

Biorefinery of Cocoa Waste: A Systematic Review and Bibliometric Analysis

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The growing demand for sustainable alternatives to produce biofuels and bioproducts has driven the development of biorefineries based on agro-industrial residues. Cocoa (*Theobroma cacao* L.), an important agricultural commodity, generates approximately 70–80% of residues during its processing, presenting significant potential for use in integrated conversion processes. This study presents a systematic literature review combined with a bibliometric analysis to answer the question: Do cocoa residue biorefineries exist? The literature search was conducted using the Scopus and Web of Science databases, resulting in the selection of 32 articles. The main publication trends, countries, journals, authors, institutions, and associated keywords were analyzed. The results show that scientific production on cocoa residue biorefineries is emerging, concentrated in cocoa producing countries in Latin America and Asia, and strongly related to bioenergy routes, bioactive compounds, and the circular economy. This analysis provides both quantitative and qualitative insights to support the development of biorefinery proposals and the identification of research gaps.

Keywords: Cacao Residues. Biorefinery. Bibliometric Analysis. Circular Economy. Sustainable Energy.

Abbreviations: WoS, Web of Science; Scopus, Elsevier Scopus database; LCA, life cycle assessment.

The growing demand for sustainable solutions in energy and materials has driven efforts toward the development of biorefineries that use agro-industrial residues as feedstock. Cocoa (*Theobroma cacao* L.), an important agricultural commodity with significant production in Brazil, Ghana, and Côte d'Ivoire, generates approximately 70–80% of residues during its processing — including husks, pulp, and mucilage — presenting significant potential for use in integrated conversion processes [1].

These residues can be converted into bioethanol, biobutanol, biogas, and high-value-added compounds, thereby fostering the circular economy and contributing to CO₂ emissions mitigation [2,3].

This study aims to conduct a systematic literature review combined with a bibliometric analysis to address the central question: Do cocoa residue biorefineries exist? The quantitative analysis of the articles seeks to identify global trends, research gaps, and potential technological routes for cocoa residue valorization, while

providing qualitative and quantitative evidence to support the development of integrated conversion processes and the identification of key opportunities in the field.

Materials and Methods

This study was conducted in three sequential stages (Figure 1):

(i) Systematic search – Literature search in Scopus and Web of Science using predefined keywords (Table 1) to maximize coverage while ensuring topic relevance.

(ii) Filtering and bibliometric analysis – Publications were screened according to the adherence criteria. VOSviewer was used for keyword co-occurrence and co-authorship network mapping. Microsoft Excel was employed for data organization, statistical summaries, and generation of charts by country, journal, and other metrics.

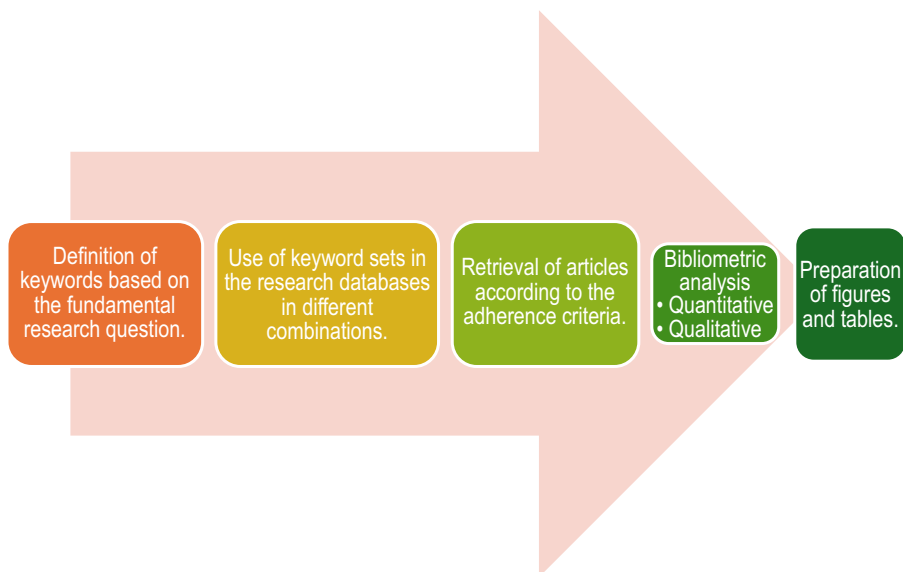
(iii) Qualitative assessment – Selection of key articles, conversion routes, and products, with emphasis on studies providing data applicable to the simulation of cocoa residue valorization processes.

Adherence Criteria

- Publications written in English and available in full text.

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Figure 1. Flowchart of the review and bibliometric analysis method.**Table 1.** Keyword sets used in the study.

