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Life Cycle Assessment and Exergetic Performance of Solar Agricultural Dryers: Scientific Trends, Technological Niches, and Transitions Toward Sustainable Postharvest Systems.

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INTRODUCTION & AIM

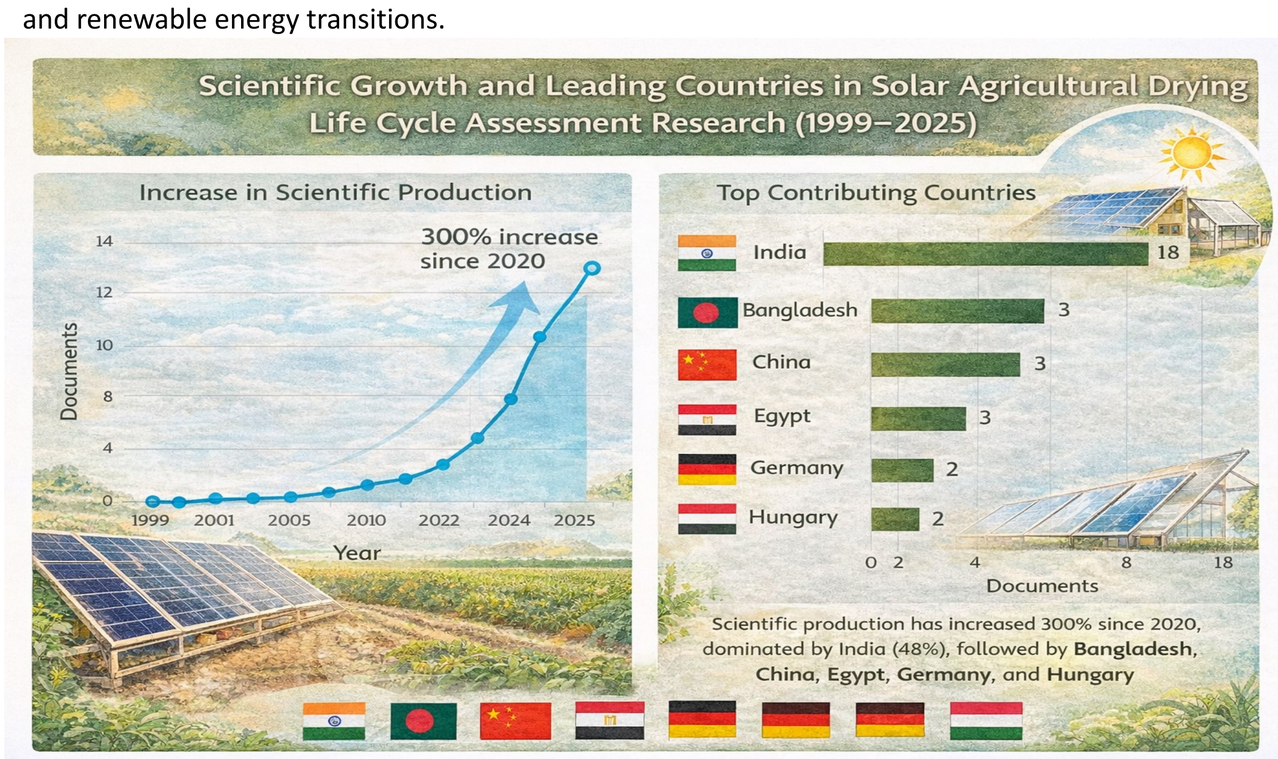
Solar agricultural drying is a key postharvest technology that reduces product losses and improves preservation using renewable energy [1]. In this context, Life Cycle Assessment (LCA) and exergetic analysis have emerged as essential tools to evaluate the environmental performance, energy efficiency, and sustainability of solar drying systems. These approaches enable the identification of technological improvements and support the transition toward low-carbon and resource-efficient postharvest processes. Therefore, the objective of this study was to analyze the scientific trends, conceptual structure, and emerging technological niches related to the life cycle assessment and exergetic performance of solar agricultural dryers through a bibliometric analysis of the Scopus database.

