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Discussion

Exploring research on ecotechnology through artificial intelligence and bibliometric maps

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ABSTRACT

Ecotechnology, quintessential for crafting sustainable socio-environmental strategies, remains tantalizingly uncharted. Our analysis, steered by the nuances of machine learning and augmented by bibliometric insights, delineates the expansive terrain of this domain, elucidates pivotal research themes and conundrums, and discerns the vanguard nations in this field. Furthermore, we deftly connect our discoveries to the United Nations' 2030 Sustainable Development Goals, thereby accentuating the profound societal ramifications of ecotechnology.

1. Ecotechnology as a research field

Ecotechnology (ECT), also known as green technology or eco-innovation, is "the strategic application of technology in ecosystem management, aiming to minimize intervention costs and reduce the negative impact on the global environment" [1]. ECT uses ecology, biology, chemistry, and engineering principles to design and implement innovative and sustainable technologies that minimize pollution, conserve natural resources, and enhance ecosystem services. It is related to various fields, including renewable energy, green chemistry, waste management, and sustainable agriculture. ECT solutions are relevant to achieve a circular economy that minimizes waste, maximizes resource efficiency, and preserves nature [2]. Therefore, it plays a crucial role in addressing environmental challenges and ensuring a sustainable future for humanity.

However, the field of ECT still has not been widely explored from a bibliometric perspective. A relevant study was developed by Haddaway, McConville, and Piniewski [3] to determine how "ecotechnology" is used in research and the main themes and results associated with this term. This kind of analysis has also been used to study specific topics related to ECT. For example, some authors analyze the literature on ecotechnological solutions related to algae [4,5], the research related to sustainable technology in the sustainability field [6], the scientific production on ecological restoration [7,8], and the state of research on the relationship between water management and constructed wetlands [9]. Except for Haddaway, McConville, and Piniewski [3], none of the previous articles analyzed ECT as a particular field of knowledge.

2. What we did

We were motivated by the following questions: How much research has been carried out by the academic community? What are the countries that have led the research? What have been the main topics and research fronts analyzed by scientific literature? How have the research results impacted the Sustainable Development Goals (SDGs) of the United Nations 2030 agenda? To explore these questions, we use a bibliometric methodology empowered by artificial intelligence and visual analytical approaches (fully described in Appendix A. Materials & Methods). The analysis was focused on the countries that show particular attention to this field, the distribution and visibility of ecotechnology research across

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various thematic domains, the exploration of the main research fronts in the scientific literature, and the research's impact on the SDGs of the United Nations' 2030 Agenda.

Web of Science (WoS) and InCites Benchmarking & Analytics (InCites) were used as data sources. We used a search strategy based on a previous systematic review [3], and we collected, processed, and analyzed 652 research articles on ECT until 2022. We introduce a neural network approach [10–12] to identify the countries more specialized in ECT research, and we use bibliometric techniques [13–15] and a new classification scheme of WoS (macro, meso, and micro citation topics) algorithmically derived from citation networks to develop a comprehensive characterization of the field. We combine methods and techniques to study how the academic community addresses ECT in scientific literature.

3. Countries' production vs specialization: a multidimensional approach

Over the last 30 years, scientific output in the field of ECT has exhibited sustained growth (See Appendix B. Complementary Results, Fig. A1). A total of 75 countries were involved in scientific production. China (81 papers, 12.4%) was the leader, followed by the USA (62, 9.5%), India (44, 6.7%), Germany (40, 6.1%) and Japan (29, 4.4%). Four developing countries were included in the top ten rankings: China, India, México (29, 4.4%), and Brazil (26, 4%). This trend underscores the significance of such research in countries facing developmental challenges, where sustainable development policies often lack sufficient resources for effective implementation. However, considering the ratio of ECT production over the total scientific output, the landscape changes drastically. Although China, the USA, and India lead the countries with a high number of documents, Latvia, Ghana, Estonia, Morocco, Bulgaria, Nigeria, Mexico, and Vietnam's production on ECT represents a higher proportion of national production, making them the most specialized countries in the field (See Appendix B. Complementary Results, Table A1).

The multidimensional comparison offers us a more comprehensive view (Fig. 1). Utilizing an artificial neural network, our study accomplished the automatic comparison, classification, and visualization of countries' multidimensional profiles in a self-organized knowledge map. The representation of the 50 most productive countries was based on six indicators: National share of ECT research, Category Normalized Citation Impact (CNCI), percentage of international collaborations, GDP per capita, Research and development (R&D) expenditure, and percentage of renewable energy consumption. The eleven colored regions denote clusters of countries with analogous profiles. Each cluster delineates a unique profile, with proximity on the map indicating similarity. Fig. 1 also features a heat map for each of the six indicators used, which helps to interpret the eleven profiles.