Sets	Keyword Set
Set 1	(cacao OR cocoa OR "cocoa waste" OR "cocoa shell" OR "cocoa pod husk" OR "cocoa by-products" OR "cocoa residues")
Set 2	(biorefinery OR biorefining OR "biomass valorization" OR "bio-based refinery" OR "bioprocessing")
Set 3	("process simulation" OR "process modeling" OR "flowsheet simulation" OR "Aspen Plus" OR "SuperPro Designer" OR "process systems engineering")
Set 4	(cacao) AND (biorefinery) AND (process simulation)

- Publications falling into at least one of the following categories:
 - o Informational research
 - o Computational simulation
 - o Experimental study
 - o Data analysis
 - o Mathematical modeling
- Studies directly contributing to the central research question, i.e., providing data suitable for the simulation and assessment of cocoa residue valorization pathways.

The Scopus data analysis tools were used with Search 5 to generate, in some cases, selected graphs for the study.

Results and Discussion

The results section presents the main findings from the systematic review, along with the bibliometric and qualitative analyses, highlighting publication trends, research networks, and thematic focuses. These outcomes provide a comprehensive overview of the scientific landscape on cocoa residue biorefineries and identify potential opportunities for technological development.

The systematic review was conducted using the keyword combinations listed in Table 2. Initially, 34 documents were identified. One duplicate and one report or book chapter were excluded during the selection process, resulting in a final set of 32 articles.

Table 2. Literature search strategy.

No*	KSet*	WOS R*	AR*	SCO R*	AR*
1	Set 1	14.559	-	136.251	-
2	Set 2	23.018	-	293.610	-
3	Set 3	27.519	-	237.318	-
4	Set 4	4	3	251	-
5	Search 1 AND Search 2 AND Search 3	0	-	382	-
6	Search 1 INCLUDE Search 2	26	9	331	-
7	Search 1 INCLUDE Search 2 INCLUDE Search 3	0	-	26	2
8	Search 4 with 5-year criterion	-	-	237	-
9	Search 5 with 5-year criterion	-	-	344	-
10	Search 6 with 5-year criterion	-	-	290	-
11	Search 4 with 2-year criterion	-	-	195	8
12	Search 5 with 2-year criterion	-	-	274	8
13	Search 6 with 2-year criterion	-	-	233	4
14	Total	-	12	-	22
15	Final Total	-	-	-	34

*No – Number of the search; AR – Articles Retrieved; WOS R – Web of Science Results; SCO R – Scopus Results; Kset – Keywords set associated.

Table 2 presents the combinations of keywords derived from those listed in Table 1, varying their arrangement to assess the breadth of articles retrieved in the databases. Subsequently, the search scope was progressively restricted to obtain more accurate and manageable results for analysis. From these refined searches, only articles meeting the previously defined adherence criteria were selected for further examination.

The analysis of the countries associated with the 32 selected articles is presented in Figure 2. Figure 3 subsequently examines the topic on a broader scale.

Figure 2 shows that, among the 32 selected articles, Brazil had the highest number of publications (8), followed by Colombia (5), China (4), and Belgium, the United States, India, and Italy, with 3 articles each. It is worth noting that the total number of occurrences in the chart

exceeds 32 because some articles include authors affiliated with institutions in multiple countries. This distribution highlights the strong presence of research in major cocoa producing countries, such as Brazil and Colombia, while also indicating significant contributions from countries with established research infrastructures, such as Belgium and the United States. These findings suggest the presence of both regional expertise and international collaboration in the field.

To determine whether this pattern resulted from search bias or the scope of the search strategy, an additional analysis was conducted using Search 5 and the Scopus analytical tools to identify the countries associated with the articles. The results presented in Figure 3 show that the ranking changed substantially, with India emerging as the leading contributor, followed by Nigeria, the United States, Malaysia, China, Brazil, Colombia,

Figure 2. Quantitative analysis of articles based on the location of the publication.

