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Smart Design and Intelligent Control of Cacao Fermentation Systems: A Technical and Bibliometric Review.

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INTRODUCTION & AIM

The global cocoa and chocolate market was valued at USD 47.1 billion in 2021 and is projected to exceed USD 68.2 billion by 2030, driven by increasing consumer demand for premium products, growing awareness of cocoa's health benefits, and continuous technological innovation across the agro-industrial value chain [1,2]. Within this expanding scenario, cocoa bean fermentation represents the most critical stage for determining the sensory quality, homogeneity, and commercial value of chocolate, as it constitutes a complex biotechnological process in which microorganisms, enzymes, and environmental and thermal conditions govern the formation of flavor and aroma precursors [3]. The process begins with an exothermic alcoholic fermentation dominated by yeasts that hydrolyze pulp sugars, followed by the metabolic activity of lactic acid bacteria and acetic acid bacteria, whose succession generates ethanol, organic acids, and heat, promoting pH shifts, embryo death, and biochemical transformations essential for the development of the final color and sensory profile of cocoa [4]. Despite its strategic importance, most fermentation systems are still operated empirically, with limited thermal control, scarce instrumentation, and minimal integration of digital technologies, thereby restricting process consistency and industrial scalability. In response to these gaps, the objective of this study is to conduct a technical–bibliometric review of recent research on cocoa fermentation systems integrating engineering design, modeling, and intelligent control approaches, aiming to identify trends, technological opportunities, and challenges for the development of sustainable, energy-efficient, and data-driven fermentation technologies.

METHOD

This study employed a technical–bibliometric review methodology to systematically analyze recent advances in cocoa fermentation systems integrating engineering design, modeling, and intelligent control strategies. A structured search was conducted in the Scopus database covering the period 2016–2025, using combinations of keywords related to cocoa fermentation, bioprocess control, smart systems, sensors, and artificial intelligence. Retrieved records were filtered according to relevance, document type, and thematic alignment, resulting in a curated dataset for analysis. Bibliometric indicators, including publication trends, authorship patterns, international collaboration, and source distribution, were evaluated, while science mapping techniques were performed using Biblioshiny to examine keyword co-occurrence networks and thematic evolution [5]. This combined quantitative and qualitative approach enabled the identification of research clusters, technological gaps, and emerging directions for the development of intelligent, energy-efficient, and scalable fermentation technologies.

