcomings in the recovery of phosphorus from swine wastewater treated with anaerobic bioreactors. The study highlights that current approaches do not align with proper chemical principles for the efficient and sustainable recovery of phosphorus [11]. India presents a study on a strategy to implement repeated batch fermentation for the production of second-generation bioethanol, using a xylose-rich hydrolysate obtained from wheat straw and employing the microorganism Scheffersomyces stipitis [12].

Figure 3 illustrates the scientific collaboration network between countries based on the affiliations of co-authors, revealing a clear structuring of thematic communities around the same article. The collaboration network shows a large group led by the United Kingdom. A notable study was conducted by professors Erbas, Allman, and Baganz, affiliated with institutions in the United Kingdom and Switzerland, which focuses on the use of a parallel mini-bioreactor system to accelerate a bacterial growth model. This approach aims to optimize and predict microbial behavior during fermentation, potentially reducing the time required to develop efficient biotechnological processes [13].

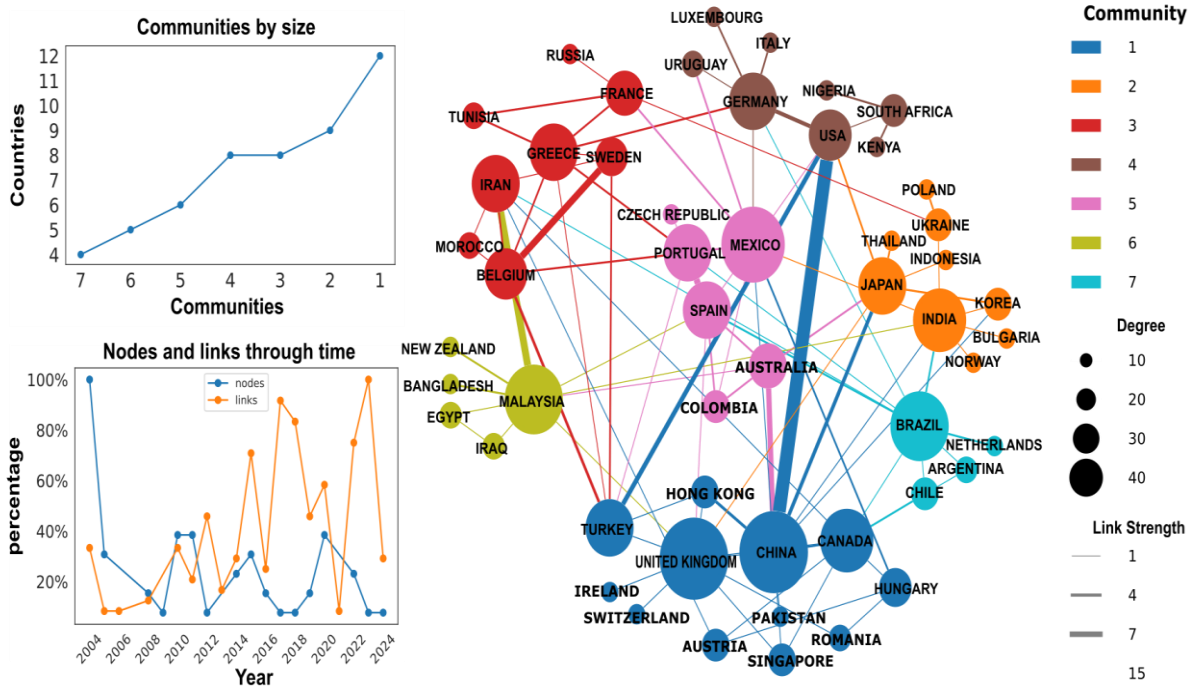

Figura 3. Scientific production by country

A recent study, resulting from a collaboration between Iran and Austria, investigates the production of P3HB (polyhydroxybutyrate), a biodegradable bioplastic, from methane (CH_4) using methanotrophic bacteria. The aim of the study is to develop a sustainable and economically viable fermentation process capable of replacing petroleum-based plastics. To achieve this, the authors analyze various types of bioreactors—such as bubble columns, vertical and horizontal loop reactors, and airlift fermenters—to compare their efficiency in converting methane into P3HB [14]. A collaboration between Brazil and Canada also stands out, presenting a technical review on the construction and operation of a packed-bed bioreactor at pilot scale for enzyme production through solid-state fermentation. The authors share their practical experience in the bioreactor's design and highlight the challenges they faced when scaling up from laboratory systems to a pilot scale [15].

Journal Analysis

Table III presents the analysis of the 10 most relevant scientific journals publishing research on bioreactors, considering aspects such as the total number of articles indexed in WoS and Scopus, the SJR index, the H-Index, and quartile ranking. Bioresource Technology stands out as the leading journal, with 38 articles, a high SJR index (2.395), and the highest H-Index (383), indicating its prestige and impact in the field. The most cited article from this journal is the work by academic researchers Lu et al; [16]. An innovative process is carried out to produce n-butanol, a promising biofuel, from cassava bagasse—the fibrous residue left after starch extraction. A fed-batch fermentation system is used with a fibrous-bed bioreactor and a continuous gas-stripping technique to recover butanol during its production. One of its most

recent articles presents a detailed study on the fermentation of the yeast Yarrowia lipolytica using crude glycerol, a byproduct of the biodiesel industry, as a carbon source. The objective was to optimize the production of biomass and lipids (microbial oils) through different fermentation modes, including an innovative process using a membrane bioreactor (MBR) [17]. The Biochemical Engineering Journal ranks second in the database. One of its recent articles presents the development and evaluation of a novel membrane bioreactor for the production of polyhydroxybutyrate (PHB), a biodegradable bioplastic, using the bacterium Cupriavidus necator. The main focus was to compare batch and fed-batch fermentation strategies to maximize biomass and PHB production [18]. Therefore, Table III reflects the maturity of the topic of bioreactors and their various applications, as it is featured in high-quality journals.

