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Cocoa pod husk utilization: A scientometric analysis of scientific production on its applications*

Aprovechamiento de la cáscara de la mazorca de cacao: Un análisis cienciométrico de la producción científica sobre sus aplicaciones

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Abstract

Repurposing cocoa pod husks (CPH) is essential for creating an additional source of income due to their chemical properties and for reducing waste associated with cocoa processing. Valorizing this byproduct not only contributes to the circular economy but also enhances environmental sustainability by decreasing waste generation and the ecological footprint of cocoa production. Moreover, the cellulose and hemicellulose content in CPH presents significant potential as a carbohydrate source for biofuel production. Additionally, its high polyphenol content and antioxidant capacity position it as a promising input for the food and pharmaceutical industries. Despite the relevance of implementing circular economy practices in this context, the existing literature remains limited and fragmented. This article aims to conduct a scientometric analysis based on searches in the Scopus and Web of Science databases. The results indicate that Nigeria leads in academic output on this topic, with Moyin-Jesu emerging as the most prolific author. These findings may assist cocoa producers in identifying various techniques for recovering and utilizing CPH, thereby encouraging its application in areas such as organic fertilizers, construction materials, and bioenergy systems, ultimately promoting greater added value and sustainability within the cocoa production chain.

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Keywords: Cocoa pod husk, Waste valorization, Processing methods, Circular economy, Environmental sustainability, Scientometric analysis.

Resumen

Dar un segundo uso a la cáscara de la mazorca de cacao (CPH) es fundamental para generar una fuente adicional de ingresos, debido a sus propiedades químicas y reducir el desperdicio asociado a los procesos de transformación del cacao. La valorización de este residuo no solo contribuye a la economía circular, sino también a la sostenibilidad ambiental, al disminuir la generación de residuos y la huella ecológica de la producción cacaotera. Además, la celulosa y hemicelulosa presentes en el CPH tienen potencial como fuente de carbohidratos en la producción de biocombustibles; y el contenido elevado de polifenoles y su capacidad antioxidante lo posicionan como una fuente prometedora para la industria alimentaria y farmacéutica. Aunque la implementación de procesos de economía circular en este contexto es de gran importancia, la literatura sobre el tema es escasa y dispersa. El objetivo de este artículo es realizar un análisis cienciométrico basado en una consulta en las bases de datos Scopus y Web of Science. Los resultados indican que el país con mayor producción académica en la materia es Nigeria, y que el autor más destacado, en función de su producción, es Moyin-Jesu. Estos hallazgos podrán ayudar a los productores de cacao a identificar diferentes técnicas para recuperar y aprovechar el CPH, promoviendo su uso en aplicaciones como fertilizantes orgánicos, materiales de construcción o mecanismos de bioenergía, promoviendo así un mayor valor agregado y sostenibilidad en la cadena productiva.

Palabras clave: Cáscara de la mazorca de cacao, Valorización de residuos, Procesos de transformación, Economía circular, Sostenibilidad ambiental, Análisis cienciométrico.

1. Introduction

Cocoa (Theobroma cacao L.) is a crop cultivated across many tropical countries in Africa, Asia, Central, and South America [1], [2]. It is characterized by high production levels and significant economic relevance [3]. Over the past decade, global cocoa production has averaged 4.3 million tons per year [4], which highlights the substantial amount of by-products generated in the process. Among these, the cocoa pod husk (CPH) stands out as the primary waste material, accounting for approximately 75% of the total fruit weight [4], [5]. Therefore, it is crucial to implement strategies for the reuse of this by-product, integrating circular economy principles and contributing to the mitigation of crop diseases in cocoa plantations [6], [7].

CPH is rich in cellulose, hemicellulose, lignin, pectin, and elements such as N, Ca, K, P, Mg, Na, Zn, Fe, Cu, and Mn [8]. However, despite this favorable composition, it can also promote the spread of diseases, most notably black pod disease, caused by the presence of Phytophthora spp. This fungus tends to proliferate when untreated CPH is left on plantation soils. Black pod disease is responsible for global yield losses ranging between 20% and 30% annually [5], [9]. As such, effective measures are needed to address this environmental concern.

Numerous studies have demonstrated both low- and high-value applications for CPH. In low-value uses, it has been employed as a fertilizer due to its high mineral content, particularly K, Ca, and P, as well as in soap production, animal feed for pigs and poultry, and in the manufacture of activated carbon. In high-value applications, CPH has been explored for paper production, biofuel generation, and human food uses [5].

Despite the pressing need to utilize CPH to alleviate environmental issues in cocoa farming, there remains a scarcity of comprehensive review studies on the topic. A review of the literature revealed only six review articles available in the Scopus and Web of Science (WoS) databases. Among them, the first is a narrative review that identifies key processes for the transformation and utilization of cocoa pods, concluding that there are still few proposed strategies for cocoa waste reuse [10]. The second explores sustainable strategies to improve soil health on cocoa farms, given the low yields currently observed, and recommends the use of CPH as an organic amendment [11]. The third review investigates biotechnological methods for converting cocoa by-products into high-value materials, emphasizing biotechnology's potential in the biotransformation of agricultural waste as a new income source for farmers [12]. The fourth focuses on the conversion of cocoa by-products into biofuels using various technological pathways, concluding that due to its abundant lignocellulosic biomass, CPH is highly suitable for biofuel production [8]. Notably, none of these studies have employed a scientometric approach to comprehensively examine the progress made in this area.

