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Trends in the use of Fermentation to Improve the Quality of cocoa Production: a Scientometric Analysis*

Tendencias en el uso de la fermentación para mejorar la calidad de producción del cacao: Un análisis cienciométrico.

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Abstract

Cocoa (*Theobroma cacao*) is the essential raw material for the production of chocolate and its derivatives. Cocoa is a crop of significant economic value with a considerable impact on the economic, social, environmental, and cultural aspects of the regions where it is produced. Currently, there is growing interest among producers in new cocoa fermentation techniques due to their potential to optimize processing and enhance the utilization of *Theobroma cacao*, including improvements in quality and attributes such as aroma and flavor. Although scientific advances in biotechnology and microbiology have driven the development of more efficient fermentation methods, their application in producing communities remains limited due to a lack of dissemination and access to this knowledge. This review aims to identify the main research contributions and advancements in fermentation, assessing their relevance through a scientometric analysis, to bridge the gap between research and its practical implementation.

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Keywords: Fermentation, Theobroma cacao, Scientometrics, quality production.

Resumen

El cacao (*Theobroma cacao*) es la materia prima indispensable para la producción de chocolates y derivados. El cacao es un cultivo de gran valor económico con un gran impacto en la economía, social, ambiental y cultural para los territorios en donde se produce. Actualmente, el interés por nuevas técnicas de fermentación del cacao ha crecido entre los productores debido a su potencial para optimizar la transformación y mejorar el aprovechamiento del *Theobroma cacao* incluyendo la calidad y atributos como aroma y sabor. Aunque los avances científicos en biotecnología y microbiología han impulsado el desarrollo de métodos de fermentación más eficientes, su aplicación en las comunidades productoras sigue siendo limitada por la falta de divulgación y acceso a estos conocimientos. Esta revisión tiene como propósito identificar los principales aportes en investigación en el área los principales avances en fermentación, evaluando su relevancia mediante un análisis cienciométrico con el fin de cerrar la brecha entre la investigación y su implementación práctica.

Palabras clave: Fermentación, *Theobroma cacao*, cienciometría, calidad de producción

1. Introduction

During the first quarter of 2024, Colombia exported approximately 93.08% of its raw cocoa bean production, generating export revenues of 51.79 million USD. Major destination countries included Mexico, the United States, Ecuador, Venezuela, and Belgium. In addition, new markets such as Indonesia, Estonia, India, Brazil, and South Korea joined the list of buyers.Research on cocoa production techniques has expanded significantly over the past decades, impacting multiple fields—particularly food production. Cocoa cultivation has been driven by the adoption of new technologies, techniques, tools, and methods essential for improving product quality. This growth has also been fueled by high global market demand. The increasing international recognition of Colombian cocoa, particularly due to its desirable characteristics such as aroma and smoothness, has contributed to its export success [1], [2]

This study examines the progress made in cocoa fermentation research, highlighting major research trends, key authors, influential articles, and the countries and journals that have made significant contributions. Two separate searches were conducted in Scopus and Web of Science (WoS), and the resulting datasets were merged to provide a broader perspective, as these are the two most widely recognized indexed databases [3].The remainder of the article is structured as follows: a methodology section detailing the article search and selection process; a results section presenting analyses of scientific production, contributing countries, journals, and authors; and a final section outlining the main conclusions.

2. Methodology

This research was conducted through an exhaustive review of two major scientific databases: WoS and Scopus, to obtain a comprehensive overview of the scientific output related to fermentation techniques in cocoa production. To this end, publications containing the keyword "cocoa" in the title were identified, and the search was further expanded to include articles with the term "fermentation" appearing in the title, abstract, or keywords, using the search operator TITLE-ABS-KEY in Scopus. After applying these search criteria, a total of 458 results were obtained from WoS and 254 from Scopus, yielding a combined total of 613 relevant publications. Additionally, document types were filtered according to the scope of this study: in WoS, the selected types were Article, Review Article, Advance Access, Correction, and Meeting Summary, while in Scopus, Article and Conference Paper were included (Table I)

Table I. Search parameter used in SCOPUS and Web Of Science databases.

Parameter	Web of Science	Scopus
Range	2000-2025	2003-2022
Date	April, 22, 2025	April, 24,2025
Document Type	Article, Review article Advance access, correction, Meeting summary	Article, Conference paper
Words	Theobroma cacao AND fermentation	(TITLE (cacao) AND TITLE-ABS-KEY (fermentation)) AND PUBYEAR > 2003 AND PUBYEAR < 2026
Results	458	254
Total (Wos+Scopus)	613	

This article aims to examine the relationship between scientific research and the practical application of cocoa fermentation techniques, with an emphasis on the transfer of biotechnological advances to production environments (see Figure 1) [4], [5], [6]. The study focuses on identifying the most relevant scientific contributions in this field through an exhaustive literature review. To this end, scientific publications were collected and analyzed using a specific search equation, detailed in Table I, in order to identify the main trends and contributions in the area. Merging both datasets is a complex process and unique in the scientometric field [7], [8], [9].