Table III. Scientific Production and Impact by Country

Journal	SN	Wos	Scopus	Total	SJR	H-INDEX	Quartile
Bioresource Technology	09608524	34	36	38	2.395	383	Q1
Biochemical Engineering Journal	1369703X	23	28	30	0.772	150	Q2
Bioprocess And Biosystems Engineering	16157591	12	17	17	0.660	88	Q2
Fermentation	23115637	0	14	14			
Applied Biochemistry and Biotechnology	02732289	11	8	11	0.659	141	Q2
Journal of Chemical Technology and Biotechnology	02682575	5	11	11	0.587	142	Q2
Chemical Engineering Journal	13858947	8	8	9	2.696	337	Q1
Process Biochemistry	13595113	7	7	9	0.694	188	Q2
Biotechnology and Bioengineering	00063592	7	8	8	0.940	219	Q2
International Journal of Hydrogen Energy	03603199	6	7	7	1.685	285	Q1

Figure 4 presents the citation network among scientific journals, highlighting three main clusters. The first cluster includes journals focused on studies related to bioreactor engineering and fermentation using different methods [19]; [20]. The second group of journals, which includes Bioresource Technology—the journal with the highest number of publications—focuses on topics related to food biotechnology and industrial biotechnology, incorporating smart technologies for bioreactors [21]; [22]. The third group provides theoretical foundations for the development of efficient bioreactors [23]; [24]. The "nodes and links through time" figure shows that the proportion of links compared to nodes (journals) has increased in recent years. This indicates that research on bioreactors and their

applications has evolved into a consolidated research area supported by international journals.