To address this gap, the present study conducted a scientometric review using two of the most comprehensive scientific databases, Scopus and Web of Science, which collectively compile the majority of global academic output [13]. Furthermore, scientometric algorithms were applied to integrate and analyze data from both databases, representing a novel methodological contribution.
A total of 126 articles were identified as relevant to the core topic of this review. The findings show that over the past twenty years, scientific production on this subject has grown by 15.86%, with Nigeria emerging as the leading country in academic output. Moreover, the most prolific journal in the field is AIP Conference Proceedings, which has published five relevant articles and holds an h-index of 90. These results underscore the growing academic interest in this field.

The remainder of this study is structured as follows: the methodology section details the search and article selection process; the results section includes an analysis of overall scientific output, leading countries, prominent journals, and the most active research communities; and finally, the discussion and conclusions are presented.

2. Methodology

For the development of this article, two databases, Scopus and WoS, were used to gather specialized and relevant studies on the utilization of CPH [14]. The search covered publications from 2004 to the present and focused on research addressing its transformation into biochar, fertilizers, and other organic amendments, with the aim of identifying the most significant advances in this field. Furthermore, the concept of circular economy was considered in order to include studies that propose new uses for this agricultural residue, thus contributing to waste reduction and more sustainable processes. The search strategy was based on the use of key terms such as “cocoa pod husk” and “cocoa shell,” combined with words like “compost,” “biochar,” and “fertilizer,” and employed Boolean operators. The complete search equation is detailed in Table I.

Table I. Search parameters used in both databases.

Parameter	Web of Science	Scopus
Range	2004-2005	
Date	May 07, 2025	
Document Type	Paper, book, chapter, conference proceedings	
Words	(TITLE-ABS-KEY ("cocoa pod husk" OR "cacao pod husk" OR "cocoa husk" OR "cacao husk") AND TITLE-ABS-KEY (compost OR biochar OR fertilizer OR amendment OR "biofertilizer")) AND PUBYEAR > 2003 AND PUBYEAR < 2026	
Results	50	110
Total (WoS+Scopus)	126	

As a result of the search process, 126 documents were retrieved, the majority of which were journal articles (82.54%) and conference papers (9.52%). Only 10 publications fell into other categories. These findings underscore the value of combining WoS and Scopus for literature reviews, as 12.7% (16 documents) were found exclusively in WoS and were not indexed in Scopus.

Figure 1 presents a flow diagram that summarizes the methodology employed to gather bibliographic information and manage the resulting data, following the guidelines of the PRISMA methodology [15]. Two distinct approaches were applied to process the results: for WoS, web scraping was used to extract data such as author names and titles, while for Scopus, text mining techniques were employed to organize the references. The outputs from both processes were then harmonized and merged into a single database. This procedure resulted in an Excel file with 22 sheets, where the data were structured and prepared for analysis [16], [17], [18], [19].

The results were organized into several sections: analysis of annual scientific production, analysis by country and journal, and evaluation of the scientific collaboration network. Finally, using Google Colab, a data network was constructed to integrate and visualize the collected information. These results provided the foundation for constructing the conceptual structure of the research field, through tables and figures, identifying key studies, and supporting the selection of the most relevant literature.