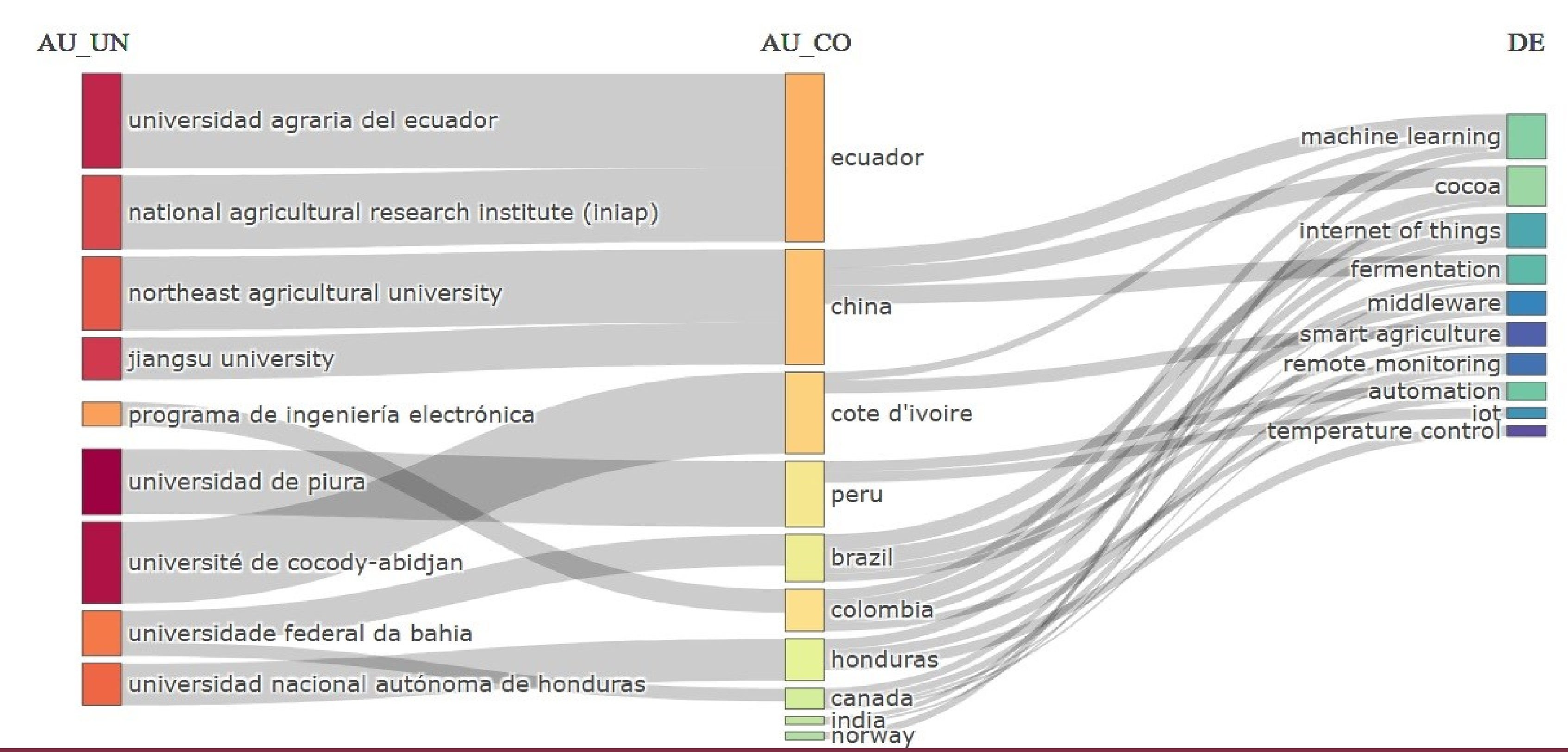
RESULTS & DISCUSSION

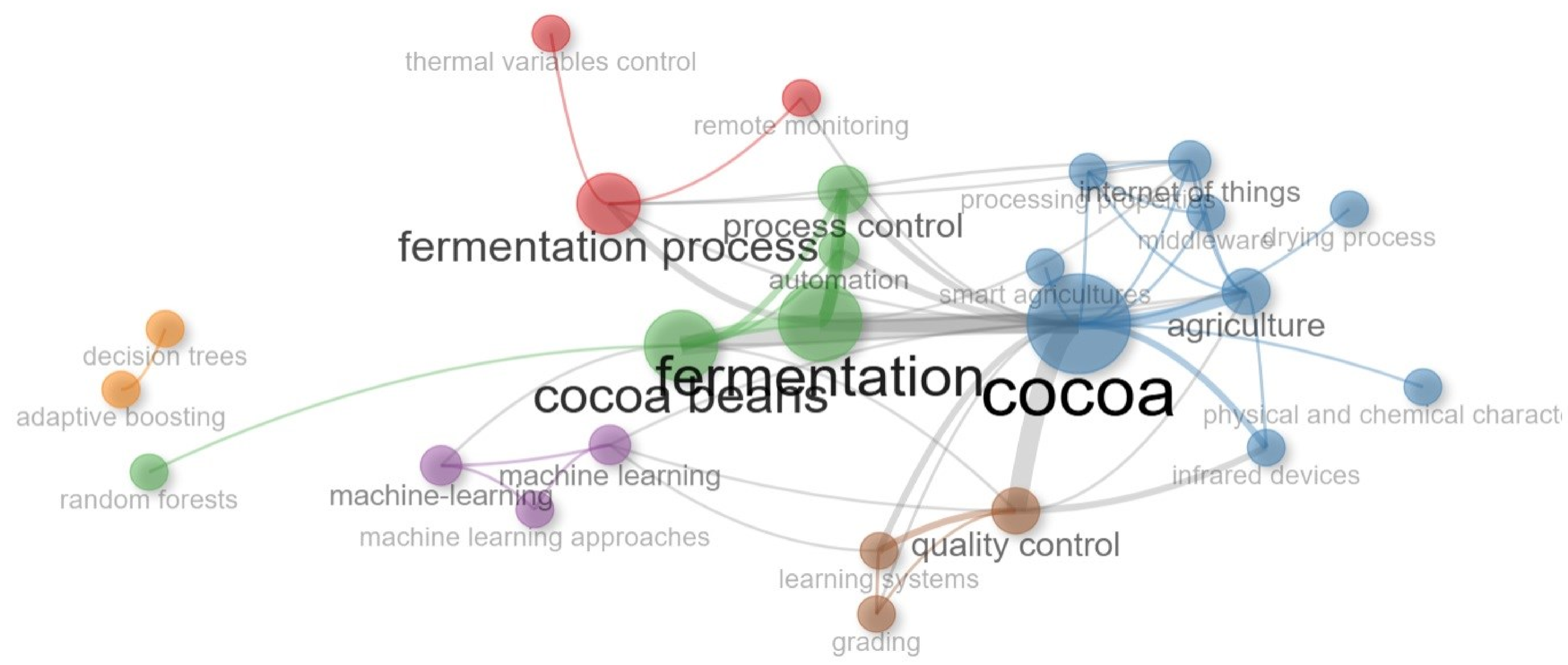
Bibliometric results – document and collaboration structure.