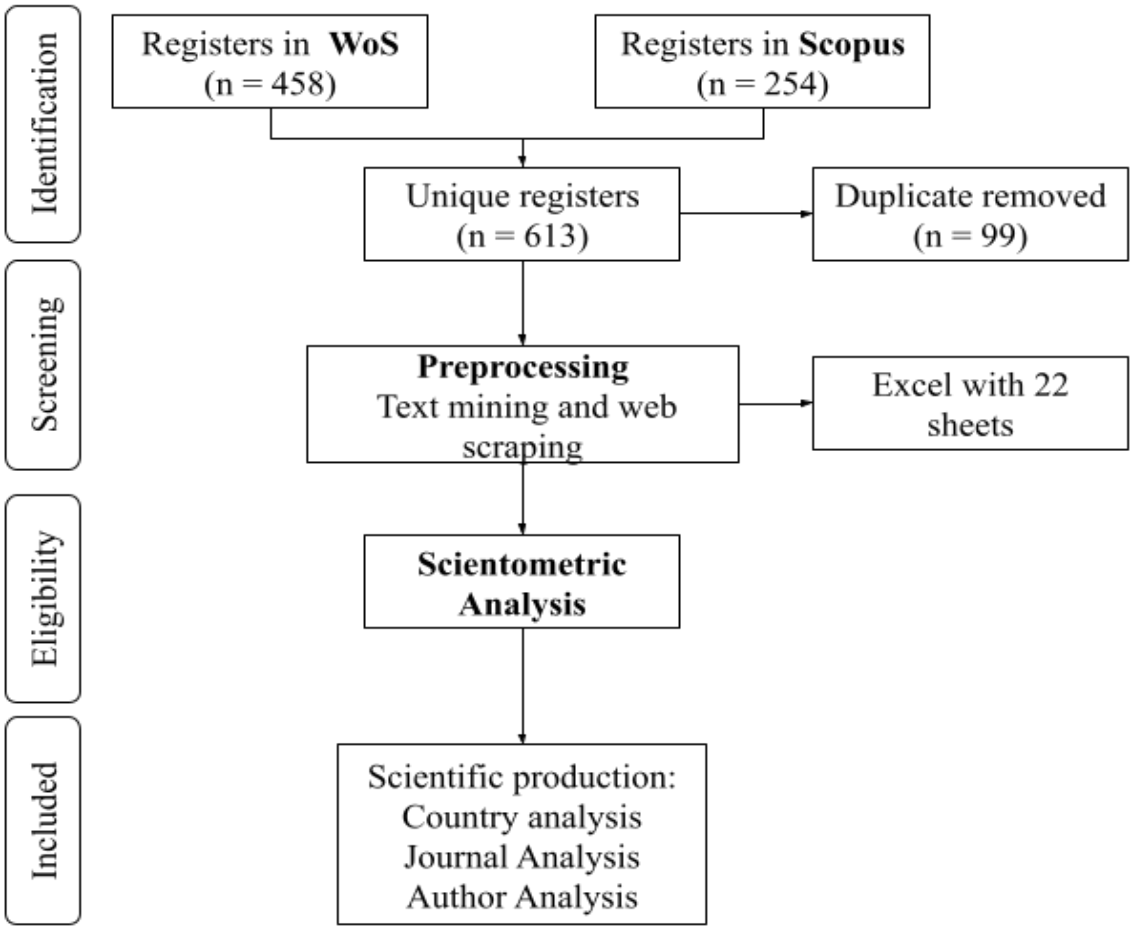

Figure 1. Data Processing Flowchart

3. Results

Scientific Annual Production

Figure 2 presents the results of scientific production over the past 20 years (2004–2024) related to the use of fermentation to enhance the quality of *Theobroma cacao* production. The findings reveal a progressive increase in the number of publications. Citation trends, however, display an unstable pattern, with noticeable peaks during the first 16 years, particularly in 2016, 2018, and 2019, followed by a declining trend in more recent years.

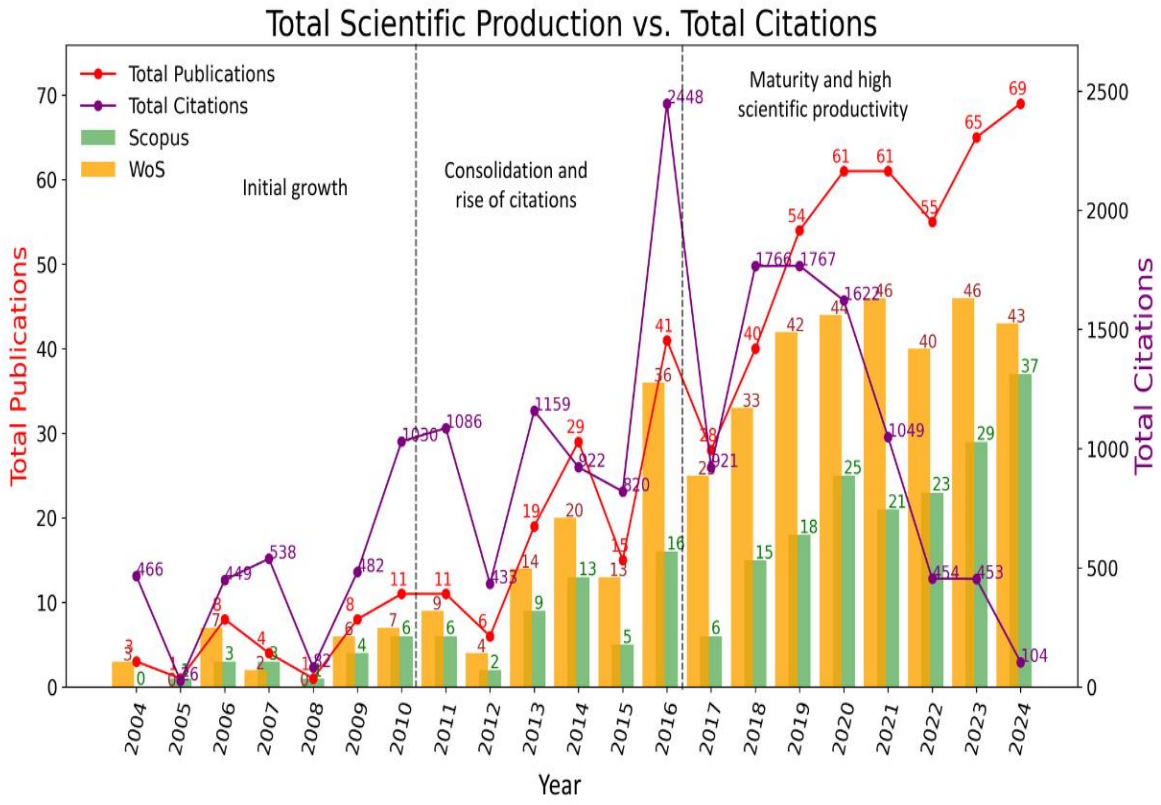

Figure 2. Annual Trends in Scientific Production and Citations in Scopus and WoS (2004-2024): *Focus on Theobroma cacao* and fermentation.

Period 1. Initial Growth (2004–2010)

This period spans from 2004 to 2010, during which 36 articles were published, representing 6.1% of the total output. During these years, scientific production was modest but steady, showing an upward trend in publications starting in 2008. The most cited article from this period is [10], which explains how cocoa fermentation—driven by microorganisms—is essential for the development of chocolate flavor and aroma precursors.

Another relevant work is [11], a review that provides scientific evidence on the health benefits of cocoa, particularly due to its bioactive compounds such as flavanols, which exhibit protective effects on the cardiovascular and neurological systems. This study contributed to transforming popular beliefs into scientifically grounded claims.

Taken together, this stage laid the groundwork for subsequent growth, marking the beginning of the academic recognition of cocoa as a subject of rigorous scientific research.