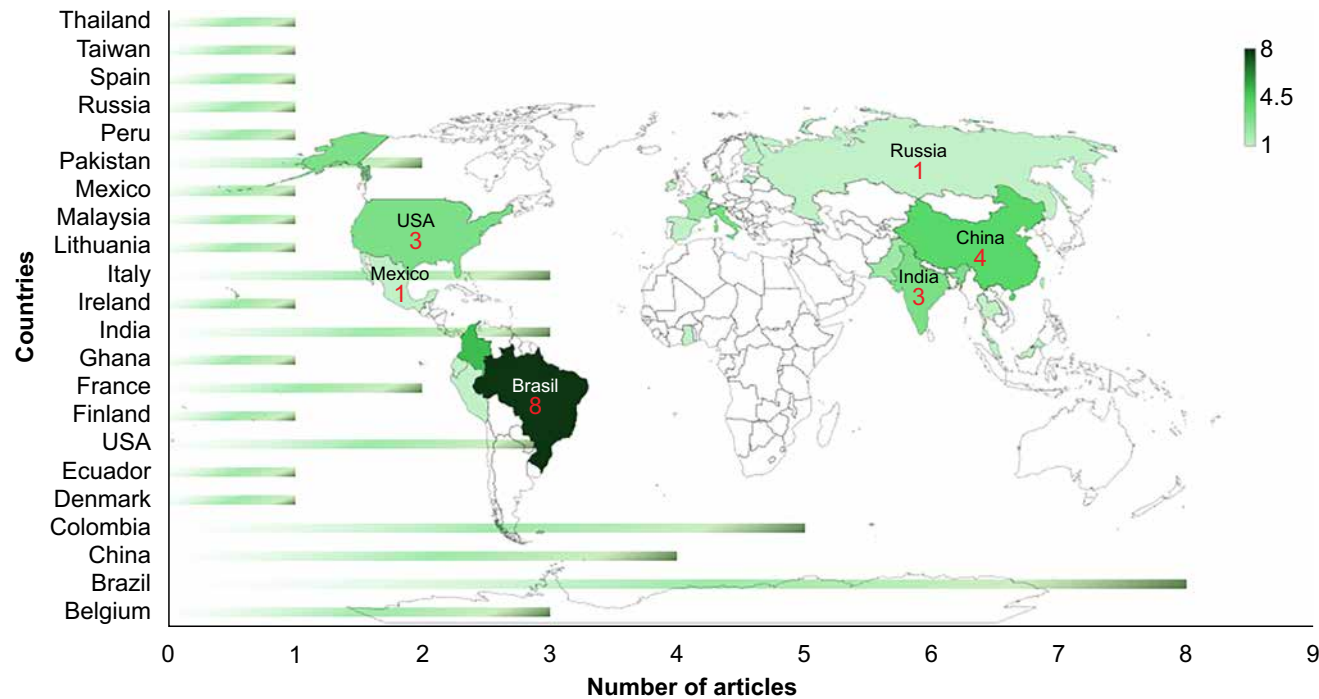
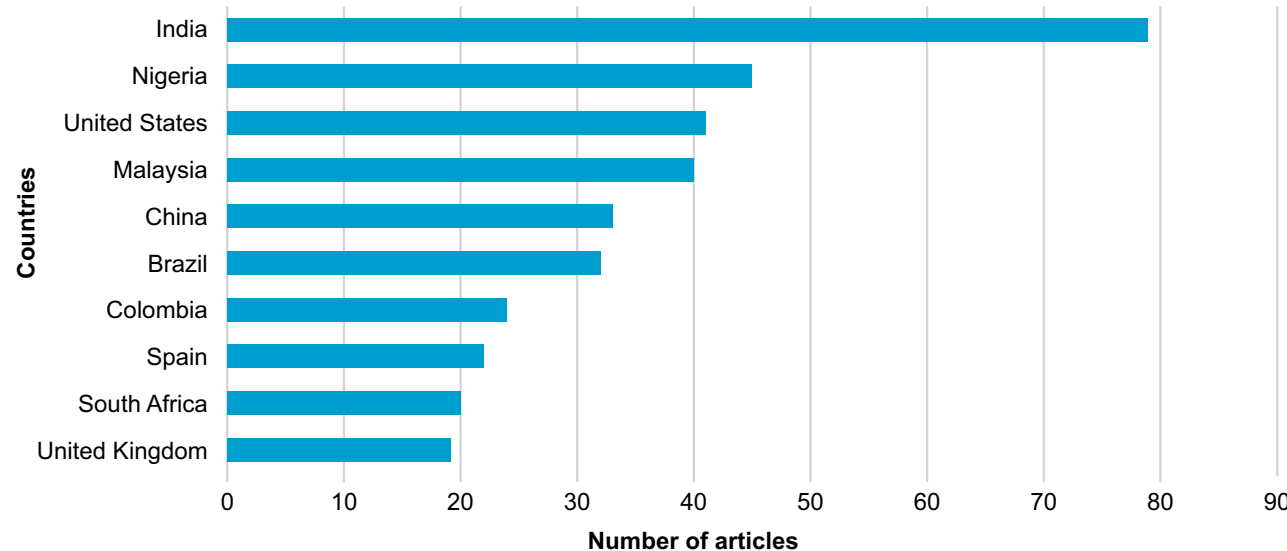


Figure 3. Quantitative analysis of articles (Scopus Analysis-Search 5) main countries of the papers.