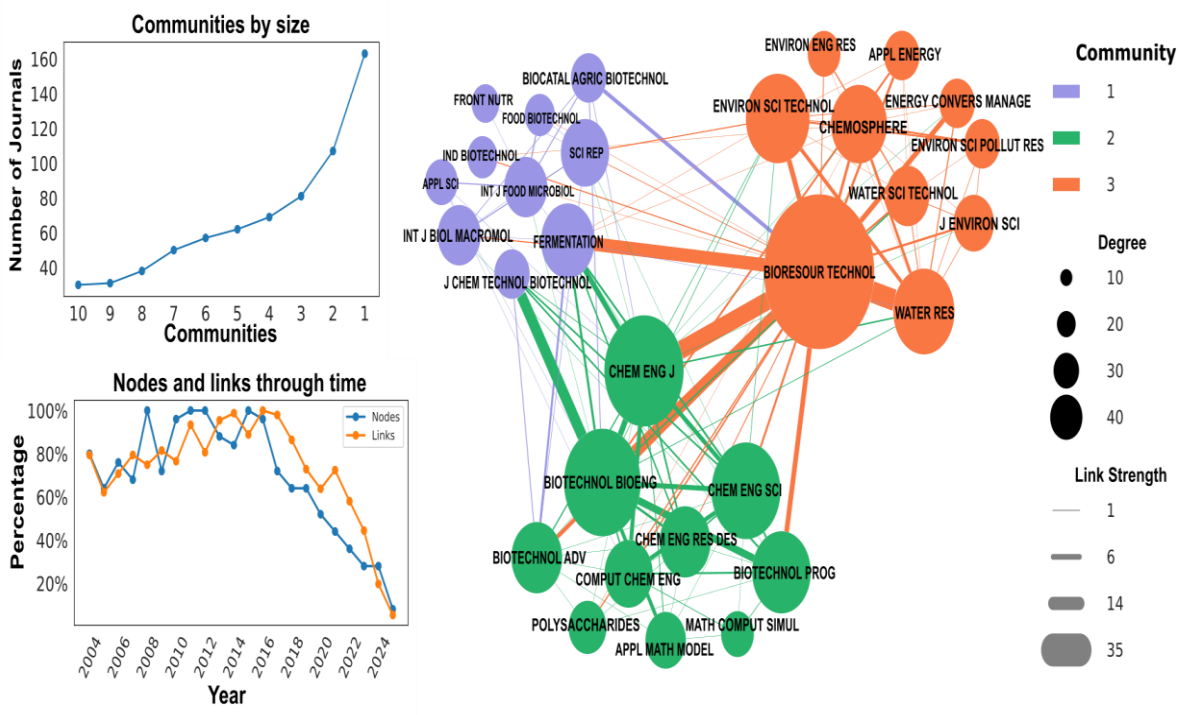

Figura 4. Journal analysis

Author Analysis

Table IV presents an analysis of the most relevant authors in scientific production on bioreactors, considering bibliometric and network indicators such as the total number of publications, citations, H-Index, effective size, constraint, and CDI (Collaborative Diversity Index). MITCHELL [25], stands out with the highest H-Index (11) and the greatest number of citations (413), reflecting his academic influence in the field. Although several authors have 8 publications, there are notable differences in impact: for example, LI X has accumulated 725 citations, whereas LAOPAIBOON L and P have only 49. In terms of network metrics, ZHANG has the highest effective size (197.53) [26], This indicates a high level of connectivity in his collaborations, while KRIEGER also stands out with a high effective size (120.7). Meanwhile, authors such as CHEN and LI X show low constraint (0.04), suggesting access to diverse networks and facilitating collaborations with multiple groups. The CDI index reveals that NAJAFPOUR (0.21) and LAOPAIBOON (0.18) demonstrate notable collaborative diversity. Overall, the table highlights not only the most productive authors but also those with the greatest influence, diversity, and connectivity within the scientific network of this field.

Table IV. Authors

Author	Papers Total	Total Citations	H-Index	Effective_Size	Constraint	CDI
Xiao Z	12	337	8	33.15	0.09	0.11
Chen C	11	372	8	84.26	0.04	0.11
Mitchell D	11	413	11	56.97	0.06	0.17
Zhang Y	10	281	6	197.53	0.02	0.1
Finkler A	8	273	8	13.3	0.18	0.13
Laopaiboon L	8	49	5	30.31	0.14	0.18
Laopaiboon P	8	49	5	30.2	0.14	0.17
Li X	8	725	8	92.39	0.04	0.13
Najafpour G	8	292	7	30.18	0.11	0.21
Krieger N	7	315	7	120.7	0.04	0.14

Figure 5 shows the scientific collaboration network among the authors listed in Table IV. This network is constructed from their personal networks, or egonetworks. The collaboration network reveals three groups. The first group displays high cohesion and includes the leading researchers. For example, researchers Zhang and Li [27] ccollaborated on a study evaluating the performance of a pilot-scale anaerobic membrane bioreactor (AnMBR) for treating pharmaceutical wastewater containing m-cresol (MC) and isopropanol (IPA). The second group (sapote color) consists of several researchers, including Finkler and Mitchell [28]; [29] who have made significant contributions to the study of mathematical models for scaling up bioreactors. Najafpour [30], meanwhile, has worked independently on research aimed at transforming agro-industrial residues—specifically orange peel—into pectinases, key enzymes in the food industry, through solid-state fermentation (SSF).

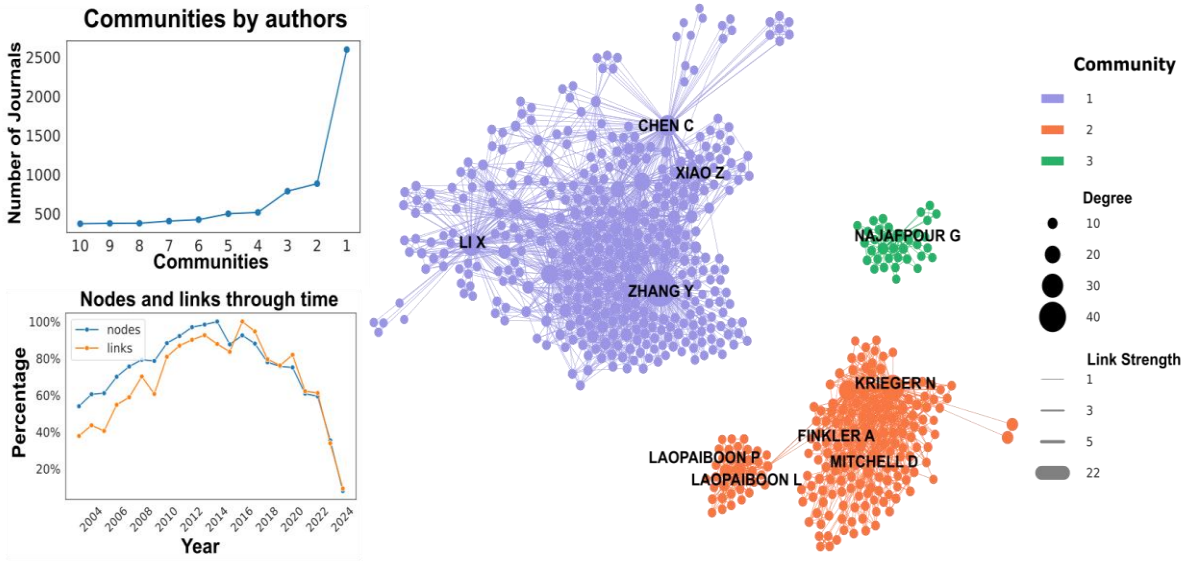

Figura 5. Author Community Analysis

Tree of science

Root

At the roots of the network lie the foundational articles on bioreactors. The first is the work developed by Pandey [31],which emphasizes solid-state fermentation (SSF), highlighting its significant potential in industrial and environmental applications. Alongside the development of bioreactors and mathematical models, another key article explores the principles and recent advances in the design and optimization of solid-state fermentation (SSF) bioreactors. It focuses on critical aspects such as mass and heat transfer, bioreactor design, process scale-up, and the control of operational variables [32]. Meanwhile, the study on the fundamentals of heat and mass transfer in solid-state fermentation bioreactors focuses on the challenges and solutions for optimizing critical processes involved in the industrial-scale production of enzymes, biochemicals, and bioproducts[33].