Period 2. Consolidation and Citation surge (2011–2016)

Between 2011 and 2016, there was a sustained increase in both the number of publications and academic impact, as evidenced by the rise in citations. Over this six-year period, more than 100 articles were published, and in 2016 the highest peak in total citations wa
s recorded (2,448), indicating a moment of high visibility and consolidation within the field. The most cited article during this period was [12], which addresses the multiple genetic, agronomic, environmental, and microbiological factors that influence the flavor profile of cocoa beans. This work synthesizes key knowledge for improving the sensory quality of the final product and has been widely referenced due to its relevance to both industry and academic research.

This growth may be linked to increased attention to the functional benefits of cocoa, growing interest in its bioactive compounds, and its potential in areas such as nutrition, pharmacology, and public health. Moreover, this period saw a diversification of research topics, expanding the interdisciplinary scope of studies in the field.

Period 3. Maturity and High Scientific Productivity (2017–2024)

From 2017 to 2024, the phase of highest scientific productivity solidified. Annual production consistently surpassed 40 articles, peaking in 2023 with 69 publications. However, in contrast to the high production, annual citations tend to stabilize or even slightly decrease when compared to the peak seen in 2016.

The most cited article during this period was Parapouli et al. [13], which highlights the central role of this yeast not only in traditional processes like alcoholic fermentation but also in emerging applications in biotechnology and the production of compounds of interest for the food, pharmaceutical, and energy industries. Its inclusion within the cocoa research corpus reflects the growing importance of understanding and leveraging the role of microorganisms in the production chain.
This period reflects the maturity of the research, where the focus is no longer just on discovery but also on deepening, refining practical applications, and addressing new questions from a well-established scientific base.

It is evident that the total scientific production (red line) shifted from very low levels in the first 5 years to significantly higher figures in the last decades, with a peak in 2024 reaching 69 publications, reflecting a consolidation in research efforts. The periods between 2019 and 2024 are particularly noteworthy, as they show stable and high publication figures.

In contrast, total citations (purple line) show an irregular trend. In 2016, a notable peak was reached with 2,448 citations, suggesting high-impact works were produced. However, by 2017, a sharp decrease occurred, followed by some recovery in years like 2019 (1,767 citations). The trend in recent years is negative, with citations dropping to just 104 in 2024. This decline suggests a disconnect between the number of publications and their impact, which could be influenced by various factors such as article quality, the topics addressed, or the visibility of the publications.

Databases such as WoS (yellow bar) and Scopus (green bar) show complementary patterns. WoS has reported a higher number of publications compared to Scopus, particularly since 2016. For example, WoS recorded 46 publications in 2021, compared to 21 in Scopus. However, it is important to note that both databases show an increasing trend in scientific production. Overall, the analysis presents a mixed picture: on the one hand, there is solid growth in scientific publications, both overall and in indexed databases; on the other hand, there is a decline in the number of citations in recent years, which poses a challenge to improving the impact and visibility of research. This gap between productivity and citation may lead to the need for dissemination strategies to enhance the impact within the scientific community.

Country Analysis

Figure 3 illustrates the global scientific collaboration network surrounding research on *Theobroma cacao*, where each node represents a country, and its size indicates the number of collaborations. The thickness of the links reflects the intensity of these interactions. The overall structure reveals both highly connected hubs, such as the United States, France, and China, as well as peripheral or closed networks with limited connections.

A representative case of a closed network is the collaboration between Bangladesh and Malaysia, where both countries appear as nodes with reduced connectivity. The study by [1] exemplifies this dynamic by evaluating the effect of superheated steam roasting on cacao beans. Their research proposes an efficient alternative to conventional roasting, achieving optimized flavor compound formation without oxidation and in a shorter processing time.

On the other hand, the most active countries in scientific collaboration in this field, based on co-authorship data, are France, Belgium, Ecuador, Brazil, and Germany. The colors assigned to the nodes in the network allow the identification of scientific communities—that is, groups of countries that tend to collaborate more frequently with one another. Within this context, Colombia's participation in international scientific networks stands out. The country has

established collaborative ties with nations such as France, Austria, Nicaragua, and Costa Rica, reinforcing its integration into both regional and global research communities.