The bibliographic dataset comprised 24 publications distributed across 23 scientific sources during the 2005–2025 period, reflecting the still emerging nature of research on hybrid solar–biomass drying technologies. Journal articles represented the dominant document type (16 papers), followed by review articles (4), conference papers (3), and one conference review, indicating that the field is primarily driven by original experimental and technical contributions rather than synthesis studies. A total of 129 authors participated in the selected publications, with no single-authored documents, highlighting the collaborative and interdisciplinary character of this research area. The average number of co-authors per document was 7.17, while the international co-authorship rate reached 25%, suggesting moderate but increasing global cooperation. The corpus included 91 author keywords and 195 references, with an average document age of seven years and 23.83 citations per publication, indicating both conceptual consolidation and growing scholarly impact.

Institutional, Geographic, and Thematic Linkages in Cocoa Fermentation Research

The Sankey diagram illustrates the structural relationships between contributing institutions, countries, and dominant research themes within the analyzed cocoa fermentation literature. Leading academic and research organizations from Ecuador, China, Côte d'Ivoire, Peru, Brazil, Colombia, and Honduras demonstrate strong regional representation from major cocoa-producing nations, highlighting the strategic and agro-industrial relevance of this topic in tropical economies. Institutional outputs are closely connected to emerging technological themes, with author keywords clustering around machine learning, Internet of Things (IoT), smart agriculture, remote monitoring, automation, and temperature control, alongside core terms such as cocoa and fermentation. This interconnected structure reveals a clear transition from traditional fermentation studies toward data-driven monitoring, intelligent sensing, and digital control approaches, evidencing the growing convergence of food bioprocess engineering, smart systems, and artificial intelligence in the modernization of cacao fermentation technologies.





The keyword co-occurrence

The keyword co-occurrence network reveals the conceptual structure and thematic convergence of research on cocoa fermentation technologies. The central positioning and larger node sizes of terms such as cocoa, fermentation, and cocoa beans indicate their role as core scientific anchors, while surrounding clusters reflect complementary technological orientations. One group connects process control, automation, and thermal variable management, emphasizing engineering strategies for stabilizing fermentation conditions. Another cluster links agriculture with Internet of Things (IoT), smart devices, and sensing technologies, highlighting the digitalization of monitoring and field-level data acquisition. A third group incorporates machine learning methods, including random forests and adaptive boosting, associated with predictive analytics and quality assessment. Together, these interconnected themes demonstrate a progressive integration of sensing, control, and data-driven intelligence, shaping a multidisciplinary research landscape that extends beyond conventional biochemical studies toward cyber-physical and smart agro-industrial systems.