Several countries share some profiles, but some are so specific that the neural network has assigned them to only one country, e.g., Latvia in Cluster 1. Latvia is the most specialized country, according to the national share indicator. Its research has achieved above-mean impact (orange color in CNCI), with a low proportion of papers co-authored internationally and low values in expenditure on R&D and in GDP per capita (green color in both indicators). Notice also that it has a renewable energy consumption above the mean, which reflects Latvia's research commitment to ECT. This country has a great development in wind energy, largely due to the high wind speed of the areas of the country bathed by the Baltic Sea and the Gulf of Riga [16]. Latvian researchers have focused on using biomass for energy production and as a fertilizer in the rural sector [17]. Additionally, Latvia has developed educational programs to replace the engineering approach, which dominates the professional environments, stimulating ecotechnological thinking in schools to ensure adaptability to a changing market of environmental jobs [18].

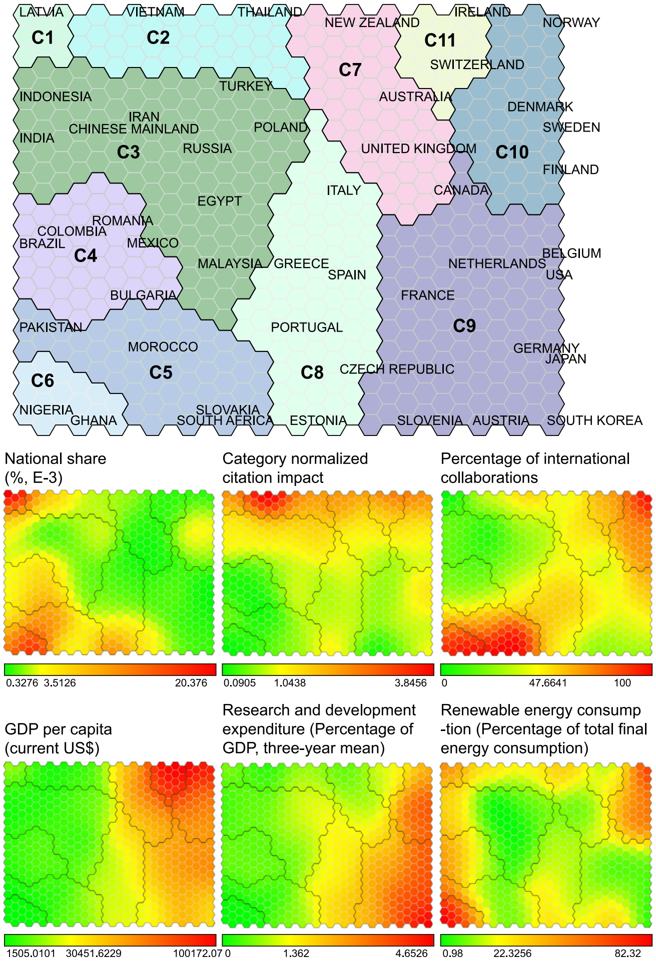

Fig. 1. Countries' multidimensional profile mapping. Proximity on the map indicates a greater similarity between countries based on six key indicators. Color bars are attached to each indicator map with its corresponding scales.

Nigeria and Ghana, two countries that lead efforts for a Green Revolution in sub-Saharan Africa [19], share Cluster 6. Both countries showed higher values of ECT specialization, renewable energy consumption, and international collaboration and lower values of CNCI, GDP per capita, and R&D expenditure. Nigeria and Ghana are the two most populous countries in West Africa, experiencing high population growth in recent years. The need to feed the large population of both nations facilitated the development and dissemination of the sawah rice-producing technology [19–21]. In the nearest cluster (C5), the other two African countries (Morocco and South Africa), as well as Pakistan and Slovakia, share similar characteristics. But they differ in renewable energy consumption, which is lower in these last countries.

Another important area to highlight on the map is Cluster 2, which comprises two countries on the Indochinese peninsula: Vietnam and Thailand. Their ECT research has the highest normalized impact, mainly using phytoremediation as an eco-friendly solution to restore the environment [22–25] and developing sustainable policies for technological intervention in delta environments [26]. This is particularly relevant for Vietnam. The Mekong Delta is a natural treasure and one of the main sources of agriculture and aquaculture for the country, but it is extremely vulnerable to climate change caused by rising sea levels, coastal erosion, and saltwater intrusion [27].