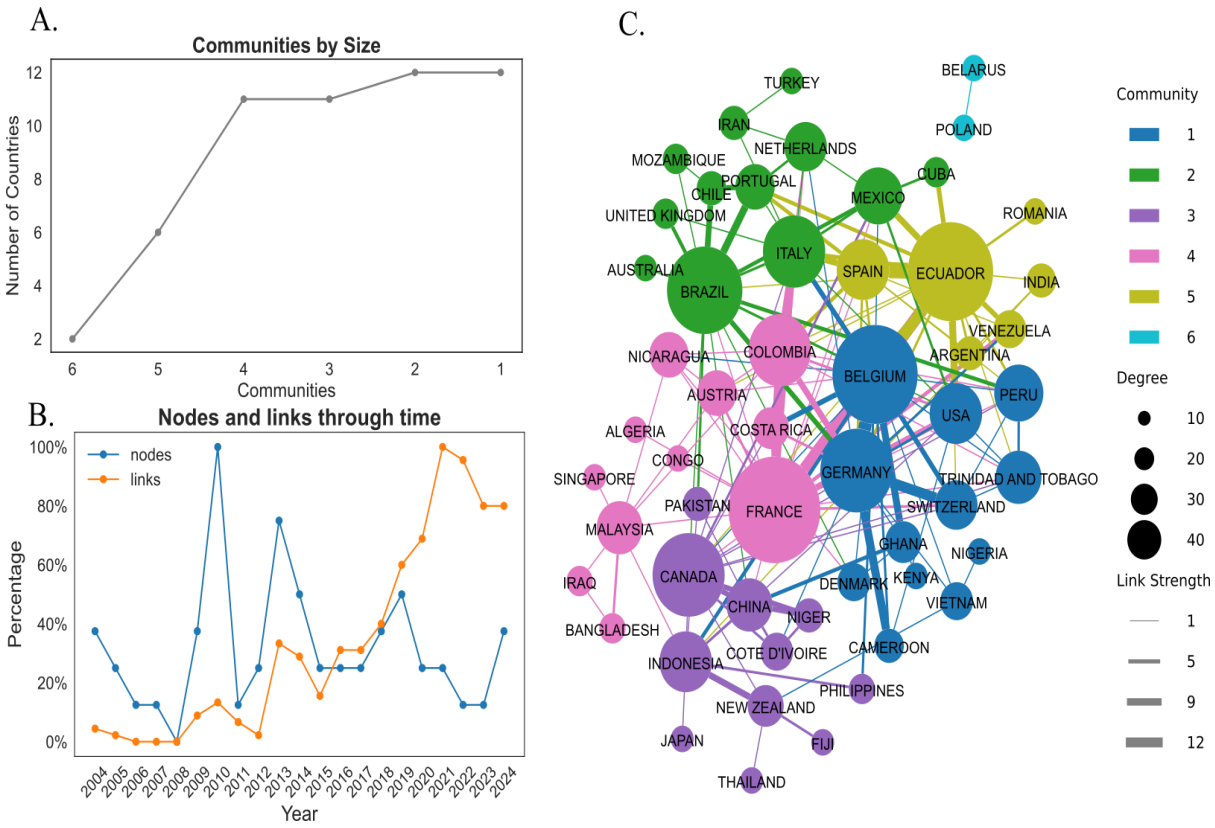

Figure 3. Global Network of Scientific Research Collaboration Between Countries in Journal Analysis

Joint research efforts between Belgium and Brazil, led by Pinto et al. [14], demonstrated that vis/NIR spectroscopy can be used to authenticate cacao beans based on their genotype and fermentation status, thereby enhancing quality control and traceability.

In parallel, researchers affiliated with Germany and Belgium conducted kinetic characterization of changes in low-molecular-weight carbohydrates during spontaneous fermentation, providing key mechanistic insights [15]. Meanwhile, John et al. [16] experimentally modeled fermentation under controlled conditions, revealing how variables such as temperature, acidity, and fermentation time influence the production of peptides, flavanols, and pH, thus strengthening our understanding of the biochemical dynamics of cacao beans.

France has led significant research efforts on cacao in collaboration with countries such as Ecuador, the United States, Brazil, and Germany. Colonges et al. [17], in partnership with institutions from Ecuador and the U.S., identified the genetic and biochemical determinants of aroma in ancestral cacao varieties from the Ecuadorian Amazon. Their study employed

sensory analysis, gas chromatography–mass spectrometry (GC-MS), and genome-wide association studies (GWAS). In another study, a collaboration between Brazil, Germany, and France proposed a cacao quality index that integrates multiple chemical, sensory, and nutritional variables, with the aim of enhancing the evaluation of cacao beans across the entire value chain [18].

The most recent collaboration between France, Italy, and Colombia was led by Santander et al. [19], who analyzed how drying technologies influence the formation of key flavor compounds in cacao, emphasizing their role in the sensory quality of the final product. In 2021, Colombia collaborated with Italy and Spain in a study [20] that assessed the functional potential of cacao husks as a source of bioactive compounds. More recently, a collaboration between Colombia, Germany, and the United States explored the concept of "microbial terroir", demonstrating that microbiomes associated with different parts of the plant can influence cacao chemistry—as well as that of other crops—opening new perspectives for agricultural valorization through microbial ecology [21].

In subgraph Figure 3b, titled *Nodes and Links through Time*, it is observed that during 2008–2010, there was a significant increase in the number of links, indicating a notable expansion in international scientific collaborations. This period marks a turning point in the consolidation of the global research network. Later, between 2020 and 2022, although the number of participating countries did not increase substantially, the intensity of connections grew, suggesting greater frequency or continuity in scientific cooperation among already established partners.

The analysis of scientific production related to the use of fermentation to improve cacao quality focused on 10 countries, as shown in Table II, taking into account publication output, impact, and article quality. For this purpose, the number of citations and the quartile classification of the journals according to the Scimago Journal and Country Rank were considered.

Table II. Breakdown of scientific production and citations by country, including quartile distribution of articles in ranked journals

Country	Production		Citation		Quality			
	Count	%	Count	%	Q1	Q2	Q3	Q4
Brazil	102	13.25	3508	17.5	53	16	5	0
Germany	68	8.83	1620	8.08	52	4	10	0
Indonesia	55	7.14	361	1.8	12	5	10	7
Belgium	50	6.49	2194	10.95	45	3	0	0
Ecuador	46	5.97	343	1.71	22	2	5	5
Colombia	45	5.84	693	3.46	28	2	4	3
Italy	43	5.58	1544	7.7	39	2	0	0
France	31	4.03	680	3.39	23	2	1	3
México	31	4.03	687	3.43	17	2	4	1
Usa	29	3.77	879	4.39	19	4	1	0

The results show that Brazil tops the list, leading with 102 publications, representing 13.25% of the total, and accounting for 17.5% of citations, indicating a substantial research output coupled with strong scholarly recognition. Moreover, over 50% of its articles are classified in Q1 journals, highlighting a high level of editorial quality.

In second place is Germany, with 68 publications, showing a balance between productivity and quality, with 52 articles in Q1. However, its citation impact stands at 8.08%, suggesting a more limited reception of its research. On the other hand, Belgium, despite having 50 publications, registers a citation rate of 10.95%, which is higher than that of Germany.

Additionally, it shows a high-impact orientation, with 45 Q1 articles. Italy also demonstrates a moderately high citation percentage (7.7%), despite a lower output of 43 articles, indicating a relatively strong research impact.

It is important to highlight that high research output does not necessarily equate to high impact, as illustrated by the case of Indonesia, which, despite producing 55 articles, shows the lowest citation proportion among the countries analyzed. Overall, Table II reveals that scientific output should not be assessed solely by the number of publications, but also by their visibility and impact within the academic community.

Journal Analysis

Table III presents the ten journals with the highest academic output related to fermentation in Theobroma cacao. It is observed that the majority of these journals fall within Quartile 1 (Q1), indicating publications with the highest impact factor, citation count, and prestige within their respective fields. Only two journals are classified within Quartiles 3 and 4 (Q3 and Q4). This reinforces the notion that research on cocoa and fermentation tends to be of high impact and scientific relevance, as it is predominantly concentrated in internationally recognized journals.