On the other hand, Rodríguez and Sanromán [34] analyzed the impact of solid-state fermentation (SSF) on the production of compounds of interest for the food industry, highlighting its efficiency compared to submerged fermentation. In a more recent study, an advanced mathematical model is proposed for simulating heat and water transfer in a packed-bed bioreactor (PBB) used in SSF. The proposed model serves as a powerful tool for improving the design and efficiency of solid-state fermentation bioreactors, helping to prevent substrate overheating and drying [35].

Trunk

This is one of the core articles that supports this topic, addressing the mathematical modeling and computational simulation of heat and mass transfer in a solid-state fermentation (SSF) bioreactor. SSF is a promising method for the production of biotechnological products due to its high volumetric productivity and low operational costs. The authors conducted a parametric analysis to better understand the physical dynamics of the system, testing variations in airflow, medium porosity, and the thermal conductivity of solids. The results demonstrated that simulation can serve as a foundation for the design and optimization of operational strategies in large-scale SSF bioreactors. One of the most important articles from the trunk was the scientometric review focused on the efficient and cost-effective production of lipases for biodiesel synthesis. Instead of conventional submerged fermentation (SmF) methods, the authors explored solid-state fermentation (SSF), using a culture medium based on wheat bran and sugarcane bagasse, supplemented only with urea [36].

On the other hand, the article on intermittent agitation contributing to bed uniformity during pectinase production by Aspergillus niger cultivated in solid-state fermentation (SSF) in a pilot-scale packed-bed bioreactor explores how intermittent agitation in SSF improves the uniformity of pectinase production [37]. This part of the tree also includes contributions with a more specialized focus; for example, Doriya & Kumar [38] Their study demonstrates that an internally designed rotary bioreactor can match the efficiency of the traditional method, while offering advantages in heat transfer and mixing.

Branch 1 - Solid State Fermentation

The first identified trend is related to bioreactor engineering within the context of the circular economy, focusing on the production of bioactive compounds through solid-state fermentation (SSF). This technique stands out for its ability to valorize agro-industrial waste by transforming it into high-value-added products in a sustainable manner [39]. In the same line, another study delves into the optimization of solid-state fermentation (SSF) by analyzing the impact of transport phenomena in process modeling, using a tubular packed-bed bioreactor with wall cooling. This research focuses on the growth of Yarrowia lipolytica 2.2ab and the production of proteases, also using agro-industrial residues as substrate [40]. Meanwhile, this study analyzes the production of a fungal aspartic protease through solid-state fermentation (SSF) in a rotating drum bioreactor. The research focuses on the use of the filamentous fungus Mucor racemosus cultivated on different solid media, with emphasis on the effects of aeration, moisture, and agitation on enzyme production [41].

In a broader context of bioreactors applied to the circular economy, Jafari and Hejazi [42].The production of PHB (a biodegradable biopolymer) was investigated in a packed-bed bioreactor, revealing that optimizing aeration significantly improved process performance. Although this study is not directly framed within SSF (solid-state fermentation), it demonstrates how bioreactor design and parameter control remain critical factors in maximizing efficiency and sustainability across different types of bioprocesses

Another study relevant to the optimization of bioreactors and the scaling-up of biotechnological processes explores the potential of packed-bed bioreactors in solid-state fermentation (SSF), focusing on the production of Beauveria bassiana conidia. The authors present scale-up experiments, analyzing how variables such as aeration, moisture content, and bed porosity affect the efficiency of the process [43].

With a focus on more traditional practices, a study was conducted to explore the use of artisanal bioreactors for controlled fermentation in the production of specialty coffees. Variables such as Brix, temperature, pH, electrical conductivity, and total dissolved solids were evaluated, demonstrating that the bioreactor enables consistent and reproducible processes, ensuring uniformity in the final quality of the coffee [44].

Branch 2 - Fermentation hydrogen production

In this branch, the main theme revolves around fermentation in bioreactors, bioenergy production, and the generation of valuable compounds. The first reviewed article analyzes the production of volatile fatty acids (VFAs) through acidogenic fermentation in anaerobic membrane bioreactors (AnMBRs), using kitchen waste as a substrate. The study evaluated two pH conditions (5 and 6) to determine their effect on process efficiency, alkali consumption, and system stability [9].

Another study, in turn, focuses on hydrogen (H_2) production through dark fermentation in a packed-bed bioreactor, followed by the conversion of the gas into electricity using a proton exchange membrane fuel cell (PEMFC) [45]. In the same thematic line, a subsequent study evaluates the impact of oxidation-reduction potential (ORP) on the dark fermentation of food waste for hydrogen production. It demonstrates that regulating the initial ORP can significantly improve yield by promoting desirable metabolic pathways and minimizing the formation of unwanted byproducts [46].Complementing this perspective, another study proposes the development and evaluation of a composite tubular bioreactor designed for hydrogen production through photo-fermentation under outdoor conditions. Batch and continuous operation modes are compared, using glucose as the substrate and assessing their efficiency [47].