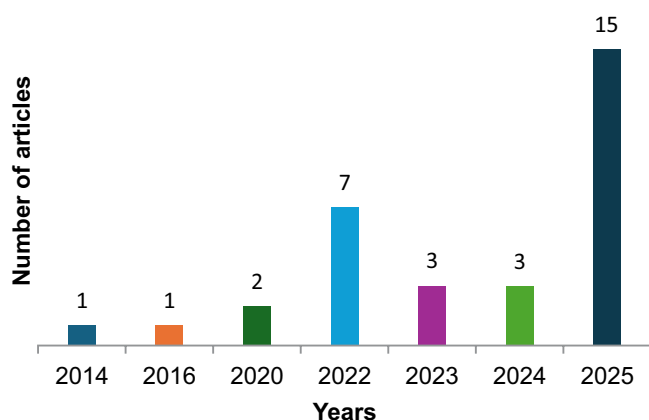


Spain, South Africa, and the United Kingdom. This shift indicates that broader search criteria capture a more diverse set of contributors, reflecting not only cocoa-producing countries but also nations with active research programs in bioenergy, waste valorization, and biorefinery technologies. These findings suggest that the observed differences may be more closely related to the scope of the

search strategy than to an inherent concentration of research in specific regions.

Subsequently, both approaches were used to assess annual publication output, as shown in Figures 4 and 5, with the aim of examining trends in interest in the topic over time. The results reveal fluctuations in publication numbers, with recent years showing a noticeable increase, suggesting

Figure 4. Quantitative analysis of articles based on year of publication.



that research on cocoa residue biorefineries is gaining momentum.

This upward trend may be linked to growing global attention to circular economy strategies, renewable energy sources, and the valorization of agricultural residues, suggesting that the field is transitioning from an emerging niche to a more established research area.

The Scopus data presented in Figure 5 include publications dated after 2025, likely because early access articles have been assigned to future issues. The leading journals within the set of 32 selected articles were analyzed, as shown in Figure 6, to identify the main publication venues in the field. The results reveal a concentration of publications in journals specializing in cocoa residue valorization

and biorefinery technologies. This concentration indicates the growing relevance and thematic consolidation of the field and may contribute to further advances.

Using the Scopus analytical tools, the institutional affiliations associated with the articles were examined, as shown in Figure 7. This analysis provides insights into which universities, research centers, and organizations are most actively engaged in studies related to cocoa residue valorization and biorefineries.

Identifying these leading institutions is valuable for mapping potential collaborators, understanding regional research capacities, and recognizing centers of excellence in the field. Moreover, affiliation patterns can reveal the extent of international cooperation, with multi institutional and cross country partnerships often indicating more comprehensive and impactful research outputs.

The most prolific authors were also analyzed using the Scopus analytical tools, as shown in Figure 8. This examination highlights researchers with a consistent track record in studies on cocoa residue valorization and biorefineries. Recognizing these leading authors is important for mapping expertise, fostering potential collaborations, and understanding the intellectual structure of the research domain. Moreover, the recurrence of certain authors across multiple publications

Figure 5. Quantitative analysis of articles (Scopus Analysis-Search 5) based on year of publication.