Table III. High-Impact Journals in AI and DE: Country, h-index, and Quartile Metrics

Journal	ISSN	Wos	Scopus	Total	SJR	Quartil	H-Index
Food Research International	9639969	48	14	51	**1.698**	Q1	231
Food Chemistry	3088146	38	6	41	**1.952**	Q1	348
Foods	23048158	16	4	18	**1.021**	Q1	123
Journal Of Agricultural And Food Chemistry	218561	17	4	18	**1.215**	Q1	358
Journal Of The Science Of Food And Agriculture	225142	13	6	15	**0.798**	Q1	187
Heliyon	24058440	8	6	13	**0.644**	Q1	115
International Journal Of Food Microbiology	1681605	11	0	11	**1.163**	Q1	227
Journal Of Applied Botany And Food Quality	1439040X	11	7	11	**0.210**	Q3	48
Revista De La Facultad De Agronomía	3787818	0	10	10	**0.130**	Q4	10
Molecules	14203049	9	0	9	**0.865**	Q1	261

Food Research International is a specialized journal focused on the areas of food science and technology. It holds the highest number of publications on cocoa and fermentation, with a total of 51 articles, a high SCImago Journal Rank (SJR) of 1.698, and an H-Index of 231. Among its most recent publications, researchers explored metabolic perspectives on the dynamics of flavor precursors during the fermentation of cocoa beans cultivated in various climatic regions of Colombia. The study found that fermentation time is the primary factor influencing the metabolomic profile of cocoa beans, identifying an optimal duration that maximizes aroma precursor concentration, with minimal influence from climate zones compared to fermentation time itself [22].

In a similar line of inquiry, the journal has also published studies investigating the use of cocoa husk as a by-product and fermentation time in the production of kombucha, based on microbiological and genetic characterization [23].
Food Chemistry ranks second with a total of 41 publications and the highest recorded SJR (1.952), indicating that it is cited more frequently by other high-impact journals. In third place is *Foods*, a peer-reviewed, open-access journal focused on food science. Overall, the aforementioned journals are globally recognized references in the field and are classified under JCR - Q1 in the category of *Food Science and Technology*.

Among the recent articles published by the *Journal of Agricultural and Food Chemistry*, one study evaluated changes in the composition of methylxanthines (a class of central nervous system stimulants), polyphenols, volatile compounds, and sensory profiles in *Theobroma cacao* beans of the SUL 1 genotype, affected by prolonged fermentation for 10 days. The

results showed that 10-day fermentation of SUL 1 beans led to significant changes in their chemical composition and sensory attributes. The fermentation index (FI) increased over time, reaching level 1, which corresponds to a sufficient fermentation period to develop the desired characteristics. After 72 hours, an optimal fermentation balance was achieved that allowed the retention of beneficial polyphenols while delivering a favorable flavor profile [24].

Hii et al. [25] published an article in the *Journal of the Science of Food and Agriculture*, aiming to improve the quality of cacao beans in Malaysia through the use of a heat pump dryer, applying constant-air drying profiles and comparing them to hot-air drying. The study found that cacao samples subjected to a progressive drying profile exhibited higher quality than commercial samples. It concluded that heat pump drying resulted in significant improvements in bean quality, acidity, and browning degree, particularly in beans dried under gradual drying conditions.

For the Journal Analysis, the H-index was considered as a general metric of scientific output and citation impact. According to the search conducted, the most influential journal is the *Journal of Agricultural and Food Chemistry*, with an H-index of 358, suggesting that at least 358 of its articles have each been cited at least 358 times. Despite this high impact, the journal has published only 18 articles related to fermentation and *Theobroma cacao*. In second place is *Food Chemistry*, with an H-index of 348 and a total of 41 relevant publications. From the results presented in Table III, we can also identify journals with relatively lower impact within the field, yet still classified in Q1, such as *Molecules* and the *International Journal of Food Microbiology*.

Figure 4 displays the three main communities, publications, and journals. The graph consists of links indicating co-citation, defined as the frequency with which two documents are cited together within the analyzed scientific articles. “Link strength” and “degree” indicate the magnitude of connections between communities and the frequency of their interrelations [26]. The graph reveals three large thematic communities, with Community 1 being the largest and most interconnected.

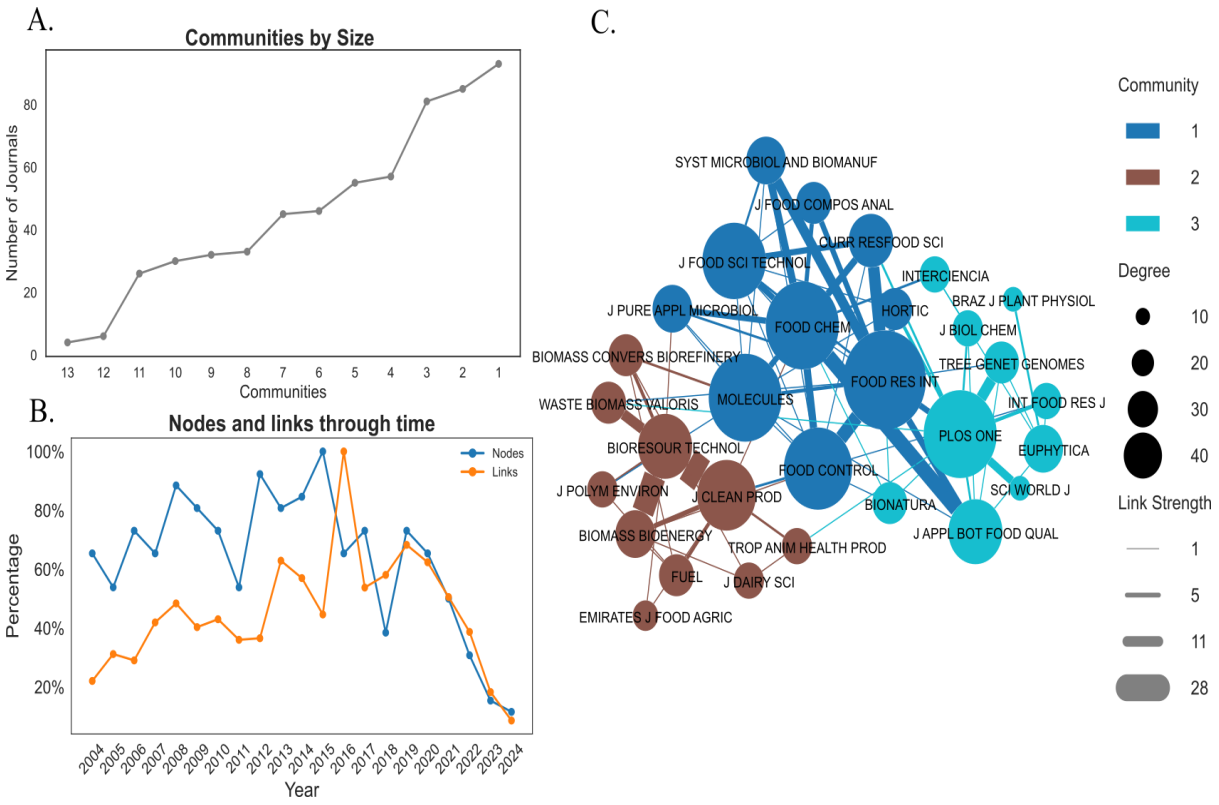

Figure 4. Network of Journal Citations Highlighting Collaborative Communities.