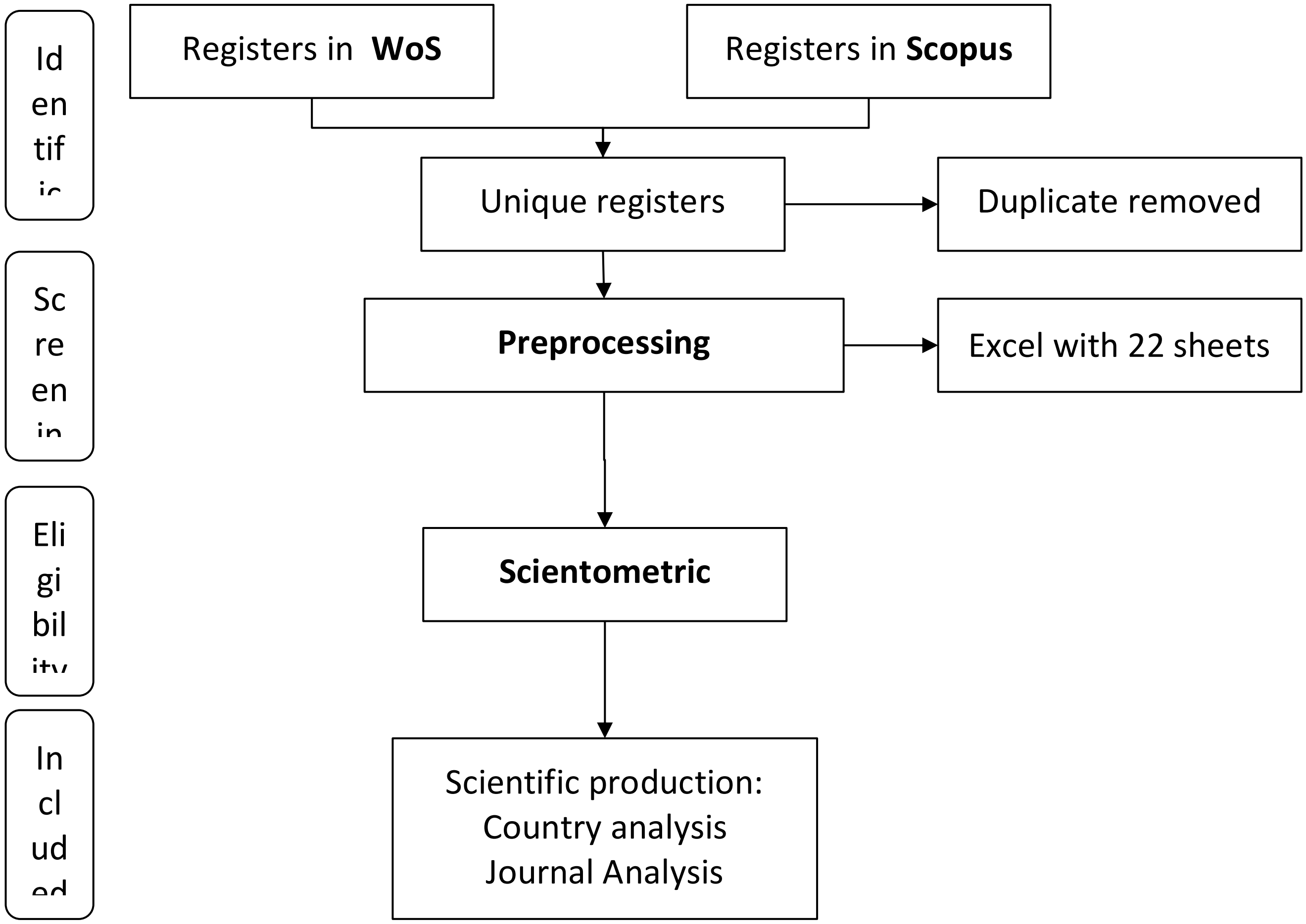

Figure 1. Detailed illustration of the collected information.

3. Results

Scientometric Analysis

Scientific Annual Production

The analysis of scientific output represents a fundamental tool within scientometric studies, as it enables the examination of the temporal evolution of knowledge in a specific field. In this case, the study of CPH highlights how scientific literature on its applications has evolved, particularly in the context of the circular economy and the valorization of agricultural waste. Assessing this body of work allows for the identification of growth patterns, periods of stagnation, and key moments of research consolidation, as well as the establishment of correlations with global dynamics, international collaborations, and shifts in research priorities.

Figure 2 presents the annual scientific output related to CPH, distinguishing records from the Scopus and WoS databases. The figure illustrates the cumulative growth in publications on this topic, which stands at 15.86%, driven mainly during Stage 3 (2017–2024). This upward trend reflects a successful scientific trajectory, with the highest productivity reached in the most recent year. The green bars, representing Scopus data, show a notable increase in publications since 2018, peaking in 2024 with 17 articles. In contrast, the orange bars, representing WoS data, although generally fewer in number, have shown consistent contributions since 2006, with a notable peak of 10 publications in 2022.