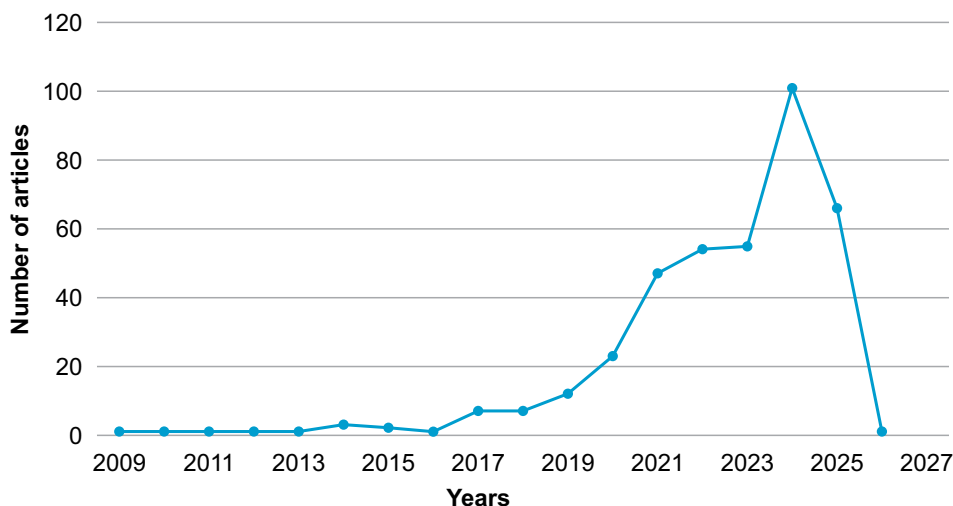
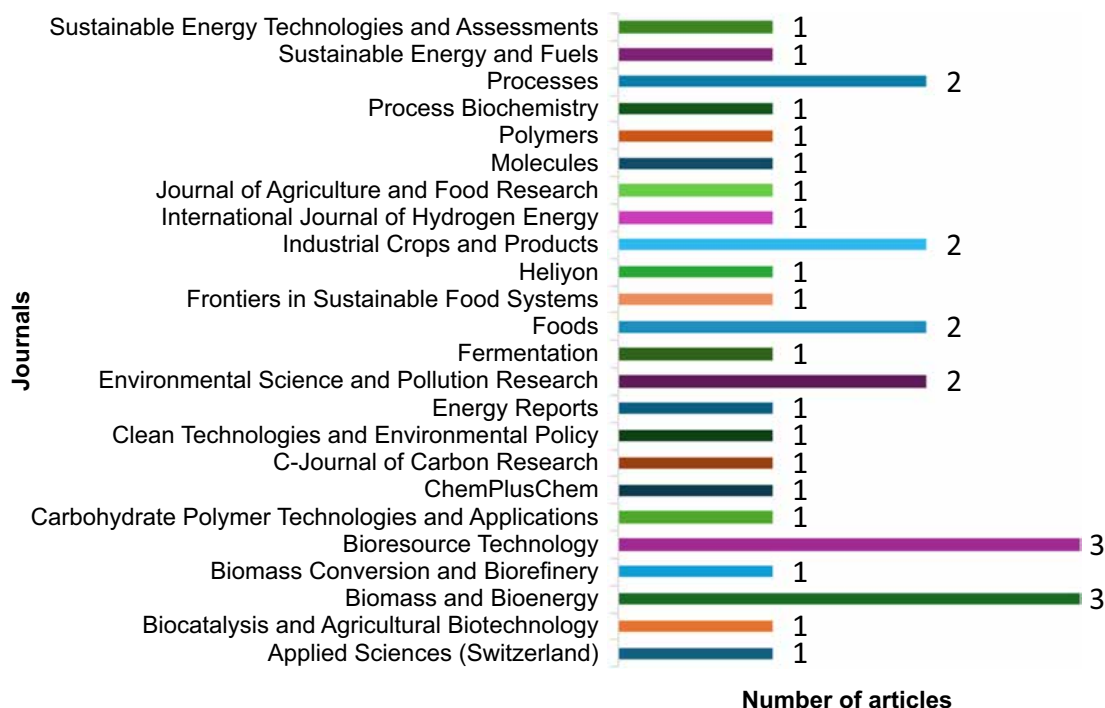
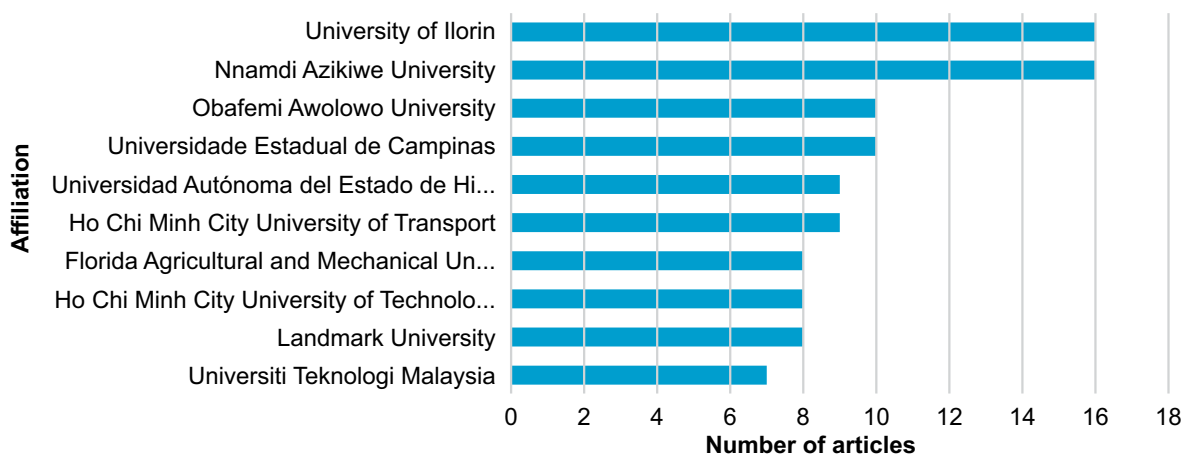