Co-citation networks allow the identification of thematic convergence among journals with different disciplinary focuses. A low level of connection between communities is observed, alongside larger intra-community structures, suggesting a consolidation of research with thematic convergence. Additionally, within each community, there is evidence of the consolidation of new research foci, particularly those related to traditional cacao production compared with new fermentation methods [27].

The network highlights central journals such as Molecules, Food Research International, Food Chemistry, and PLOS ONE, which exhibit significant degrees of connection with others, including the Journal of Applied Botany and Food Quality.

Author Analysis

Table IV presents the ten most productive authors in research on Theobroma cacao, considering not only the number of publications but also their scientific impact and the roles they play within the academic collaboration network. In terms of the number of publications, Boulanger R ranks first with 23 articles, followed by Schwan R with 20, and Kuhnert N and Lieberei R with 15 articles each. However, it is Schwan who stands out with the highest number of citations (1,656), followed by Afoakwa E (692) and Dewettinck K (682), suggesting that despite not leading in the number of publications, their impact within the scientific community is significant.

Table IV. Author Productivity and Institutional Affiliations

Author	Papers Total	Total Citations	H-Index	Effective Size	Constraint	CDI
Boulanger R	23	415	12	142.21	0.03	0.08
Schwan R	20	1656	16	114.29	0.03	0.13
Kuhnert N	15	495	12	55.03	0.06	0.13
Lieberei R	15	463	10	75.05	0.05	0.14
Ullrich M	14	445	11	17.08	0.15	0.1
Dewettinck K	13	682	10	129.21	0.03	0.08
D'souza R	12	434	10	14.83	0.16	0.1
Pereira G	12	636	10	131.54	0.03	0.07
Afoakwa E	10	692	8	31.15	0.09	0.09
Caligiani A	10	472	9	36.57	0.09	0.16

The H-index evaluates both the productivity and the scientific impact of an author's research. Schwan, Boulanger, and Kuhnert exhibit the highest values (16, 12, and 12, respectively), underscoring their relevance within the field. On the other hand, the Effective Size measures the diversity of connections within collaboration networks. Authors such as Boulanger, Schwan, Dewettinck, and Pereira attain the highest scores, indicating their involvement in less redundant and more varied networks, which facilitate access to diverse knowledge and create greater opportunities for generating innovative research.

The constraint values (0.03, 0.05, 0.06, 0.15, and 0.16) reflect varying levels of structural constraint within the network. The lower values (0.03, 0.05, and 0.06) suggest that these authors have minimal redundancy in their connections, enabling them to bridge different groups and thus promote diverse collaborations and information exchange. In contrast, those with higher values (0.15–0.16) are embedded in denser networks, where their contacts are highly interconnected, thereby limiting their brokerage capacity.

Figure 5 illustrates the scientific collaboration network among the most productive researchers. The network depicted in the figure is divided into three groups or components, where each node represents an author, and the links between them indicate joint publications. Node size corresponds to the number of publications, while the density of the links reflects the intensity and frequency of collaboration among peers.

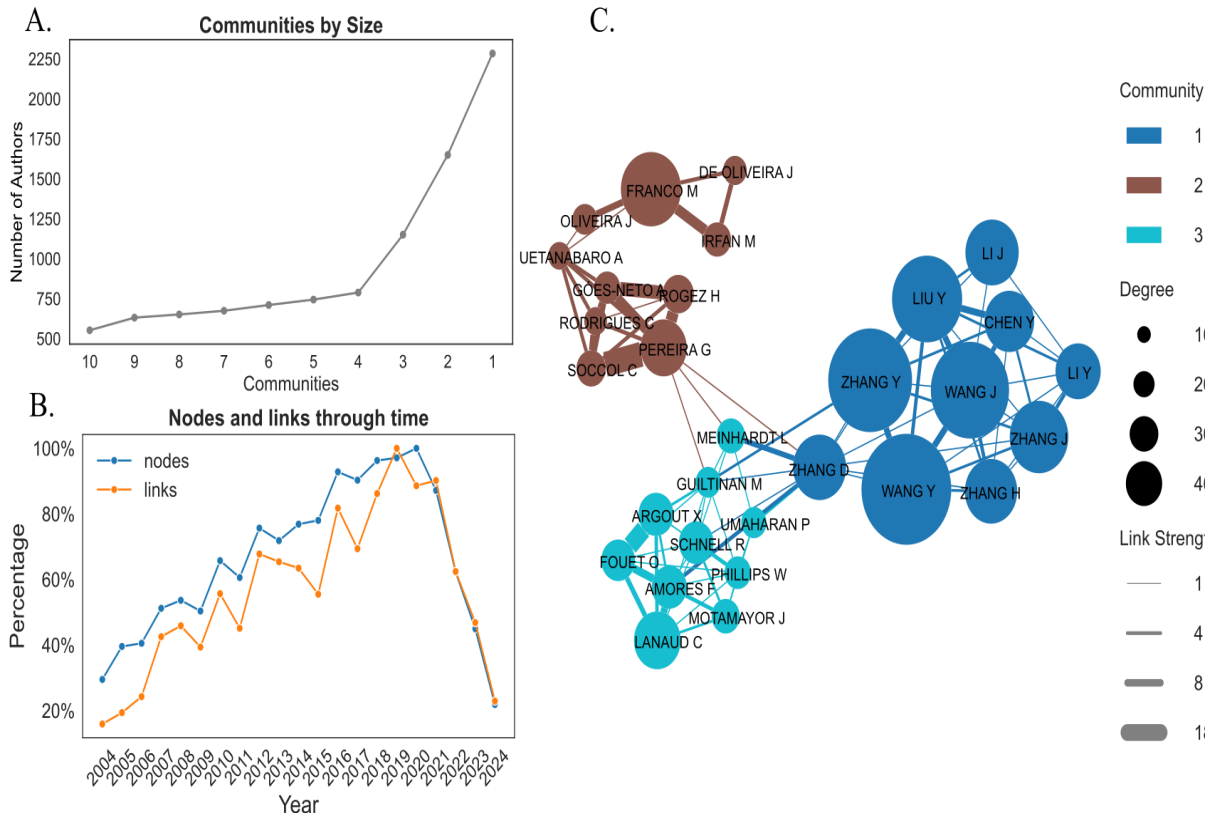

Figure 5. Collaborative Network of Prominent Authors and Their Interconnections.