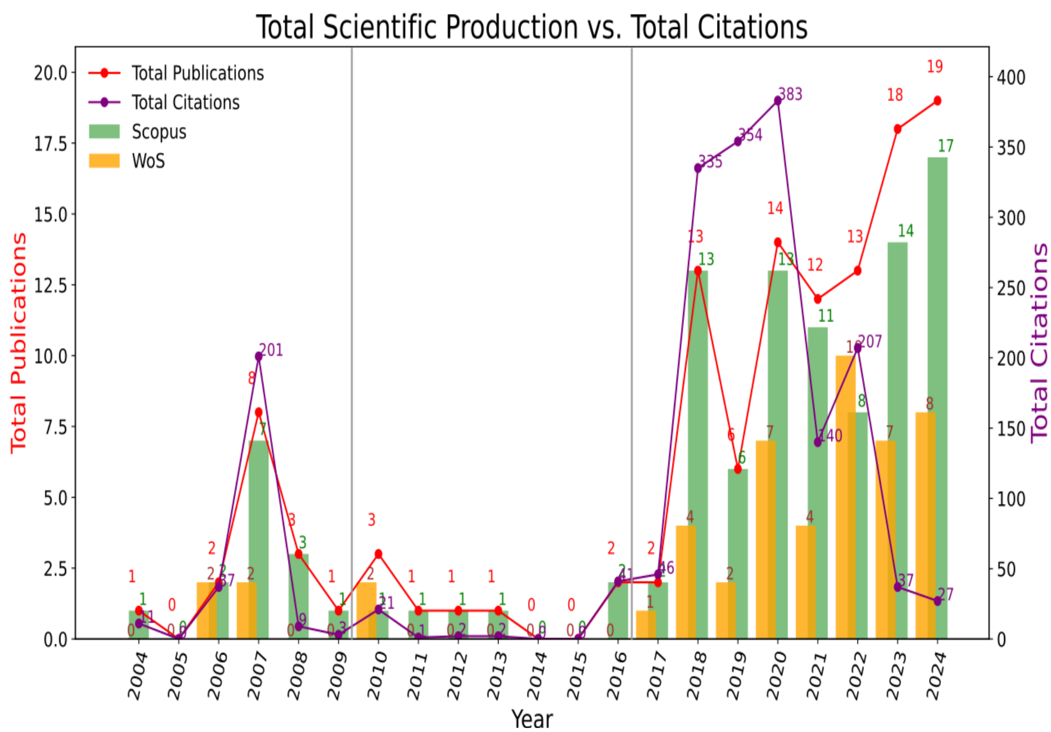

Figure 2. Scientific production vs. total annual citations on CPH applications between 2004 and 2024.

Period 1: Initial Stage and Thematic Exploration (2004–2009)

During this period (2004 to 2009), scientific output related to the topic experienced relatively low growth, with the exception of 2007, which recorded 7 publications and 201 citations. Notably, there was no output in 2005. Due to the limited number of publications, particularly in the WoS database, the growth observed during this stage is marginal compared to Period 3. However, the 2007 publications were particularly influential in subsequent years, notably in studies focused on the use of organic waste. One frequently cited article from that year, authored by Moyin and cited 71 times, examined the “use of plant residues to improve soil fertility, pod nutrients, root growth, and pod weight in okra.” This study demonstrated that using plant-based residues, specifically including cocoa husks, was the most effective treatment for enhancing pod weight, nutrient content, root length, and soil fertility. The findings suggested long-term benefits such as reducing consumers' need for supplements and farmers' reliance on synthetic fertilizers while maintaining productivity [20]. Despite this high citation count in 2007, no comparable growth occurred in the following years. Both publication and citation activity remained low and lacked a clear upward trend. This period represents the foundational stage of the field, characterized by minimal infrastructure and nascent scientific processes.

Period 2: Transition Phase and Research Uncertainty (2010–2016)

This stage shows a decline of -6.53%, indicating that the field struggled to gain momentum, maintain productivity, and increase visibility. This drop may be associated with resource reallocation or the accumulation of unpublished data that would later emerge in Period 3. There was low visibility and discontinuity in publications across both Scopus and WoS, particularly in 2014 and 2015, where no related research output was recorded. Nevertheless, the most cited article during this period (26 citations) was published in Scopus in 2016. This study, focused on "Anaerobic co-digestion of organic waste from different productive sectors in Colombia: Evaluation of biomethanization potential", evaluated the anaerobic digestion potential of various organic residues, including cocoa husks. The findings revealed that the most efficient combination included cocoa waste, fruit residues, and pig manure. However, the overall methane potential of the mixture was lower than the sum of the individual potentials, indicating substrate interactions that negatively affected total biogas production [21].

Period 3: Scientific Consolidation and Expansion (2017–2024)

This phase marks a significant increase of 37.94%, indicating a period of consolidation and transition into scientific expansion. There is clear evidence of improved research capacity, enhanced international collaboration, and a notable rise in both publications and citations, with Scopus showing a higher volume and impact than WoS. The peak in total publications was reached in 2024 with 19 articles, followed by 2023 with 18 and 2020 with 14. This growth reflects a phase of heightened research activity, characterized by strategic collaborations and impactful studies. The most prominent citation peak occurred between 2018 and 2020. Although total citations dropped notably in 2023 (37) and 2024 (27) across both Scopus and WoS, this decline is not a cause for concern, as these are recent publications and have not yet had time to accumulate significant citations

.

Country Analysis

Table 1 presents the top 10 countries with the highest scientific output related to CPH applications, along with corresponding impact metrics (citations) and quality indicators (Scimago quartiles). Nigeria ranks first in terms of productivity, contributing 17.69% of the total publications, followed by Indonesia with 16.15%. Although both countries show relatively similar productivity percentages, Nigeria leads in research impact, accounting for 16.34% of total citations.

Regarding publication quality, notable differences are observed between the two countries; however, most of the research in this area appears in journals classified in Q3 and Q4 quartiles.

Additionally, countries such as Ghana, Mexico, Colombia, and India are increasingly contributing to the scientific literature on this topic. Nevertheless, aside from Nigeria, the countries with the highest research impact are France and China, with 8.30% and 8.49% of citations, respectively.

Table II. Scientific production on CPH applications, number of citations, and quartile distribution by country.

Country	Production		Citation		Q1	Q2	Q3	Q4
Nigeria	23	17.69%	254	16.34%	4	1	4	9
Indonesia	21	16.15%	56	3.60%	2	0	6	3
Ghana	10	7.69%	35	2.25%	2	3	2	2
Mexico	7	5.38%	51	3.28%	0	5	0	1
Colombia	6	4.62%	74	4.76%	3	2	1	0
India	6	4.62%	93	5.98%	3	1	1	1
Ecuador	5	3.85%	5	0.32%	2	0	0	1
France	5	3.85%	129	8.30%	5	0	0	0
China	4	3.08%	132	8.49%	1	3	0	0
Cuba	4	3.08%	7	0.45%	0	0	1	1

One recent study conducted by researchers in Nigeria found that the application of CPH represents a better alternative compared to mineral fertilizers. Specifically, they identified that using a pre-treated CPH at an optimal ratio significantly improved banana yield when applied at a rate of 10 tons per hectare [22].