METHOD

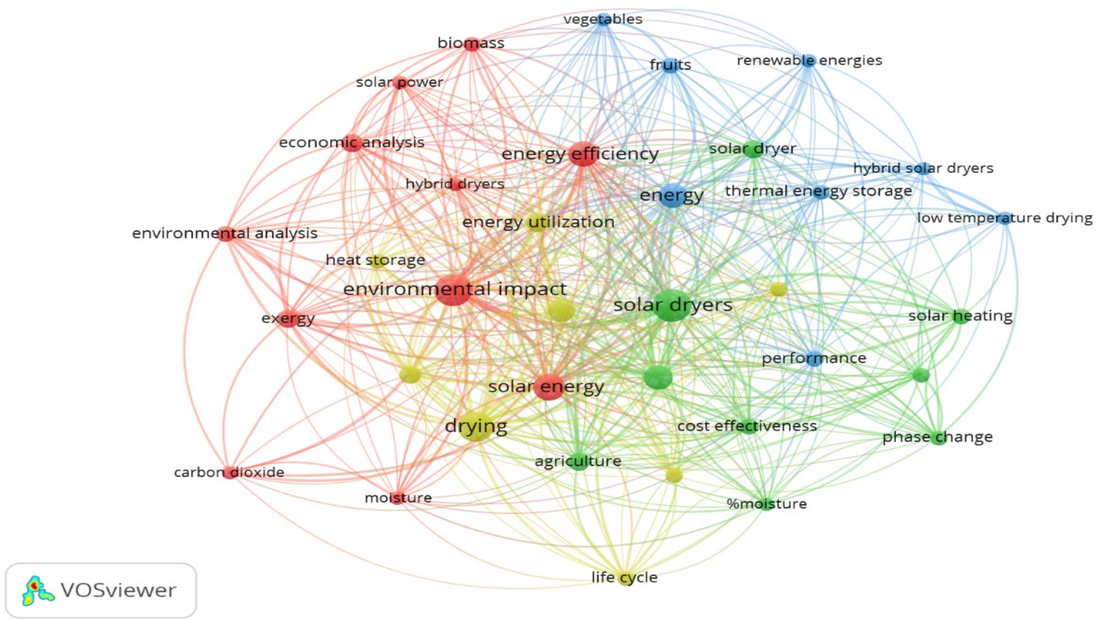
A bibliometric analysis was conducted using scientific publications indexed in the Scopus database between 1999 and 2025, resulting in a total of 42 documents related to life cycle assessment and exergetic performance of solar agricultural dryers. Bibliometric indicators such as annual scientific production and country contribution were analyzed. In addition, keyword co-occurrence analysis was performed using VOSviewer to identify the conceptual structure, and thematic mapping was developed using Bibliometrix to determine research trends, technological niches, and emerging themes in solar drying sustainability research [2].

RESULTS & DISCUSSION

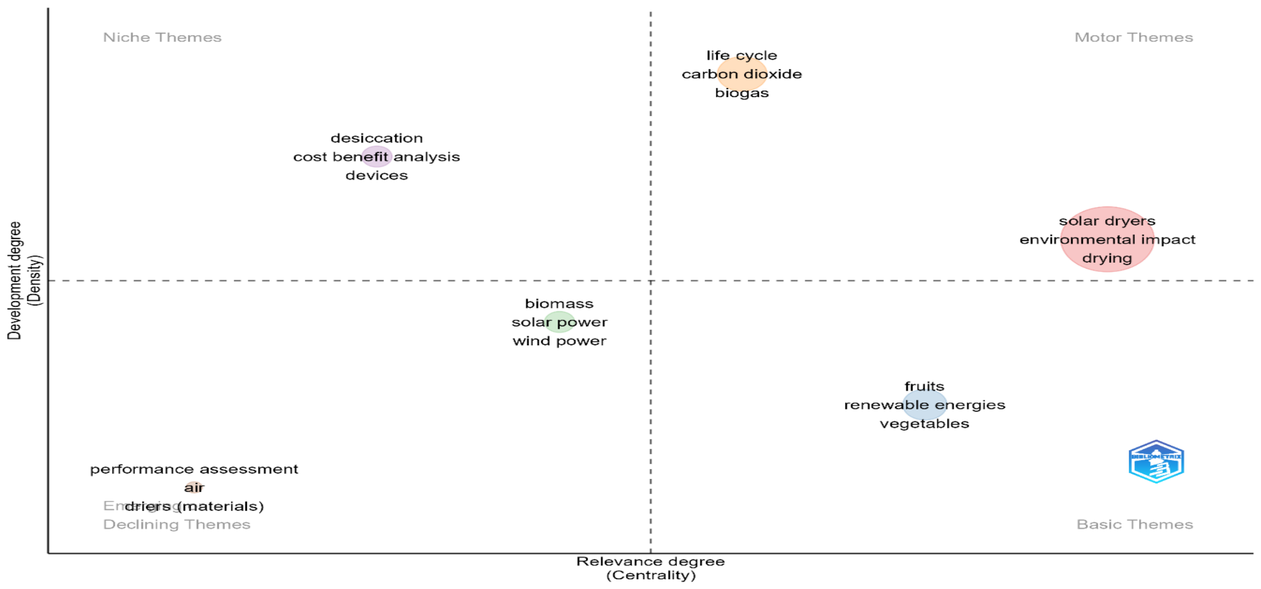
The temporal and geographical analysis confirms that Life Cycle Assessment (LCA) research applied to solar agricultural dryers has experienced accelerated growth, particularly since 2020, with an increase of approximately 300%, reflecting the rising global interest in sustainable postharvest technologies. This expansion is strongly dominated by Asian countries, especially India, which accounts for 43% of the total scientific production, followed by Bangladesh, China, and Egypt, while contributions from Europe and the Americas remain comparatively limited but emerging. This distribution highlights a regional leadership associated with high solar radiation availability, the strategic importance of solar drying in agro-industrial chains, and increasing investments in renewable energy research. In addition, the rapid increase in publications reflects a conceptual transition from conventional energy efficiency evaluations toward more comprehensive sustainability frameworks. The convergence of Life Cycle Assessment with exergy analysis and thermoeconomic approaches has led to the consolidation of the 4E framework (Energy–Exergy–Environment–Economics) as the dominant paradigm for solar dryer assessment. This evolution demonstrates that current research is no longer focused solely on improving thermal performance, but also on optimizing environmental impact, carbon footprint, and economic feasibility. Overall, these trends confirm that solar drying technologies are evolving toward integrated, low-carbon, and resource-efficient postharvest systems, playing a key role in supporting sustainable food production and renewable energy transitions.