Additionally, the study examines how high salinity and pH adjustment affect both process efficiency and microbial composition in alkaline fermentation systems. The study concludes that AnMBRs (Anaerobic Membrane Bioreactors) represent a viable alternative for the production of VFAs (volatile fatty acids) from organic waste, with applications in wastewater treatment and the generation of bioproducts [48].

Finally, another relevant approach within this topic is the use of bioreactors for sulfate reduction. A study suggests that the addition of fermentable substrates can enhance this process, reducing costs and optimizing the remediation of water contaminated by mining activities. The authors analyze the interaction between fermentative microorganisms and sulfate-reducing microorganisms (SRM), highlighting the role of hydrogen production as a key intermediate [49].

Branch 3 - Fermentation

This trend is particularly directed toward fermentation, offering a broad approach within the context of bioreactors, considering the relevance of this process. For instance, the study analyzing bioethanol production through fed-batch fermentation of cassava in a membrane bioreactor by pervaporation with fractional condensation of the permeate presents an innovation in bioreactor design. It enhances ethanol separation and recovery, reduces product inhibition, and optimizes energy efficiency [50]. In contrast, the study of new technologies for butyric acid fermentation using cellulosic biomass, a rapid bioreactor, and efficient product recovery offers innovations in the fermentation process of butyric acid through advanced bioreactor technologies. This is particularly relevant for the design and optimization of bioprocesses [51] . On the other hand, this study addresses the enhanced production of rhamnolipids (RLs) through fermentation in a membrane bioreactor using a novel strain of Pseudomonas aeruginosa BC1. The research explored how pervaporation technology can boost production by in situ removal of volatile organic compounds that inhibit cell growth. The results validate the use of membrane bioreactors as an effective strategy to improve biosurfactant production, with applications in environmental remediation and enhanced oil recovery [52].

From the perspective of bioethanol production from cellulosic fiber waste through fermentation in bioreactors, this approach presents a strategy to convert industrial waste into an alternative energy source. It involves a combination of physical, chemical, and enzymatic treatments to maximize the release of fermentable glucose. The study demonstrated that fermentation in bioreactors can significantly enhance bioethanol production, offering a viable alternative for the utilization of cellulosic waste [53].

Finally, the study analyzing repeated-batch fermentation in a fibrous-bed bioreactor (FBB) using Clostridium beijerinckii NCIMB 8052 for the production of acetone-butanol-ethanol (ABE) is highlighted. The research focused on optimizing the productivity and stability of the process by comparing fermentation with immobilized cells in the FBB against free cells in a conventional bioreactor. The study demonstrated that cell immobilization in fibrous-bed bioreactors enhances both stability and productivity in repeated fermentations, showing strong potential for industrial scale-up in the production of biofuels and solvents [54].

Conclusions

This scientometric analysis on bioreactors provides a comprehensive and methodical overview of the evolution of scientific production in this field over the last two decades, from 2004 to 2024. The results show a sustained growth both in the volume of publications and in their impact, indicating thematic consolidation and increasing interest from the scientific community. This growth has been particularly significant between 2009 and 2018, a period marked by an acceleration in knowledge generation and a considerable increase in citations received.

From a geographical perspective, countries such as China, Brazil, and the United States lead scientific production in this field, standing out not only for the number of publications but also for the high volume of articles published in top-quartile journals (Q1), confirming their influence in the development of the field. The international collaboration network, represented graphically, illustrates how science related to bioreactors has formed interconnected communities, with China emerging as a central node in terms of global cooperation.

Meanwhile, the analysis of scientific journals shows that there are specialized publications that serve as pillars of the field, with Bioresource Technology and Chemical Engineering Journal being the most influential due to their high SJR and H-Index scores. These journals not only lead in terms of publication volume, but also in impact, as they concentrate a significant portion of citations and address the most relevant topics in bioprocesses, sustainability, and applied biotechnology.

Regarding the author analysis, prominent researchers such as Xiao Z, Chen C, and Mitchell D were identified, whose scientific output and connectivity within co-authorship networks position them as central figures in the research landscape of bioreactors. These networks reveal highly cohesive communities, some with strong international collaborations and others with more local or institutional connections.

On the other hand, the "Tree of Science" section confirmed the direct impact that bioreactors have on various disciplines focused on research and production. This is evident in the structure of the tree, where the development, modeling, and scaling of bioreactors are shown to improve processes in many ways—whether in the area of waste utilization or in the production of new products—primarily by focusing their application on the fermentation stage. Over the years, studies have been dedicated to implementing or enhancing bioreactors, highlighting through scientific evidence the importance of continued research and the development of new technologies. These advances enable the scientific community to optimize processes in multiple fields, including biotechnology, agro-industry, renewable energy, and the production of food and/or industrial products.

In general, this study not only provides an understanding of the evolution and current state of research on bioreactors, but also offers a solid foundation for strategic decision-making in research, development, and innovation. Additionally, it identifies thematic gaps, regional strengths, and emerging trends that can guide future research in various fields. The scientometric tool used proves its usefulness in mapping knowledge, evaluating scientific impact, and visualizing collaborative dynamics within a multifaceted area that is constantly expanding, such as biotechnology applied to bioreactors.