Technical analysis

Recent advances in intelligent sensing and non-destructive quality assessment demonstrate the growing role of smart instrumentation in cocoa fermentation control. A colorimetric sensor electronic nose (CS e-nose) combined with a near-infrared chemo-dye spectroscopy technique (NIR-CDS) and chemometric algorithms including extreme learning machines (ELM), support vector machines (SVM), linear discriminant analysis (LDA), and k-nearest neighbors (k-NN)enabled the classification of cocoa beans into fully, partially, and non-fermented grades with high predictive performance (85–94%). The integration of SVM and ELM achieved classification rates up to 94%, supporting in situ and non-destructive evaluation of fermentation levels. Moreover, the proposed NIR-CDS strategy provided a systematic approach for selecting sensitive chemo-dyes for sensor arrays, reducing the limitations of traditional trial-and-error methods and extending detection capabilities to volatile compounds [6]. Complementing sensing approaches, digitalization and connectivity technologies are being incorporated into fermentation management through Internet of Things (IoT) and distributed architectures. An IoT-based prototype equipped with temperature, oxygen, and carbon dioxide sensors enabled real-time data acquisition, transmission, and visualization to monitor fermentation dynamics in cocoa-producing communities in Peru [7]. Similarly, a blockchain–IoT framework was proposed to ensure secure traceability and process transparency, using smart contracts to register fermentation events and operational parameters. This system was validated through simulation and preliminary field experiments, demonstrating the feasibility of combining distributed databases with sensor networks to enhance process control, reduce data exchange overhead, and strengthen information integrity across the production chain [8]. At the same time, data-driven modeling and artificial intelligence are being applied to interpret fermentation outcomes and sensory development. Computer vision methods have been systematically used to evaluate bean quality and fermentation indices, with statistical approaches such as Partial Least Squares (PLS) frequently employed for image classification, while color, fat content, and pH were identified as key measurable indicators through FT-NIR and chemometric analysis [9]. Additionally, machine learning models trained on volatile compound profiles obtained via HS-SPME-GC–MS demonstrated strong predictive capabilities for linking microbial metabolism with sensory attributes, revealing the contribution of specific yeasts and bacteria to aroma formation and carbohydrate degradation. These results support the potential of predictive analytics and starter culture design to better understand and steer fermentation performance [10].

CONCLUSION

This review demonstrates that cocoa fermentation research is progressively transitioning from empirical practices toward intelligent, data-driven, and digitally connected systems. The integration of smart sensors, IoT monitoring, chemometric analysis, computer vision, and machine learning has enabled more accurate quality assessment, real-time process supervision, and improved understanding of microbial and biochemical dynamics. These advances collectively support the modernization of fermentation operations, enhancing consistency, traceability, and technological reliability within tropical agro-industrial contexts.

REFERENCES

1. Innovation in Cocoa Fermentation: Evidence from Patent Documents and Scientific Articles. 2. World Intellectual Property Organization—WIPO. Frequently Asked Questions (FAQs). 3. Dynamics of cocoa fermentation and its effect on quality. 4. Dynamics and biodiversity of bacterial and yeast communities during fermentation of cocoa beans. 5. Artificial Intelligence in Solar-Assisted Greenhouse Systems: A Technical, Systematic and Bibliometric Review of Energy Integration and Efficiency Advances.6. In situ cocoa beans quality grading by near-infrared-chemodyes systems. 7. Internet of Things applied to monitoring fermentation process of Cocoa at the Piura's mountain range. 8. Improving Data Security with Blockchain and Internet of Things in the Gourmet Cocoa Bean Fermentation Process. 9. Analysis of Computer Vision Algorithms to Determine the Quality of Fermented Cocoa (Theobroma Cacao): Systematic Literature Review. 10. Investigation of aromatic compounds and olfactory profiles in cocoa pulp fermentation using yeast-based starters: A Volatilomics and machine learning approach.