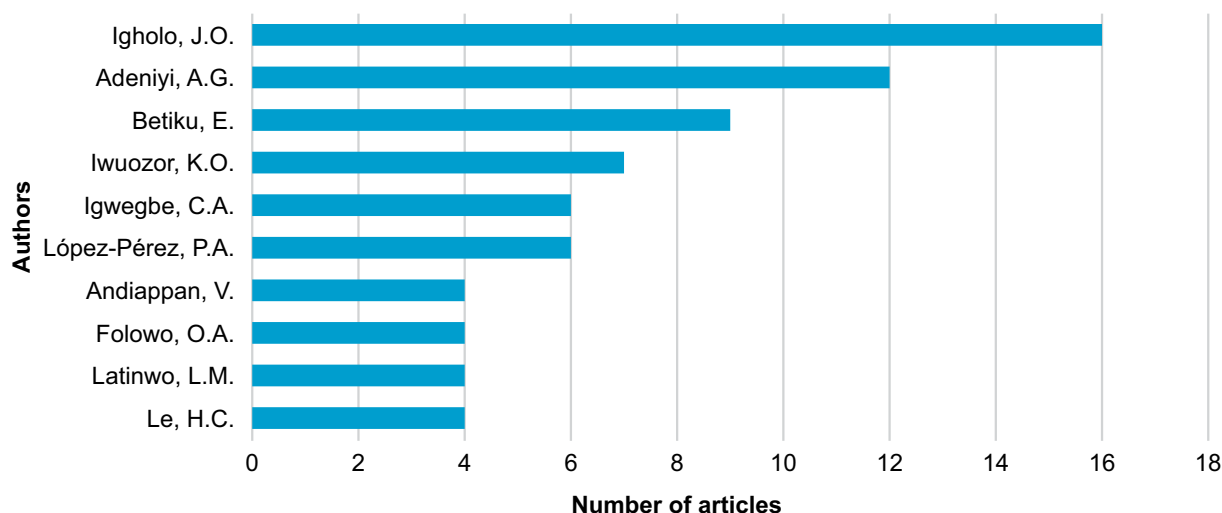
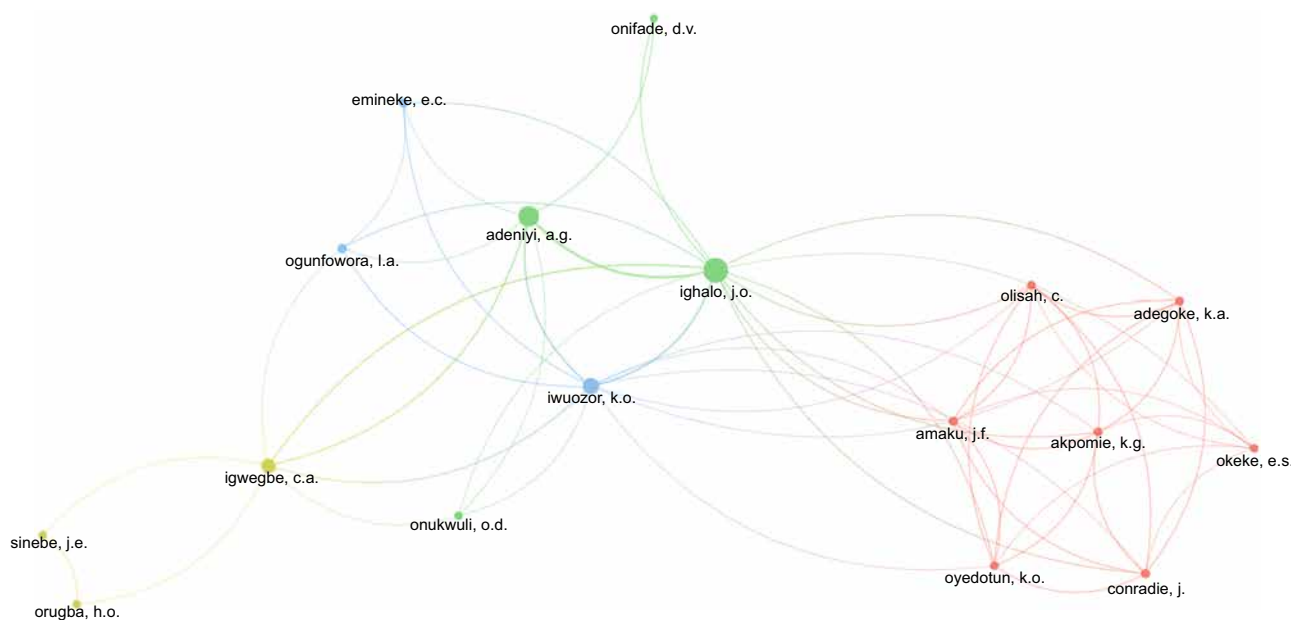
Figure 6. Quantitative analysis of articles based on journal publication.**Figure 7.** Quantitative analysis of articles (Scopus Analysis-Search 5) affiliation of the papers.

highlights their sustained research activity in the field and may reflect their contribution to the development of thematic trends and research directions. Subsequently, co authorship and keyword co occurrence analyses were performed using VOSviewer® for both the 32 selected articles and the results of Search 5, as presented in Figures 9, 10, and 11.