The more developed countries are located on the right side of the cluster map (Clusters 7, 8, 9, 10, and 11). Among these higher-income nations, Nordic countries (Norway, Denmark, Sweden, and Finland, Cluster 10) are highlighted by higher values of renewable energy consumption. Nordic countries have a deep-rooted culture of environmental research, with a wide diversified scientific production on ecotechnologies. Authors from these countries have focused on various topics, which include the recycling of carbon and nutrients from domestic and industrial wastewater [28]; the conversion of organic waste into several products, such as electricity, biodiesel, and organic fertilizer [29]; the development of more environmentally friendly production technologies to curb the negative environmental impacts of salmon aquaculture [30], and even the use of artificial intelligence and robotics in eco-technological projects [31]. The experience of these countries in integrating renewable energy sources into different sectors, particularly wind generation in the electricity market, is remarkable [32].

The Latin American countries (Mexico, Colombia, and Brazil) are in Cluster 4, along with Bulgaria and Romania. Countries exhibit relatively low values of GDP per capita, insufficient investment in R&D, low impact, and ECT research characterized by intense international collaboration. However, the correlation between the high scores in consumption of renewable energies and ECT specialization is the main characteristic of the cluster. Mexico is the most productive country in the group, with stable activity since the 1990s and notable thematic diversity. Social inclusion is a key topic in Mexican scientific production, considering traditional ecotechnologies for industry processes and practices [33,34]. Brazilian authors achieved high visibility with research on composting to recycle aquaculture wastes [35–37].

Finally, countries in Cluster 3 only stand out for their normalized impact, which stands slightly above the world average. China is the most productive country of the group, with a long tradition in the development of agro-ecological engineering [38], as well as relevant research measuring eco-efficiency [39]. Russia also contributes to many topics and brings the ecotechnological perspective of space exploration [40]. Relevant papers from Indian authors were focused on wastewater treatment [41,42], particularly in the textile industry [43], while Poland authors explored the use of ECT for recycling carbon, heavy metal removal, and recovery of nitrogen and phosphorus from wastes [44–46].

4. Thematic analysis using macro, meso, and micro topics: expected vs real impact

Previous ECT studies used heat maps to identify emergent themes, knowledge clusters, or knowledge gaps [3,47]. Here we performed the thematic characterization of the domain using the macro, meso, and micro topics recently launched by Clarivate Analytics. In general, ECT research was distributed into ten macro topics (100% of 10, inner circle), 100 meso topics (30.67% of 326, intermediate circle), and 188 micro topics (7.65% of 2457, peripheral circle) (See Appendix B. Complementary Results, Fig. A2a, b).

Traditionally, journals covered by the Journal Citation Report are ranked and distributed in quartiles of visibility, according to Garfield's Impact Factor (GIF). In this context, papers published in journals with the highest GIF have a higher probability of receiving citations (expected impact). Here, 30.46% of ECT papers were published in Q1 journals, less than the 47.62% of world papers in Q1 journals; the rest was distributed as follows: 33.7% in Q2, 18.6% in Q3, and 17.25% in Q4. At the same time, none of the ten macro topics, only 27 from the 100 meso topics (27%), and 45 from the 188 micro topics (23.9%) showed a percentage in Q1 journals above the global baseline (>47.62%) (See Appendix B. Complementary Results, Fig. A2a). This effort does not result in high citation activity during the analyzed period (real impact). Only two of the ten macro topics (20%, Social Sciences and Engineering & Materials Science), 16 of the 100 meso topics (16%), and 35 of the 188 micro topics (18%) showed a CNCI above the global baseline (>1.00) (See Appendix B. Complementary Results, Fig. A2b).

Bioengineering was the most represented meso topic, covering highly visible literature on constructed wetlands [48]. In the scientific output covered by the macro topic Social Sciences, papers indexed by meso topics Sustainable Sciences, Economics, and Agricultural Policy showed CNCI values above the world mean (>1.00). In this context, papers using emergy-based indices to evaluate the sustainability of ecotechnological processes [49] and papers that use Data Envelopment Analysis as a measure of the efficiency of ECT [50] achieved the highest visibility. Finally, in the literature covered by the macro topic Engineering & Materials Science, papers indexed by meso topics Mineral & Metal Processing, particularly research on bioleaching [51], showed a high normalized impact.