Another line of research on CPH has focused on the integration of circular economy principles. For instance, researchers in Colombia conducted a study on the impact and feasibility of using CPH as an organic fertilizer to strengthen practices within a circular economy framework [23]. Their findings emphasize the need to promote this model and to actively involve farmers in the implementation of alternatives that maximize the use of organic waste on small-scale cocoa farms.

Figure 3 illustrates the scientific collaboration network among countries. Six distinct communities or clusters of countries involved in CPH-related research are represented. A notable aspect of this network is that the first community identified exhibits multiple connections among its member countries, indicating a well-integrated collaborative structure. In contrast, the second community, led by Ghana and Nigeria, is the second largest in terms of participating countries, yet it displays only one significant connection between them. Similarly, the fourth community (shown in pink) also demonstrates a relevant level of international collaboration.

Interestingly, Spanish-speaking countries are scattered across different communities, rather than forming a unified group. Additionally, the node-link timeline figure reveals that, since 2020, the proportion of links has surpassed the proportion of new nodes (i.e., countries), indicating that the academic community has strengthened and consolidated its international collaborations in recent years.

Another relevant observation from this figure is that from 2006 to 2017, the proportion of links remained relatively stable, showing no evident growth and thus suggesting limited international collaboration during that period. Likewise, from 2009 to 2015, the number of new nodes also showed no significant increase, meaning that no new countries entered the research landscape on this topic during those years.

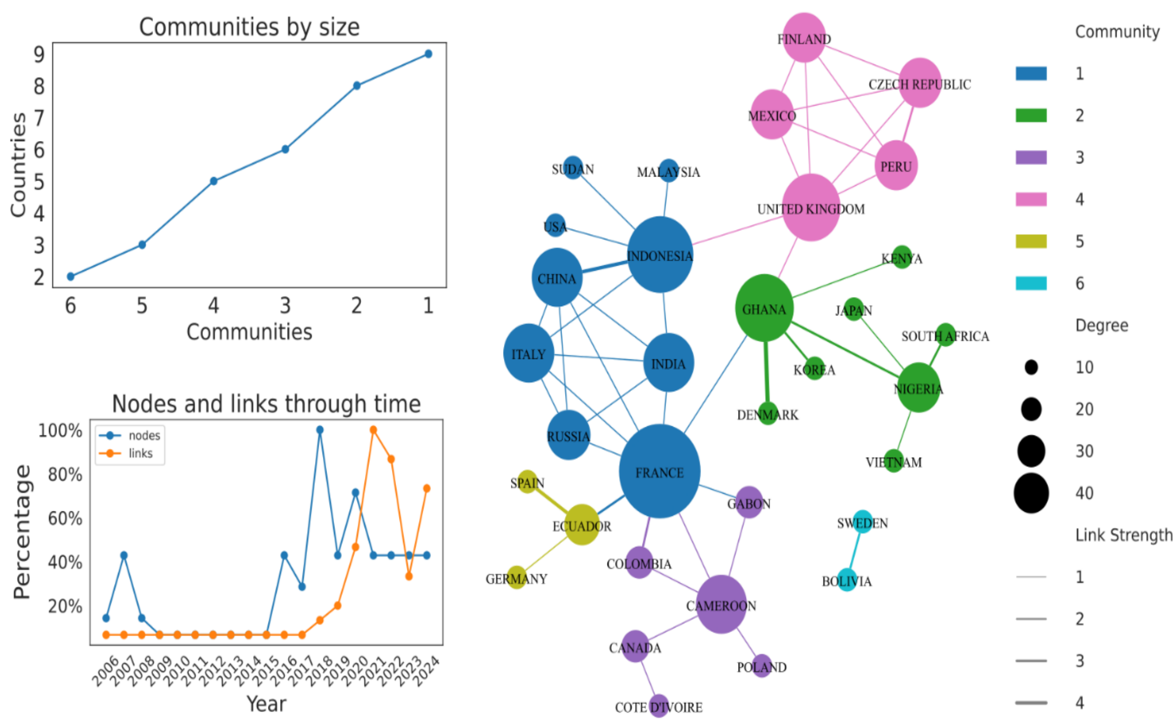

Figure 3. Scientific collaboration network among countries in research on CPH applications.

One noteworthy example of international scientific collaboration is between Colombia and France. Researchers from these two countries have worked on utilizing biochar derived from CPH for the production of high-purity biogas, specifically by removing carbon dioxide (CO_2) from the fuel [24]. The authors highlight that this approach holds significant promise for industrial applications and aligns with the principles of the circular economy.