References

[1]P. Çalik, E. Bilir, G. Çalik, and T. H. Özdamar, "Bioreactor operation parameters as tools for metabolic regulations in fermentation processes: influence of pH conditions," Chem. Eng. Sci., vol. 58, no. 3–6, pp. 759–766, Feb. 2003.

[2]F. Oliveira, J. M. Salgado, N. Pérez-Rodríguez, J. M. Domínguez, A. Venâncio, and I. Belo, "Lipase production by solid-state fermentation of olive pomace in tray-type and pressurized bioreactors," J. Chem. Technol. Biotechnol., vol. 93, no. 5, pp. 1312–1319, May 2018.

[3]P. Richard and S. Hilditch, "D-galacturonic acid catabolism in microorganisms and its biotechnological relevance," Appl Microbiol Biotechnol, vol. 82, no. 4, pp. 597–604, Mar. 2009.

[4]A. Durand, D. de la Broise, and H. Blachère, "Laboratory scale bioreactor for solid state processes," J. Biotechnol., vol. 8, no. 1, pp. 59–66, May 1988.

[5]J. Teixeira Freire, A. Maria da Silveira, and M. do Carmo Ferreira, Eds., Transport Phenomena In Particulate Systems. BENTHAM SCIENCE PUBLISHERS, 2012.

[6]Q. Carboué, C. Rébufa, N. Dupuy, S. Roussos, and I. Bombarda, "Solid state fermentation pilot-scaled plug flow bioreactor, using partial least square regression to predict the residence time in a semicontinuous process," Biochem. Eng. J., vol. 149, no. 107248, p. 107248, Sep. 2019.

[7]J. Pandey, S. Majumdarr, R. Farooq, S. Gupta, and P. Bose, "Knowledge sharing in the era of Covid-19: a bibliometric analysis using scopus and web-of-science (WoS)," Glob. Knowl. Mem. Commun., Oct. 2023, doi: 10.1108/gkmc-02-2023-0051. Available: https://www.emerald.com/insight/content/doi/10.1108/GKMC-02-2023-0051/full/html

[8]T. Robinson and P. Nigam, "Bioreactor design for protein enrichment of agricultural residues by solid state fermentation," Biochem. Eng. J., vol. 13, no. 2–3, pp. 197–203, Mar. 2003.

[9]X. Xiao, Z. Shan, T. Pan, Z. Huang, and W. Ruan, "Characteristics of volatile fatty acids production and microbial succession under acid fermentation via anaerobic membrane bioreactor treating kitchen waste slurry," Bioresour Technol, vol. 429, p. 132502, Aug. 2025.

[10]A. F. Camargo et al., "Trichoderma koningiopsis fermentation in airlift bioreactor for bioherbicide production," Bioprocess Biosyst Eng, vol. 47, no. 5, pp. 651–663, May 2024.

[11]A. P. Mathews, "Discussion of 'Recovery of high-quality calcium phosphate fertilizer products from anaerobic fermentation bioreactor treated swine wastewater', published by Kannan et al. (2023)," Chem. Eng. J., vol. 496, no. 153989, p. 153989, Sep. 2024.

[12]P. Singh, U. Kiran, and S. Ghosh, "Repeated batch fermentation of xylose-rich hydrolysate obtained from wheat straw in a bioreactor to produce second-generation bioethanol," Fuel (Lond.), vol. 387, no. 134383, p. 134383, May 2025.

[13]A. Erbas, T. Allman, and F. Baganz, "Bacterial growth modeling for rapid fermentation process development using a parallel mini-bioreactor system," N. Biotechnol., vol. 31, p. S124, Jul. 2014.

[14]P. Safaeian, F. Yazdian, K. Khosravi-Darani, H. Rashedi, and M. Lackner, "P3HB from CH using methanotrophs: aspects of bioreactor, fermentation process and modelling for cost-effective biopolymer production," Front Bioeng Biotechnol, vol. 11, p. 1137749, Jun. 2023.

[15]D. A. Mitchell, L. O. Pitol, A. Biz, A. T. J. Finkler, L. F. de Lima Luz Jr, and N. Krieger, "Design and Operation of a Pilot-Scale Packed-Bed Bioreactor for the Production of Enzymes by Solid-State Fermentation," Adv Biochem Eng Biotechnol, vol. 169, pp. 27–50, 2019.

[16]C. Lu, J. Zhao, S.-T. Yang, and D. Wei, "Fed-batch fermentation for n-butanol production from cassava bagasse hydrolysate in a fibrous bed bioreactor with continuous gas stripping," Bioresour Technol, vol. 104, pp. 380–387, Jan. 2012.

[17]A. Tsirigka, A. Aggeli, E. Theodosiou, A. M. Makris, A. J. Karabelas, and S. I. Patsios, "Model-based study of Yarrowia lipolytica cultivation on crude glycerol under different fermentation modes: Development of a membrane bioreactor process," Bioresour Technol, vol. 417, p. 131773, Feb. 2025.

[18]B. Akkoyunlu, S. Daly, E. Syron, and E. Casey, "Fermentation strategies for PHB production in a novel membrane bioreactor: Investigating batch and fed-batch operations," Biochem. Eng. J., vol. 204, no. 109239, p. 109239, Apr. 2024.

[19]M. Moresi, "Design and operation of a multifunctional pilot-scale bioreactor for enhanced aerobic fermentation," Fermentation, vol. 11, no. 2, p. 101, Feb. 2025.