These network maps illustrate the main research collaborations and thematic areas, highlighting

prominent authors, recurring topics, and emerging themes. They are useful for identifying research groups, tracking thematic shifts, and identifying opportunities for new collaborations.

The co authorship network analysis revealed a relatively fragmented research structure, with several small to medium sized clusters and limited interconnections among them. Among the most prominent and prolific authors in the network were Ighalo, I.O., and Adeniyi, A.G., whose

Figure 8. Quantitative analysis of articles (Scopus Analysis-Search 5) main authors of the papers.**Figure 9.** Co-authorship analysis in network format generated by VOSviewer (Search 5).

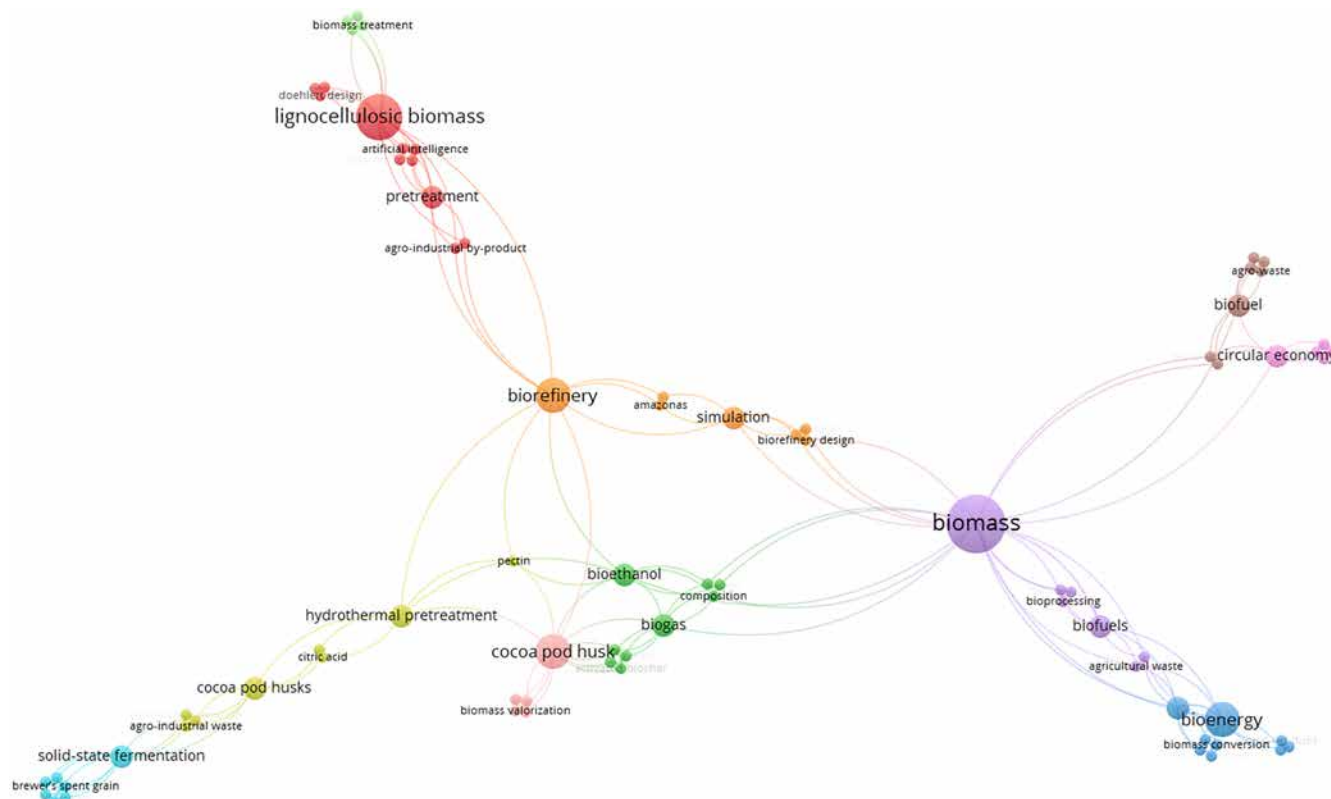
publications frequently address thematic areas related to biomass utilization, waste valorization, and sustainable process development. Their prominence within the network indicates a high level of research activity, with collaborations spanning multiple institutions and, in some cases, national borders.