Despite an increasing evolution of the normalized impact of papers (CNCI) (See Appendix B. Complementary Results, Fig. A3), which demonstrates the increasing relevance of the field, the value of this indicator for the whole period is slightly below the world average (CNCI = 0.84). In fact, only 9.36% and 0.61% of the articles were ranked in the Top 10% and Top 1% of the most cited articles according to their thematic category, respectively. This citation rate demonstrates that ECT is still an emerging and less visible field in mainstream literature. In addition, only 26.8% of papers were published in open-access journals, limiting research availability for the scientific community.

5. Characteristics of the main research fronts on ecotechnology

A general comprehensive thematic characterization of ECT research was developed using a classic bibliometric technique (bibliographic coupling) [13]. The main research fronts were identified in the bibliographic coupling network using VOSviewer (See Appendix B. Complementary Results, Fig. A4). The principal component of the network reveals 18 thematic clusters, covering 61% (400 articles) of the total output (Box 1).

Effective wastewater treatment covers the three most relevant clusters identified in our study (Clusters 1, 2, and 3). Large-scale wastewater treatment strategies have recently gained significant attention [52]. In this context, constructed wetlands have been an innovative approach to wastewater treatment, stormwater management, and habitat restoration [53,54]. Clusters 1 and 3 cover many papers focused on developing innovative and sustainable approaches to treat wastewater generated from various sources, such as domestic, industrial, and agricultural activities. The authors explored advanced treatment technologies, such as membrane filtration, oxidation processes, and biological treatment methods, and the design, operation, and performance of constructed wetlands for various applications. Particularly, Cluster 3 analyzes the role of wetland types and national strategies in treating different types of pollutants, optimizing hydraulic and pollutant removal efficiency, and evaluating the ecological and socio-economic benefits of constructed wetlands [55–57]. On the other hand, Cluster 2 includes pioneers' studies on ecological engineering as a research field [58,59], strongly related to environmental management strategies [1,60,61].

Box 1.
Characterization of the main research fronts.

1	Large-scale wastewater treatment: Constructed wetlands and general issues	10	Evaluation of Sawah rice-producing technology in African countries
2	Ecological engineering and environmental management	11	Ecotechnologies for recovering and reuse of carbon and nutrients from wastewaters
3	Large-scale wastewater treatment: Sustainable strategies for emission control	12	Composting for recycling aquatic and animal wastes: Fly larvae and algae
4	Ecotechnological innovation efficiency in energy production	13	Eco-technoeconomic analysis and social adoption
5	Forestation and ecosystems restoration	14	Biogas production
6	Sustainable metrics and models for ecotechnologies assessment	15	Wastewater treatment with multi-soil layering ecotechnology
7	Ecotechnologies management in urban contexts	16	Licensing Strategies of Ecotechnologies to control emissions from production processes
8	Philosophical, economic, and ethical issues related to ecotechnologies	17	Development of pavements with high permeability for stormwater management
9	Studies on microbial communities in constructed wetlands	18	Processing and hydrophilization of textiles with biomaterials

The efficiency of ecotechnological innovations in energy production (Cluster 4) is another significant research front [62,63]. Papers were mainly focused on the environmental assessment and protection in energy industries and modern business, developing technologies and processes that maximize the efficiency of energy production from renewable sources, and promoting the transition to a low-carbon and sustainable energy future [50,64–66]. On the other hand, Cluster 5 focused on restoring and managing forest ecosystems to mitigate climate change, enhance biodiversity, and promote sustainable resource management. This research front involves different forestation techniques [67–69], including natural regeneration and assisted restoration approaches, as well as the assessment of the ecological, social, and economic impacts of forestation efforts.

Four interdisciplinary clusters closed the list of the most productive research fronts. Cluster 6 involves the development of quantitative and qualitative assessment tools to evaluate the sustainability performance of ECT [49]. Cluster 7 reflects organic and sustainable agriculture [70] and ECT in urban contexts [71]. Cluster 8 includes papers covering philosophical, economic, and ethical issues related to ECT [72–76]. Cluster 9 analyzes the complex microbial communities and processes in constructed wetlands. This implies the study of diversity, dynamics, and functions of microbial communities and their roles in nutrient cycling, pollutant removal, and ecosystem functioning [77–79].