Another important collaboration is between Ghana and Nigeria. Scientists from both countries have collaborated to enhance the nutritional value of cattle manure for use as fertilizer by incorporating CPH, along with other compounds such as palm kernel cake (PKC) and rock phosphate (RP) [25]. The study found that combining cattle manure, PKC, CPH, and RP significantly improved soil fertility and maize crop yields.

A third collaboration worth highlighting is between Bolivia and Sweden, which has shown continued cooperation. Researchers from these two countries conducted a study on the applicability of processes such as pyrolysis for the decomposition of organic waste materials like CPH and açaí stems to produce biochar, biogas, and bio-oil [26]. The authors concluded that both CPH and açaí stems are efficient feedstocks for generating these high-value products, which can be used for soil enhancement, industrial processes, and energy generation.

Journal Analysis (Jeniffer)

Table III presents the ten journals with the highest scientific output related to CPH. Notably, four out of these ten journals are ranked in Q1, indicating that they are considered top-tier publications. It is also important to highlight that two of the listed journals do not have a Scimago quartile classification. These are AIP Conference Proceedings and IOP Conference Series: Earth and Environmental Science. The primary reason for the absence of quartile information is that both journals specialize in the publication of conference proceedings, which can affect their classification within thematic categories.

Interestingly, the two journals with the highest number of publications on the topic are precisely the ones without quartile rankings. Nevertheless, the journals with the greatest impact are Journal of Cleaner Production and Waste Management, with h-index values of 354 and 239, respectively.

Table III. Journal rankings in research on CPH applications: statistics and impact.

Journal	ISSN	WoS	Scopus	Total	SJR	H-Index	Quartile
AIP Conference Proceedings	15517616	0	5	5	0.153	90	–
IOP Conference Series: Earth and Environmental Science	17551307	0	5	5	0.214	58	–
International Journal of Recycling of Organic Waste in Agriculture	21953228	3	4	4	0.239	44	Q3
Journal of Cleaner Production	09596526	4	2	4	2.174	354	Q1
Bulgarian Journal of Agricultural Science	13100351	0	3	3	0.183	33	Q3
Journal of Environmental Chemical Engineering	22132929	2	2	3	1.454	151	Q1
Biomass Conversion and Biorefinery	21906815	3	3	3	0.702	56	Q2
Scientific African	24682276	1	2	3	0.609	52	Q1
Revista Colombiana de Química	01202804	1	2	3	0.109	10	Q4
Waste Management	18792456	0	3	3	1.726	239	Q1

The journal AIP Conference Proceedings has recently published research on the applications of CPH. In one of these recent studies, the authors compared four different treatments to determine which could best enhance the nutritional quality of bokashi, a type of fermented organic fertilizer [27]. Their findings indicated that the most nutrient-rich treatment was the combination of CPH, the weed Ageratum conyzoides L. (commonly known as babadotan), cow manure, and PGPR (Plant Growth-Promoting Rhizobacteria).

On the other hand, the journal IOP Conference Series: Earth and Environmental Science has also published recent work on the management of organic waste through a Closed-Loop Supply Chain (CLSC) framework [28]. This study examines how value losses occur during cocoa storage, negatively impacting profits. As a solution, the authors propose integrating the CLSC system, which aims to reuse and valorize cocoa residues as organic fertilizers, thereby increasing profitability among stakeholders, reducing environmental impact, and promoting a circular economy.

Figure 4 illustrates the citation network among scientific journals that publish on topics related to this review, revealing three main clusters. The first cluster includes journals that focus on environmental engineering, sustainability, and the valorization of agricultural residues such as CPH [29], [30]. The second group consists of journals specifically addressing the application of various technologies aimed at achieving energy and chemical valorization of waste materials [22], [31]. Finally, the third cluster focuses on research concerning the applications and effects of CPH, along with the utilization of other by-products [32]. Additionally, the "Nodes and links through time" figure shows that the proportion of links relative to nodes (journals) has increased in recent years. This indicates the establishment of stronger interconnections among journals publishing on the topic of CPH valorization.