Component one includes Wang Y, Wang J, and Zhang Y, authors recognized for their contributions to cacao genomics, such as the assembly of the Criollo variety genome [28] and the study of cacao defense genes against pathogens [29]. Yu-Ying Chen also stands out in this component for investigating the effects of high-pressure fermentation processes on cacao beans [30]. Component two is led by Franco, the author with the largest node in the network due to his high productivity. His recent publications have explored the valorization of cacao mucilage as a substrate for kombucha-type fermentations [31].

Component three, smaller in size, plays an articulating role within the network. It includes, among others, Guiltinan and Meinhardt, who collaborate on key studies regarding the physiology and gene expression during Moniliophthora roreri infections [32], [33]. Their collaboration connects the genomic analysis of component one with the biotechnological applications of component two, facilitating the circulation of knowledge among scientific communities.

Figure 5B presents the temporal evolution of the scientific collaboration network related to the studied topic, showing the number of authors (nodes) and collaborations (links) recorded per year. A progressive growth is observed from 2004 onwards, with a marked increase in research activity beginning in 2010. This growth reaches its peak between 2018 and 2019, the period during which the highest number of co-authorships is recorded, suggesting the consolidation of broader and more stable research networks. Subsequently, there is a sharp

decline in both the number of authors and collaboration links, likely associated with incomplete indexing of recent articles or a reorganization of research dynamics in the post-pandemic period.

Conclusions

The present scientometric analysis demonstrates a significant evolution in research on fermentation applied to the improvement of Theobroma cacao quality. The scientometric analysis conducted on research related to Theobroma cacao reveals a sustained growth in scientific production, particularly between 2019 and 2024. However, this increase is not proportionally reflected in citation impact, indicating a clear disconnect between the quantity of publications and their relevance within the scientific community.

Countries leading in production, such as Brazil, Germany, and Belgium, stand out for the impact and quality of their publications, as measured by their quartile rankings and citation metrics. Furthermore, the analysis identified robust networks of international scientific collaboration, within which Colombia is beginning to integrate, generating opportunities to strengthen the transfer of knowledge to local productive contexts.

The journals that account for the majority of the scientific output are ranked in high-impact quartiles (Q1), underscoring the relevance of this research within the field of biotechnology. Likewise, the most influential authors are distinguished not only by their productivity but also by their capacity to collaborate within diverse networks, which facilitates scientific innovation.

The scientific collaboration network reflects the active participation of authors from various countries, evidencing an international collaborative structure around the study of Theobroma cacao. The connection among researchers from regions such as Latin America, Asia, Europe, and North America indicates that progress in this area largely depends on the global exchange of knowledge.

Overall, the findings of this study highlight the need to promote strategies that enhance the dissemination and practical application of scientific advances in cacao fermentation, particularly in producing countries where this knowledge has yet to translate into significant technological improvements. Closing this gap may represent a key challenge in leveraging the potential of biotechnology for the benefit of cacao-producing communities.

References

[1]W. Zzaman, R. Bhat, T. A. Yang, and A. M. Easa, "Influences of superheated steam roasting on changes in sugar, amino acid and flavour active components of cocoa bean (Theobroma cacao)," J Sci Food Agric, vol. 97, no. 13, pp. 4429–4437, Oct. 2017.

[2]A. K. Kouassi et al., "Tree growth in West African cocoa agroforestry systems: high timber yields and superior performance of natural regeneration," Ann. For. Sci., vol. 82, no. 1, Apr. 2025, doi: 10.1186/s13595-025-01286-7. Available: https://annforsci.biomedcentral.com/articles/10.1186/s13595-025-01286-7

[3]J. H. Culbert et al., "Reference coverage analysis of OpenAlex compared to Web of Science and Scopus," Scientometrics, vol. 130, no. 4, pp. 2475–2492, Apr. 2025.

[4]S. D. M. Oñate and A. F. T. Herazo, "Agrivoltaic systems: a contribution to sustainability," interfaces, vol. 7, no. 2, 2024, Available: https://revistas.unilibre.edu.co/index.php/interfaces/article/view/12713. [Accessed: Jan. 07, 2025]

[5]A. J. B. Berrocal and D. M. C. Rizo, "Scientometric Analysis of the Relationship Between Artificial Intelligence and Data Engineering: Trends,Collaboration, and Evolution," interfaces, vol. 7, no. 2, 2024, Available: https://revistas.unilibre.edu.co/index.php/interfaces/article/view/12714. [Accessed: Jan. 07, 2025]

[6]K. M. Romero Villareal and M. C. M. Murgas, "Antimicrobial Potential of Secondary Metabolites: AScientometric Review," interfaces, vol. 7, no. 2, 2024, Available: https://revistas.unilibre.edu.co/index.php/interfaces/article/view/12712. [Accessed: Jun.10, 2025]

[7]S. Valencia, M. Zuluaga, M. C. Florian Pérez, K. F. Montoya-Quintero, M. S. Candamil-Cortés, and S. Robledo, "Human Gut Microbiome: A Connecting Organ Between Nutrition, Metabolism, and Health," Int J Mol Sci, vol. 26, no. 9, Apr. 2025, doi: 10.3390/ijms26094112. Available: http://dx.doi.org/10.3390/ijms26094112

[8]S. Robledo, D.-C. Gil-Silva, E.-J. Villegas-Jaramillo, and C. Osorio, "Examining the role of monetary incentives and tie strength in mediating satisfaction and word of mouth in multilevel marketing companies: an entrepreneurial marketing perspective," J. Res. Mark. Entrep., Mar. 2025, doi: 10.1108/jrme-07-2023-0117. Available: http://dx.doi.org/10.1108/jrme-07-2023-0117

[9]S. Robledo, L. Valencia, M. Zuluaga, O. A. Echeverri, and J. W. A. Valencia, "tosr: Create the Tree of Science from WoS and Scopus," J. Sci. Res., vol. 13, no. 2, pp. 459–465, Aug. 2024.

[10]R. F. Schwan and A. E. Wheals, "The microbiology of cocoa fermentation and its role in chocolate quality," Crit Rev Food Sci Nutr, vol. 44, no. 4, pp. 205–221, 2004.