Another nine less productive (but no less important) fronts were identified. Cluster 10 is a very locally based research front that assesses the sustainability and effectiveness of Sawah rice production systems, particularly in West African countries [21,80]. Cluster 11 focuses on developing sustainable ECT, such as anaerobic digestion, algae cultivation, and bio-electrochemical systems for recycling carbon and nutrients [81] and recovering phosphorus and nitrogen from wastewater [82]. Composting for recycling aquatic and animal wastes (Cluster 12) is basically centered on using algae and fly larvae, particularly *Hermetia illucens* (black soldier fly) [36,83], in composting processes to recycle organic wastes from aquatic and animal sources.

The research included in Cluster 13 presents an eco-technoeconomic analysis and social adoption of ECT [84,85]. In this context, an Eco Technological Transfer Index (ETI) was proposed to measure the sociotechnical pertinence of ECT in social environments to identify external and internal factors that affect its social adoption [85]. Cluster 14, dominated by Polish authors, focuses on producing biogas through the anaerobic digestion of organic wastes, such as agricultural residues, food waste, and wastewater sludge [86]. Cluster 15 explored using multi-soil layering (MSL) as a sustainable and cost-effective ECT. MSL is a passive treatment system that uses a combination of natural processes, such as filtration, adsorption, and biological degradation, in multiple soil layers to treat wastewater and remove pollutants [87–89].

A social science-based research front on ECT licensing strategies to control emissions from production processes (Cluster 16) was also identified [90,91]. On the other hand, Cluster 17 concerns the design and development of permeable pavements as a sustainable solution for managing stormwater runoff in urban areas [92,93]. Finally, Cluster 18 focuses on developing sustainable and eco-friendly methods for processing textiles and imparting hydrophilic properties to them using biomaterials [94]. Research lines with still low productivity values were not represented by the bibliometric technique.

6. Ecotechnological practices and the united Nation's 2030 agenda for sustainable development

The social impact of ECT was another issue covered by our study. We identified the SDGs involved in papers on ECT (14 SDGs) and its citing papers (16 SDGs) (See Appendix B. Complementary Results, Table A2). Clean and water sanitation (SDG 06) and underwater life (SDG 14) were the most represented SDGs, which confirms that water and wastewater treatment is one of the most relevant topics analyzed by researchers. The articles were mainly published in journals specializing in aquatic ecology, environmental engineering, and toxicology, focusing on water resource management and conservation. Water quality and pollution, aquatic ecosystem conservation, and environmental toxicology are key topics related to these SDGs.

Research impacting life on land (SDG 15) and climate action (SDG 13) also have high levels of productivity and impact, covering journals specialized in forestry, geography, mining, and mineral processing and analyzing topics related to the management and conservation of terrestrial natural resources, CO_2 emission control, and climate change mitigation. On the other hand, sustainable cities and communities (SDGs 11) comprise articles published in journals with a wide scope, covering meteorology and atmospheric sciences, computer science, metallurgical engineering, urban planning, and community sustainability. Key areas include urban natural resource management and planning, climate and air quality modeling and prediction in urban areas, and metallurgical engineering and materials technology for infrastructure and construction.

Literature impacting SDG 12 (responsible consumption and production) involved journals on agronomy, biodiversity conservation, management, material sciences, applied mathematics, operations research, and interdisciplinary social management. This may indicate the wide thematic range, which includes research on sustainable management of natural resources, process optimization, and techno-economic measures. Other highly productive SDGs were industry, innovation, and infrastructure (SDG 09), covering journals specialized in economics, industrial engineering, and multidisciplinary engineering; affordable and clean energy (SDG 07), involving journals specialized in environmental science and technology, energy and fuels, agricultural and industrial engineering, applied physics, green and sustainable science and technology, and environmental sciences, with a focus on research topics related to renewable energy and energy sustainability; and zero hunger (SDG 02), covering journals specialized on biotechnology and applied microbiology, food sciences, and polymer technology, indicating a focus on sustainable food production and food processing technology research. The less represented SDGs were headed by good health and well-being (SDG 03), covering journals on telecommunications, communication and information, plant sciences, and public, environmental, and occupational health.

We also observed a strong relationship between the SDGs of papers on ecotechnology and the SDGs of articles citing these papers (See Appendix B. Complementary Results, Fig. A5). However, this bibliographic relationship does not allow us to understand the traditional synergies and trade-offs between SDGs [95], for which it is necessary to consider other variables and a qualitative investigation.

7. What we found

Our study provided a comprehensive characterization of ECT research, identifying literature trends and patterns and the geographical distribution of research groups.