In Figure 10, the most prominent keywords were biomass and sustainable development, which appeared in the same cluster. Overall, six distinct clusters were

identified, focusing on biodiesel, lignocellulosic biomass, adsorption, fermentation, sustainability, and the circular economy. This thematic segmentation illustrates the breadth of research topics represented in the dataset, ranging from technological conversion processes to broader sustainability frameworks.

The presence of clusters dedicated to both specific processing routes, such as biodiesel production and adsorption techniques, and overarching concepts, such as sustainability and the circular economy,

Figure 11. Keyword co occurrence analysis in clusters through network visualization in VOSviewer.®



for renewable fuel production. Meanwhile, the prominence of lignocellulosic biomass and biorefinery related terms indicates that studies on cocoa residues are aligned with established biomass valorization strategies, suggesting opportunities to integrate cocoa waste research into broader biorefinery and circular economy frameworks. Finally, a categorical analysis, presented in Figures 12 and 13, classified the studies as informational research, computational simulation, experimental study, data analysis, or mathematical modeling, clarifying their thematic focus, methodological diversity, and applicability.

This classification provides a clearer understanding of the methodological diversity of the selected studies and helps identify their thematic focus, technical depth, and potential applicability. The results indicate a predominance of informational studies, with fewer studies involving computational simulations

or experimental approaches. This distribution suggests that, although the topic is conceptually established, significant opportunities remain for applied and integrative research that could bridge the gap between theoretical propositions and practical implementation.

Among the 32 selected articles, none employed process simulation to address the central research question. However, the studies by Valladares Diestra and colleagues [4] and Santos and colleagues [5] address cocoa residue biorefineries and may serve as key references by providing relevant data and methodological approaches for future research and the development of integrated, scalable, and economically viable processes.

The direct answer to the article's central question is a qualified yes: studies on cocoa residue biorefineries do exist in the scientific literature; however, no studies employing process simulation were identified.

Figure 12. Distribution of the selected articles by study category.

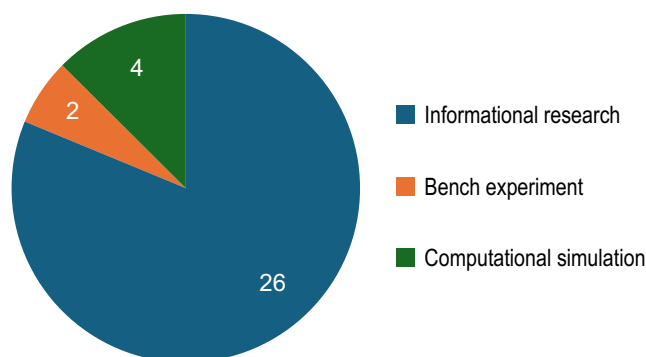
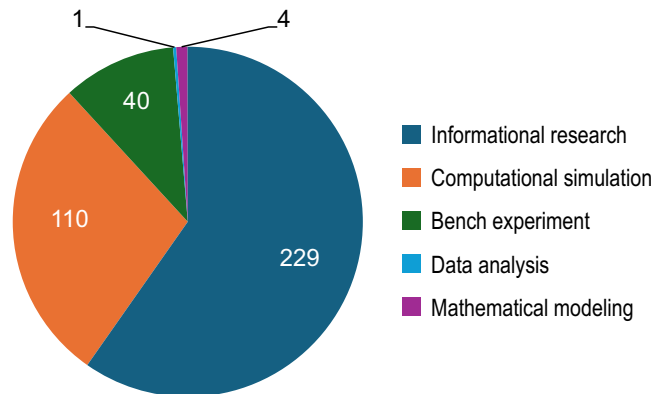


Figure 13. Distribution of articles by study category according to Scopus Search 5.



The field remains at an emerging stage, with considerable scope for further research, particularly regarding the integration of simulation based approaches with experimental and analytical studies. Expanding research on process integration, large scale feasibility, and sustainability assessment will be essential to advancing this field.

Conclusion

The analysis confirmed that studies on cocoa residue biorefineries exist, although no research employing process simulation was identified.

The field remains at an early stage, with research concentrated in regional initiatives. Bioenergy and bioactive compounds are the most explored themes, while research on integrated process design, large scale feasibility, and economic viability remains limited.

These findings highlight the need for applied interdisciplinary approaches and stronger collaboration. Future research should prioritize process simulation alongside experimental studies and techno economic assessments to support the development of sustainable cocoa based biorefineries.

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