[20]A. Barrios-Nolasco, C. O. Castillo-Araiza, S. Huerta-Ochoa, M. I. Reyes-Arreozola, J. J. Buenrostro-Figueroa, and L. A. Prado-Barragán, "Evaluating the performance of Yarrowia lipolytica 2.2ab in solid-State Fermentation under bench-scale conditions in a packed-tray bioreactor," Fermentation, vol. 10, no. 7, p. 344, Jun. 2024.

[21]M. G. Hajaya and T. Shaqarin, "Multivariable advanced nonlinear controller for bioethanol production in a non-isothermal fermentation bioreactor," Bioresour Technol, vol. 348, p. 126810, Mar. 2022.

[22]C. Yay, Z. O. Cinar, S. Donmez, T. B. Tumer, O. Guneser, and M. I. Hosoglu, "Optimizing bioreactor conditions for Spirulina fermentation by Lactobacillus helveticus and Kluyveromyces marxianus: Impact on chemical & bioactive properties," Bioresour Technol, vol. 403, p. 130832, Jul. 2024.

[23]M. Matsumoto, "In situ Extractive Fermentation of Lactic Acid by Rhizopus oryzae in an Air-lift Bioreactor," Chem. Biochem. Eng. Q., vol. 32, no. 2, pp. 275–280, Jul. 2018.

[24]Q. Chi, W. Zhang, Z. Fei, and J. Liang, "A two-level measurement-based dynamic optimization strategy for a bioreactor in penicillin fermentation process," Chin. J. Chem. Eng., vol. 23, no. 1, pp. 112–120, Jan. 2015.

[25]D. A. Mitchell, A. Pandey, P. Sangsurasak, and N. Krieger, "Scale-up strategies for packed-bed bioreactors for solid-state fermentation," Process Biochem., vol. 35, no. 1–2, pp. 167–178, Oct. 1999.

[26]X. Zhang, H. Zhang, C. Ye, M. Wei, and J. Du, "Effect of COD/N ratio on nitrogen removal and microbial communities of CANON process in membrane bioreactors," Bioresour Technol, vol. 189, pp. 302–308, Aug. 2015.

[27]Z. Chen et al., "Performance and methane fermentation characteristics of a pilot scale anaerobic membrane bioreactor (AnMBR) for treating pharmaceutical wastewater containing m-cresol (MC) and iso-propyl alcohol (IPA)," Chemosphere, vol. 206, pp. 750–758, Sep. 2018.

[28]A. T. J. Finkler, L. F. de Lima Luz Jr, N. Krieger, D. A. Mitchell, and L. M. Jorge, "A model-based strategy for scaling-up traditional packed-bed bioreactors for solid-state fermentation based on measurement of O2 uptake rates," Biochem. Eng. J., vol. 166, no. 107854, p. 107854, Feb. 2021.

[29]A. T. J. Finkler et al., "Estimation of heat and mass transfer coefficients in a pilot packed-bed solid-state fermentation bioreactor," Chem. Eng. J., vol. 408, no. 127246, p. 127246, Mar. 2021.

[30]M. Mahmoodi, G. D. Najafpour, and M. Mohammadi, "Bioconversion of agroindustrial wastes to pectinases enzyme via solid state fermentation in trays and rotating drum bioreactors," Biocatal. Agric. Biotechnol., vol. 21, no. 101280, p. 101280, Sep. 2019.

[31]A. Pandey, "Solid-state fermentation," Biochem. Eng. J., vol. 13, no. 2–3, pp. 81–84, Mar. 2003.

[32]K. S. M. S. Raghavarao, T. V. Ranganathan, and N. G. Karanth, "Some engineering aspects of solid-state fermentation," Biochem. Eng. J., vol. 13, no. 2–3, pp. 127–135, Mar. 2003.

[33]D. A. Mitchell, M. Berovič, O. F. von Meien, and L. F. L. Luz Jr, "Basics of heat and mass transfer in solid-state fermentation bioreactors," in Solid-State Fermentation Bioreactors, Berlin, Heidelberg: Springer Berlin Heidelberg, 2006, pp. 45–56.

[34]S. R. Couto and M. Á. Sanromán, "Application of solid-state fermentation to food industry—A review," J. Food Eng., vol. 76, no. 3, pp. 291–302, Oct. 2006.

[35]F. P. Casciatori, A. Bück, J. C. Thoméo, and E. Tsotsas, "Two-phase and two-dimensional model describing heat and water transfer during solid-state fermentation within a packed-bed bioreactor," Chem. Eng. J., vol. 287, pp. 103–116, Mar. 2016.

[36]L. O. Pitol et al., "Optimization studies to develop a low-cost medium for production of the lipases of Rhizopus microsporus by solid-state fermentation and scale-up of the process to a pilot packed-bed bioreactor," Process Biochem., vol. 62, pp. 37–47, Nov. 2017.

[37]A. T. J. Finkler et al., "Intermittent agitation contributes to uniformity across the bed during pectinase production by Aspergillus niger grown in solid-state fermentation in a pilot-scale packed-bed bioreactor," Biochem. Eng. J., vol. 121, pp. 1–12, May 2017.