[11]M. Rusconi and A. Conti, "Theobroma cacao L., the Food of the Gods: a scientific approach beyond myths and claims," Pharmacol Res, vol. 61, no. 1, pp. 5–13, Jan. 2010.

[12]J. E. Kongor, M. Hinneh, D. Van de Walle, E. O. Afoakwa, P. Boeckx, and K. Dewettinck, "Factors influencing quality variation in cocoa (Theobroma cacao) bean flavour profile — A review," Food Res. Int., vol. 82, pp. 44–52, Apr. 2016.

[13]M. Parapouli, A. Vasileiadis, A.-S. Afendra, and E. Hatziloukas, "and its industrial applications," AIMS Microbiol, vol. 6, no. 1, pp. 1–31, Feb. 2020.

[14]A. Pinto et al., "Advances in the individual authentication of cocoa beans: Vis/NIR spectroscopy as a tool to distinguish fermented from unfermented beans and classify genotypes in the eastern Amazonia," Food Control, vol. 164, no. 110559, p. 110559, Oct. 2024.

[15]R. Megias-Perez, M. Moreno-Zambrano, B. Behrends, M. Corno, and N. Kuhnert, "Monitoring the changes in low molecular weight carbohydrates in cocoa beans during spontaneous fermentation: A chemometric and kinetic approach," Food Res. Int., vol. 128, no. 108865, p. 108865, Feb. 2020.

[16]W. A. John et al., "Experimentally modelling cocoa bean fermentation reveals key factors and their influences," Food Chem., vol. 302, no. 125335, p. 125335, Jan. 2020.

[17]K. Colonges et al., "Variability and genetic determinants of cocoa aromas in trees native to South Ecuadorian Amazonia," Plants People Planet, vol. 4, no. 6, pp. 618–637, Nov. 2022.

[18]Q. R. Araujo et al., "Cocoa Quality Index – A proposal," Food Control, vol. 46, pp. 49–54, Dec. 2014.

[19]M. Santander et al., "Unravelling cocoa drying technology: A comprehensive review of the influence on flavor formation and quality," Foods, vol. 14, no. 5, Feb. 2025, doi: 10.3390/foods14050721. Available: http://dx.doi.org/10.3390/foods14050721

[20]C. Botella-Martínez et al., "Ghanaian cocoa (Theobroma cacao L.) bean shells coproducts: Effect of particle size on chemical composition, bioactive compound content and antioxidant activity," Agronomy (Basel), vol. 11, no. 2, p. 401, Feb. 2021.

[21]D. Johnston-Monje, L. I. Vergara, J. Lopez-Mejia, and J. F. White, "Plant microbiomes as contributors to agricultural terroir," Front. Agron., vol. 5, Oct. 2023, doi: 10.3389/fagro.2023.1216520. Available: http://dx.doi.org/10.3389/fagro.2023.1216520

[22]S. Llano et al., "Metabolomic insights into flavour precursor dynamics during fermentation of cacao beans cultivated in diverse climatic production zones in Colombia," Food Res. Int., vol. 205, no. 115978, p. 115978, Mar. 2025.

[23] F. A. de Oliveira Duarte, K. K. Ramos, C. Gini, R. M. Morasi, N. C. C. Silva, and P. Efraim, "Microbiological characterization of kombucha and biocellulose film produced with

black tea and cocoa bean shell infusion," Food Res. Int., vol. 190, no. 114568, p. 114568, Aug. 2024.

[24]N. A. Febrianto and F. Zhu, "Changes in the composition of methylxanthines, polyphenols, and volatiles and sensory profiles of cocoa beans from the Sul 1 genotype affected by fermentation," J. Agric. Food Chem., vol. 68, no. 32, pp. 8658–8675, Aug. 2020.

[25]C. L. Hii, C. L. Law, M. Cloke, and S. Sharif, "Improving Malaysian cocoa quality through the use of dehumidified air under mild drying conditions," J. Sci. Food Agric., vol. 91, no. 2, pp. 239–246, Jan. 2011.

[26]H. Small, "Co-citation in the scientific literature: A new measure of the relationship between two documents," J. Am. Soc. Inf. Sci., vol. 24, no. 4, pp. 265–269, Jul. 1973.

[27]M. Hamawi, I. Rohimin, and U. Isnatin, "Significant potential of tape yeast and plant leaves as a cover for fermented cocoa (Theobroma cacao L.) beans to generate qualities of dry cocoa beans," Food Res., vol. 8, no. Supplementary 2, pp. 66–77, Apr. 2024.

[28]X. Argout et al., "The genome of Theobroma cacao," Nat Genet, vol. 43, no. 2, pp. 101–108, Feb. 2011.

[29]A. S. Fister, L. C. Mejia, Y. Zhang, E. A. Herre, S. N. Maximova, and M. J. Guiltinan, "Theobroma cacao L. pathogenesis-related gene tandem array members show diverse expression dynamics in response to pathogen colonization," BMC Genomics, vol. 17, p. 363, May 2016.

[30]Y.-H. Lin, B.-C. Huang, X.-R. Song, Z.-J. Lin, Y.-Y. Chen, and C.-Y. Wang, "Effects of high pressure processing on the biosynthesis of γ-aminobutyric acid in cocoa beans fermented with Lactobacillus senmaizukei," Research Square, Oct. 07, 2024. doi: 10.21203/rs.3.rs-5034500/v1. Available: http://dx.doi.org/10.21203/rs.3.rs-5034500/v1

[31]R. Rodríguez-Castro, R. Guerrero, A. Valero, J. Franco-Rodriguez, and G. Posada-Izquierdo, "Cocoa Mucilage as a Novel Ingredient in Innovative Kombucha Fermentation," Foods, vol. 13, no. 11, May 2024, doi: 10.3390/foods13111636. Available: http://dx.doi.org/10.3390/foods13111636

[32]L. W. Meinhardt et al., "Genome and secretome analysis of the hemibiotrophic fungal pathogen, Moniliophthora roreri, which causes frosty pod rot disease of cacao: mechanisms of the biotrophic and necrotrophic phases," BMC Genomics, vol. 15, p. 164, Feb. 2014.

[33]B. A. Bailey et al., "Dynamic changes in pod and fungal physiology associated with the shift from biotrophy to necrotrophy during the infection of Theobroma cacao by Moniliophthora roreri," Physiol. Mol. Plant Pathol., vol. 81, pp. 84–96, Jan. 2013.