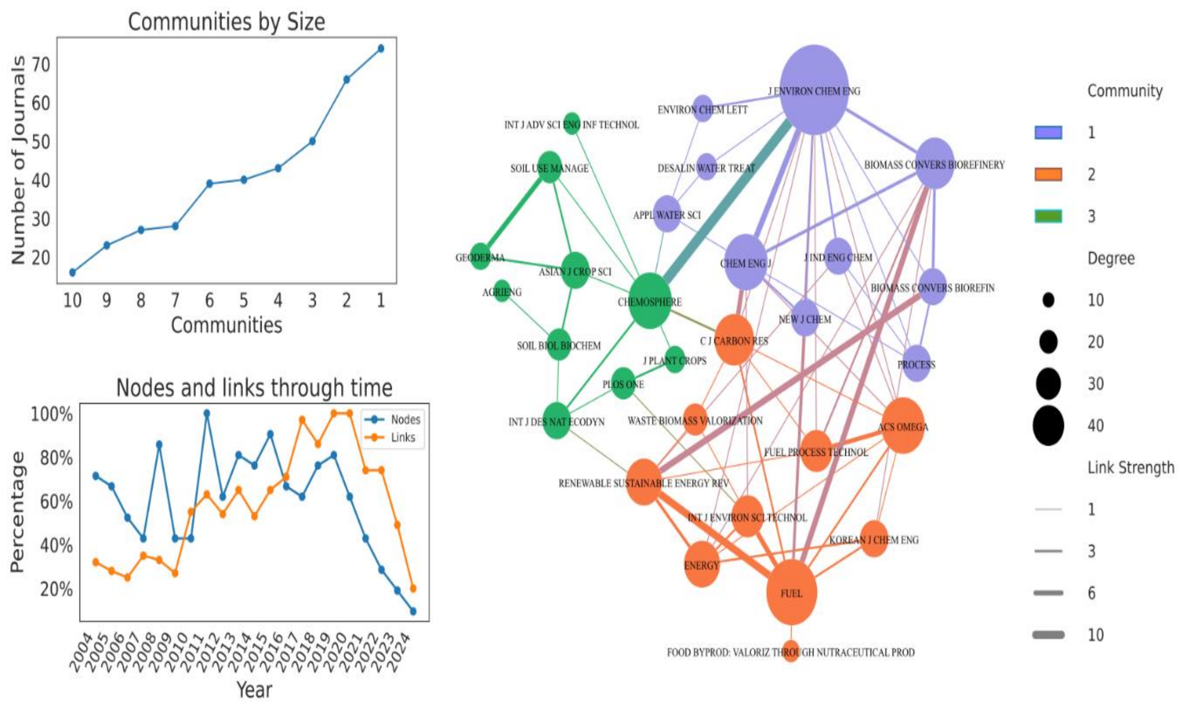

Figure 4. Citation network among scientific journals: communities and interrelations in research on CPH applications.

Author Analysis

The analysis of scientific collaboration networks enables the identification of researchers' networking strategies. Additionally, it allows for the assessment of individual researchers' importance based on their publication output and the impact of their work. For instance, Table 4 presents the eight most prolific researchers in the field of CPH applications. The results show that Rahim leads in academic output (5 publications), followed by Nartey, who, despite ranking second in number of publications (4), stands out for his higher impact (122 citations) and higher h-index (4), indicating significant scholarly influence. An interesting case is Asiedu, who, although having only three publications, holds the second-highest number of citations (90), highlighting the relevance of his contributions. In terms of social network metrics, the Effective Size reflects the level of collaboration among authors. For example, Rahim, Asrul, and Awodun exhibit the lowest Effective Size value (1.0), suggesting that they operate within tightly-knit networks, where their collaborators are strongly connected to one another. This is further supported by their relatively high Constraint values (0.77 and 1.12), indicating a greater dependency on close contacts and lower structural diversity in their collaborative networks. Regarding the Collaboration Diversity Index (CDI), Barrezueta presents a value of 0.56, suggesting active participation in diverse research collaborations across his publications.

Table IV. Production by authors.

Author	Papers Total	Total Citations	H-Index	Effective_Size	Constraint	CDI
Rahim I	5	18	2	1.0	0.77	0.25
Nartey E	4	122	4	1.0	1.12	0.5
Adeoye G	3	10	2	1.0	0.65	0.2
Asiedu N	3	90	1	9.33	0.24	0.27
Asrul L	3	18	2	1.0	0.77	0.25
Awodun M	2	7	2	1.0	1.12	0.5
Barrezueta-Unda S	3	0	0	4.2	0.4	0.56
Cruz G	3	61	2	26.15	0.11	0.13

Figure 5 presents a structure composed of nodes representing clusters of authors who form a collaboration network based on scientific publications within the research area of CPH (Cocoa Pod Husk) applications. The network reveals seven components resulting from the analysis, most of which are small and distinguishable from one another. However, some components stand out due to their higher number of interconnections. The largest community is led by Cruz G, a member of the Department of Forest Engineering and Environmental Management at the Faculty of Agricultural Sciences, Universidad Nacional de Tumbes. His research focuses on the valorization of agricultural residues, such as CPH, for the development of materials with environmental and energy-related applications. A relevant example of this collaboration is the study [29], which demonstrates the conversion of CPH residues into biochar and hydrocarbons, materials capable of absorbing water pollutants and storing energy.