One important result has been the higher level of specialization in ECT research observed in low-income countries. In previous reports, the geographical analysis was limited to identifying the leadership of the USA and China as the most productive countries [3,8,9]. In this study, the use of relative bibliometric measures (e.g., National share or CNCI) and their combination with other size-independent indicators has been fundamental. Although the more developed countries produce most of the total research, some developing countries devote a larger share of their total scientific production to ECT. These countries often face significant socio-environmental challenges such as deforestation, natural disasters, soil degradation, water scarcity, air pollution, and changes in agricultural productivity. In all these cases, ecotechnologies offer a low-cost, sustainable, and eco-friendly solution to these challenges, helping to build resilience and mitigate the effects of climate change. The results also tell us about the low priority of ECT in developed countries, indicating that the global policies aimed at this end are still not achieving the expected results. Only Nordic countries showed a solid and highly visible research output, in alignment with national policies that promote using renewable energies to change their energetic matrices [96]. As can be corroborated by Fig. 1, more than a third of the energy supply of Nordic countries comes from renewable sources, and half of all the energy consumed is CO_2-free [97].

We identified that wastewater treatment and ecosystem preservation are among the most prominent topics and research fronts in the field of ECT. Also, the constructed wetlands strategy was clearly identified as relevant, corroborating the findings of Zhang et al. [9]. Restoring degraded ecosystems is crucial for maintaining biodiversity, regulating climate, and providing essential ecosystem services that sustain human well-being. Previous findings reported by Liu et al. [7] and Wei et al. [8] support our idea that ecological restoration might soon be one of the most promissory research lines. Ecotechnologies such as bioremediation and phytoremediation can restore degraded ecosystems and increase their resilience. Furthermore, the importance of sustainable energy production appeared as an outstanding research front. Bioenergy, related to geothermal energy and energy storage, has the potential to make a significant contribution toward the transition to a low-carbon economy.

8. Limitations

The main limitations of this study were related to the restricted search strategy. The syntaxis “ecotech” is not included in titles, abstracts, or keywords from all ecotechnological papers. Another limitation is related to the use of WoS as a unique data source, causing the loss of articles from other databases. Finally, we were also challenged by the complexity involved in evaluating the social impact of ECT. Haddaway, McConville, and Piniewski [3] communicated the difficulties in ascertaining whether ecotechnologies are undertaken for nature or society. They noted a dichotomy: some ecotechnologies are used to reduce human impacts, while others are used to improve natural ecosystems. Also, they could not identify with clarity whether ecotechnologies make nature work for society or whether they make society work for nature.

In general, the relationship between ECT research and the SDGs is complex since each SDG objective has multiple dimensions and is interconnected with other objectives. Some SDGs are inextricably linked to the achievement of another goal. However, there are also no significant positive or negative interactions, and some SDGs could limit or clash with another goal [98]. Our bibliometric approach did not provide sufficient granularity to capture the synergies and trade-offs between SDGs [95]. Also, the complexity lies in the need to address a series of interconnected variables, which are influenced by social, political, and economic factors, as well as by the geographical and cultural context. Therefore, analyzing this relationship requires an interdisciplinary approach and complex research methods, including collecting and analyzing quantitative and qualitative data.

9. Implications for further studies

Various actions and approaches can be considered for future bibliometric studies of ECT research. Firstly, expanding search strategies to include a wider array of terms related to ECT may yield a more exhaustive corpus of relevant literature. Secondly, it is crucial to investigate the engagement and impact on local communities by ECT projects, particularly in terms of gender inclusion, equity, and social justice. These aspects are integral to several United Nations SDGs (SDGs 5, 10, and 16) and are vital in addressing global challenges and fostering a more equitable world. Furthermore, a deeper exploration into the transfer of ECT between regions and nations is essential to identify obstacles and promote worldwide adoption. Investigating collaboration networks among ECT researchers and organizations could also provide insights into partnership dynamics and their role in knowledge generation.

Finally, analysis derived from this study may be important for policymakers and society in general. Our results offer a reflective lens on the importance of ECT research and its potential impact in solving global challenges.

CRediT authorship contribution statement

Ricardo Ruiz-Sánchez: Data Curation, Formal Analysis, Investigation. **Julia Tagüeña:** Conceptualization, Project Administration. **Ricardo Arencibia-Jorge:** Validation, Visualization, Writing - Original Draft. **JosÉ Luis Jiménez-Andrade:** Methodology, Visualization, Software. **Humberto Carrillo-Calvet:** Supervision, Writing - Reviewing & Editing.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Supplementary data

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