The keyword co-occurrence network confirms that research on solar agricultural dryers is organized into four main technological domains. The first domain focuses on exergetic efficiency and thermal energy storage, including heat storage systems and phase change materials, highlighting efforts to improve thermodynamic performance. The second domain is associated with environmental analysis and carbon footprint, where terms such as life cycle, carbon dioxide, and environmental impact confirm the central role of Life Cycle Assessment (LCA) in evaluating sustainability. The third domain addresses energy hybridization, integrating hybrid solar–biomass dryers and photovoltaic/thermal systems to enhance system efficiency and reliability. Finally, the fourth domain is linked to agro-industrial applications, particularly the drying of fruits, vegetables, and high-value crops.



In addition, the thematic structure positions the solar dryers–environmental impact–drying cluster as the motor theme of current research, reflecting its high relevance and development. At the same time, the life cycle–carbon dioxide cluster emerges as a specialized niche associated with advanced environmental modeling and carbon footprint assessment. These findings confirm a clear transition toward integrated sustainability approaches, where LCA, exergy analysis, and hybrid energy systems are combined to optimize the environmental and thermodynamic performance of solar agricultural dryers.



The thematic map indicates a clear differentiation in the maturity and role of research topics within this field. The solar dryers–environmental impact–drying cluster is positioned with high centrality and density, demonstrating its strong consolidation and strategic importance in guiding current technological development. In contrast, the life cycle–carbon dioxide–biogas cluster shows high development but lower centrality, suggesting a specialized line of research with growing scientific depth. Additionally, themes such as renewable energy applied to fruits and vegetables appear as foundational topics, supporting the expansion and practical implementation of solar drying technologies in agro-industrial systems.

CONCLUSION

The bibliometric analysis confirms that Life Cycle Assessment and exergetic analysis are key tools for advancing solar agricultural dryers toward sustainable postharvest systems. Scientific production has grown rapidly, driven mainly by Asia, and shows a transition toward integrated 4E approaches combining energy efficiency, environmental impact, and economic evaluation. The consolidation of environmental assessment and emerging carbon footprint research indicate that solar dryers are evolving into low-carbon, efficient technologies that support sustainable food systems and renewable energy transitions.

FUTURE WORK / REFERENCES

Future research should prioritize life cycle assessment, redesign of greenhouse resource flows, and Future research should focus on developing dynamic and comparative Life Cycle Assessment methodologies, as well as integrating AI-assisted control and adaptive optimization to improve the performance of solar drying systems. Additionally, circular models of energy and material flows should be promoted to transform solar agricultural drying into a low-carbon and resource-efficient process aligned with sustainable food systems and renewable energy transitions.

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