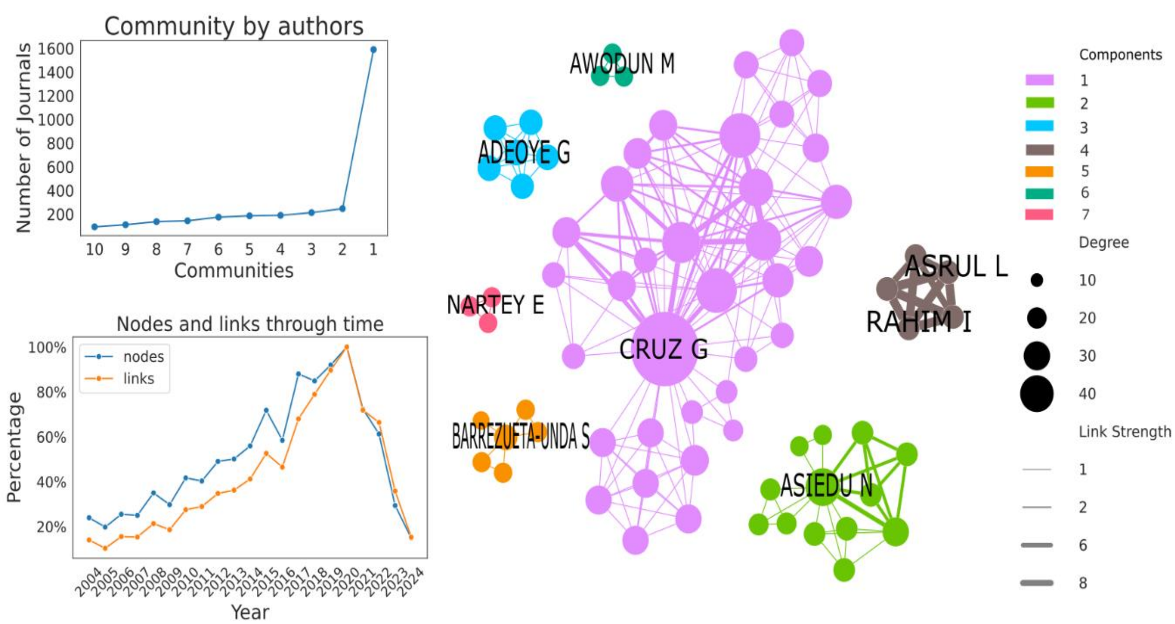

Figure 5. Groups of authors

Other notable groups include the one led by Asrul L and Rahimi I, which, although comprising only two lead authors and exhibiting a smaller number of connections, reflects strong local collaboration. Both researchers are affiliated with institutions in Indonesia, specifically the Faculty of Agriculture. One illustrative example of their joint work is the article [6], focused on sustainable agriculture and particularly on transforming CPH into fertilizer using beneficial fungi to enhance cacao seedling growth.

In this regard, the findings illustrate how social network analysis enables a broader understanding of the collaboration strategies adopted by researchers in this emerging field.

Conclusions

This scientometric review focused on characterizing the scientific production, leading countries, specialized journals, and collaboration networks related to the valorization of cocoa pod husk (CPH). Two searches were conducted, one in Web of Science and another in Scopus, and the results were integrated using advanced data mining and web scraping algorithms. The final dataset comprised 126 documents. Findings indicate that Nigeria leads in scientific output, with authors such as Rahim and Nartey standing out for their productivity and impact. Moreover, the field has shown significant growth between 2017 and 2024, with a cumulative increase of 15.86%, confirming the expansion and growing academic interest in this research area.

Over the past two decades, studies on CPH utilization have followed a notable trajectory, which can be divided into three distinct phases: initiation and exploration; transition and uncertainty; and a recent phase of consolidation and scientific expansion. In particular, since 2017, academic production has steadily increased, reaching its peak in 2024. This surge reflects the growing interest in agricultural waste valorization, driven by the circular economy and sustainable development frameworks. The adoption of emerging technologies, such as biotechnology, pyrolysis, and the development of biofertilizers and biofuels, has shifted the perception of CPH from a mere by-product to a strategic resource for multiple industries.

One of the most relevant findings is Nigeria’s leading position in the field. It not only accounts for the highest number of publications (17.69%) but also for the largest share of citations (16.34%), highlighting the relevance and influence of its academic output on CPH. Nigeria is followed by Indonesia, Ghana, India, and Mexico. Although Colombia has a strong cocoa-producing tradition, it represents only 4.62% of the total scientific production, revealing an underexploited potential that calls for greater research investment and integration with sustainable technological practices.

In terms of publication outlets, AIP Conference Proceedings and IOP Conference Series: Earth and Environmental Science have published the highest number of related articles (five each), although neither is ranked in the Scimago Journal & Country Rank (SJR) quartiles. Conversely, high-impact Q1 journals such as the Journal of Cleaner Production and Waste Management stand out, with h-indexes of 354 and 239, respectively. Regarding authorship, Rahim leads in publication count, while Nartey demonstrates greater scholarly influence based on citation count and h-index. These trends suggest that CPH valorization is an emerging area in which a scientific community committed to sustainability and agricultural waste innovation is progressively consolidating.

These patterns are exemplified by studies such as Moyin-Jesu (2007), which demonstrated the positive effects of CPH on soil fertility and crop yield [20]. More recently, Cruz et al. (2021) explored its use in the production of biochar for environmental and energy applications [29], thus expanding the scope of potential uses for this agro-industrial by-product.

One of the main limitations of this review is the exclusive reliance on Scopus and Web of Science databases, which may have excluded relevant literature available in regional repositories or other academic platforms. In addition, the most prolific journals, AIP Conference Proceedings and IOP Conference Series, lack SJR quartile rankings, which restricts qualitative impact assessment.

Furthermore, although international collaboration networks were identified, the factors underlying their formation, such as funding policies, academic mobility programs, or language barriers, were not explored in depth. Future research is encouraged to integrate qualitative approaches and expand the data sources, in order to better understand the dynamics of collaboration and the enabling conditions for CPH-related research at both local and global levels.

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