[38]K. Doriya and D. S. Kumar, "Solid state fermentation of mixed substrate for l-asparaginase production using tray and in-house designed rotary bioreactor," Biochem. Eng. J., vol. 138, pp. 188–196, Oct. 2018.

[39]G. A. Gómez-Ramos et al., "Bioreactor engineering for circular economy: Bioactive compound production in solid-state fermentation—review," Chem. Eng. Technol., vol. 48, no. 1, Jan. 2025, doi: 10.1002/ceat.202400289. Available: https://onlinelibrary.wiley.com/doi/10.1002/ceat.202400289

[40]M. Couder-García, L. A. Prado-Barragán, S. Huerta-Ochoa, and C. O. Castillo-Araiza, "Assessing the impact of transport phenomena on modeling and optimization of solid-state fermentation for the revalorization of Agro-industrial residues in a wall-cooled packed-bed bioreactor," Chem. Eng. Res. Des., vol. 210, pp. 365–381, Oct. 2024.

[41]F. Qasim, S. Diercks-Horn, L.-M. Herlevi, and H. M. Fernandez-Lahore, "Production of a fungal aspartic protease via solid-state fermentation using a rotating drum bioreactor," J. Chem. Technol. Biotechnol., vol. 100, no. 1, pp. 273–285, Jan. 2025.

[42]M. S. Jafari and P. Hejazi, "Poly(3-hydroxybutyrate) production using supplemented corn-processing byproducts through Cupriavidus necator via solid-state fermentation: Cultivation on flask and bioreactor scale," J Biotechnol, vol. 392, pp. 1–10, Sep. 2024.

[43]A. Sala, A. Artola, R. Barrena, and A. Sánchez, "Harnessing packed-bed bioreactors' potential in solid-state fermentation: The case of Beauveria bassiana conidia production," Fermentation, vol. 10, no. 9, p. 481, Sep. 2024.

[44]E. I. M. Reyes, M. A. B. González, J. O. C. Balcazar, and J. S. Velasco, "Controlled fermentation in artisanal bioreactors to produce specialty coffees," Ciênc. Agrotecnologia, vol. 48, 2024, doi: 10.1590/1413-7054202448007524. Available: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1413-70542024000100221&tlng=en

[45]L. E. Vanegas, L. A. Hurtado, K. L. Fuentes, M. A. Escobar, and T. R. Chaparro, "Wastewater treatment and energy generation for dark fermentation bioreactor: preliminary results," Int. J. Environ. Sci. Technol. (Tehran), vol. 22, no. 10, pp. 8719–8730, Jun. 2025.

[46]A.-R. Fleitas García, J.-S. Guez, C. G. Dussap, P. Fontanille, and G. Christophe, "Effect of redox potential on biohydrogen production during dark fermentation of food wastes in bioreactor," Int. J. Hydrogen Energy, Feb. 2025, doi: 10.1016/j.ijhydene.2025.02.089. Available: https://linkinghub.elsevier.com/retrieve/pii/S0360319925006548

[47]C. Ren et al., "Pilot composite tubular bioreactor for outdoor photo-fermentation hydrogen production: From batch to continuous operation," Bioresour Technol, vol. 401, p. 130705, Jun. 2024.

[48]X. Xiao et al., "Volatile fatty acids production from kitchen waste slurry using anaerobic membrane bioreactor via alkaline fermentation with high salinity: Evaluation on process performance and microbial succession," Bioresour Technol, vol. 399, p. 130576, May 2024.

[49]T. Hessler, S. T. L. Harrison, J. F. Banfield, and R. J. Huddy, "Harnessing Fermentation May Enhance the Performance of Biological Sulfate-Reducing Bioreactors," Environ Sci Technol, vol. 58, no. 6, pp. 2830–2846, Feb. 2024.

[50]H. Jiang et al., "Bioethanol production from cassava fed-batch fermentation in pervaporation membrane bioreactor with permeate fractional condensation," Sep. Purif. Technol., vol. 354, no. 128807, p. 128807, Feb. 2025.

[51]N. Qureshi, R. D. Ashby, N. N. Nichols, and R. Hector, "Novel technologies for butyric acid fermentation: Use of cellulosic biomass, rapid bioreactor, and efficient product recovery," Fermentation, vol. 10, no. 3, p. 142, Mar. 2024.

[52]Y. Zhang et al., "Enhanced fermentation for rhamnolipid production in a membrane bioreactor with a new strain Pseudomonas aeruginosa BC1," Ind. Eng. Chem. Res., Jul. 2023, doi: 10.1021/acs.iecr.3c01475. Available: https://pubs.acs.org/doi/10.1021/acs.iecr.3c01475

[53]A. E. Mansy, E. El-Desouky, H. El-Gendi, M. A. Abu-Saied, T. H. Taha, and R. A. Amer, "Cellulosic fiber waste feedstock for bioethanol production via bioreactor-dependent fermentation," Fermentation, vol. 9, no. 2, p. 176, Feb. 2023.

[54]J. Liu, Z. Liu, and T. Guo, "Repeated-batch fermentation by immobilization of Clostridium beijerinckii NCIMB 8052 in a fibrous bed bioreactor for ABE (acetone-butanol-ethanol) production," J. Renew. Sustain. Energy, vol. 10, no. 1, p. 013101, Jan. 2018.