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Green techs, clean techs, and disruptive technologies: a bibliometric analysis of trends and literature landscape

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Abstract
With the growing environmental awareness of consumers in the global market, companies need to keep pace with the emergence and application of new technologies for sustainable solutions to maintain their competitive advantage. Thus, this study presents a bibliometric analysis of research on disruptive technologies and sustainable solutions, focusing on the evolution, approaches, and trends of these technologies, known as cleantechs and green techs. A total of 140 articles published between 2003 and 2022 were analyzed using the VOSviewer software to identify research clusters focused on blockchain and smart electricity. The results show that these technologies have the potential to contribute to sustainability and the United Nations Sustainable Development Goals (SDGs), although challenges and limitations have been identified.

Keywords: technologies, sustainable energy, sustainability, blockchain, bibliometrics.

1. Introduction

Economic development and sustainability have been interconnected since the United Nations Conference on Environment and Development in Stockholm in 1972 (Berchin, 2016). Later, the Brundtland Report in 1987 popularized one of the most widely cited definitions of sustainable development: “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland, 1987, p.16).

In the subsequent decades, environmental monitoring satellites made a notable advancement in monitoring climate and territorial changes, thereby emphasizing the need to formulate and implement comprehensive environmental plans that need appropriate technologies (Pellegrino et al., 2007). Technologies aimed at environmental conservation and preservation have come to be categorized under the terms cleantechs and greentechs, with important distinctions. Cleantechs refer to innovations focused on reducing environmental impact by decreasing emissions and natural resource use compared to conventional technologies, commonly applied in areas like renewable energy generation, energy efficiency, and waste management. Greentechs, on the other hand, encompass a broader approach, including technologies that seek to restore and protect the environment, promoting practices such as eco-friendly mobility and sustainable water management (Truffer, 2012; KPMG, 2013).

The relevance of studying these technologies becomes even more evident in the current context, marked by climate change and the growing need for sustainability. The adoption and development of clean and green technologies represent a response to contemporary environmental and economic challenges, while also providing solutions to reduce environmental impact and support a transition toward a more sustainable future.

In 2015, the United Nations Summit on Sustainable Development recognized the emergence of these clean technologies and their pivotal role in fostering sustainable development. Consequently, the global agenda of the Sustainable Development Goals (SDGs) was established (United Nations, 2015), consisting of 17 goals and 169 practices to be achieved by 2030 (Figure 1). SDG 9 aims to promote the development of innovative and sustainable solutions that help to solve environmental problems (such as global warming) and social problems (such as poverty and access to basic services). Among the 17 goals, Goal 9 will be this study's most highlighted sustainable objective. This United Nations' Goal 9 points towards a breakthrough in infrastructure and innovation to achieve the planet's sustainable economic and social development.

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Figure 1. 17 Sustainable Development Goals.

Considering that more than half of the global population lives in cities, according to 2022 data from the World Bank (2022), issues such as waste, transport, and energy are increasingly relevant.

Thus, technological progress and promoting scientific research are essential to solving economic and environmental challenges (United Nations, 2015). Since environmental issues have occupied more space in all spheres, the industrial sector has been most transformed in recent years. Many companies have had to adapt to new legislation, introduce new technologies, make new investments, and even reinvent themselves for environmental reasons (Ford & Despeisse, 2016).

Landrum (Landrum, 2018; Landrum & Ohsowski 2018) states that companies have sought to incorporate actions and practices toward environmental sustainability into their business models to increase their social responsibility. However, according to the author, with the current model prevailing in industries and markets and rapid technological evolution, improving corporate social responsibility is disconnected from environmental preservation.

The constant innovations and new versions of products and processes generate a shorter life cycle in manufacturing. In consumers' daily lives, this evolution is noticeable from the so-called planned obsolescence (Reinecke & Pezzoli, 2015), in which the consumer purchases new products more frequently, generating greater consumption and, consequently, a greater amount of waste for the planet.

Furthermore, as global competition increases, industries are increasingly pressed to achieve better performance and profits with lower costs and shorter lead times (Adebayo & Kirikkaleli, 2021). In this context, it is necessary to rethink production-consumption methods to consume fewer resources and protect the ecosystems that generate them. In this way, innovative and sustainable products and services have drawn the attention of academics and professionals worldwide. In this sense, Galanakis et al. (2021) consider that great lessons were learned from previous catastrophic global events, such as the COVID-19 crisis, Spanish flu or the Black Death, where inspiration must lead to changes in social, environmental, and technological paradigms to generate disruption. These technologies are characterized by producing highly efficient products and services with more competitive prices, less complicated to use, and more accessible than the established sustaining technologies (Christensen, 1997; Christensen & Bower, 1996; Schuelke-Leech, 2018; Barbalho et al., 2018).

In general, disruptive technologies are technological developments that can modify how our society lives and significantly change the market to which they are connected (Denkena et al., 2020). Thus, scientific and technological development has played an important role in sustainable development. In the scientific literature, publications related to disruptive technologies and sustainability for sustainable development are divided into three types of studies (Qi et al., 2024):

a) Economic feasibility studies employing the term "sustainability" in the context of the economic and financial sustainability of businesses;

b) Technology-focused studies addressing sustainability as a common element to be considered in analyses, along with social, economic, and human resource aspects; and to a lesser extent,
c) Studies addressing the connection between technological development and environmental preservation.

In this context, limited studies have thoroughly explored the technologies that support companies and industries actively engaged in environmental preservation. Investigating the technologies driving environmental initiatives not only facilitates the emergence of new studies but also paves the way for businesses that can contribute to preservation efforts. These include meeting the growing demand for sustainable products and organic food, utilizing renewable resources, producing non-toxic materials, and addressing consumer backlash against polluting companies.

This study seeks to address a critical research question: What are the trends and patterns identified in the published literature regarding the role of disruptive technologies in developing and promoting green and clean technologies?

Given the increasing interest and investment in these areas, the study aims to conduct a bibliometric analysis of trends and the literature landscape concerning greentechs, cleantechs, and disruptive technologies. By identifying key intersections and gaps within the field, the research seeks to provide insights into how these technologies are framed in academic literature and their potential to drive sustainable solutions in the future.

To achieve this objective, the study is structured as follows: the next section presents a literature review on disruptive technologies and sustainability, narrowing the scope of the study within the broader field of sustainability. Section 2 details the methodology used, while section 3 provides results and discussions. Finally, the concluding section summarizes the findings and highlights implications for future research.

2. Disruptive Technologies and sustainability

2.1. Historical Evolution of Sustainable Technologies

Christensen (1997) named disruptive technologies as those responsible for changing a market with smarter, cheaper, and easier ways of doing things. Despite analyzing the computer industry, the author reinforced their findings by looking for the same phenomena in heavy machinery, motorcycles, printers, robots, and many economic sectors. Disruptive technologies can drive creative destruction, as Schumpeter (1942) suggested at the beginning of the 20th Century.

Our civilization has many examples of disruptive technologies, such as the Ford® T car, which takes the carriage market to death, compact discs to long plays, digital photography against film-based devices, smartphones versus traditional cell phones, electricity against kerosene-based illumination, and so on. Large consulting companies have tried to predict which technologies can be able to change the current way of doing things (Accenture, 2023). Predicting more promising technologies can direct Research and Development (R&D) investments and influence the technology and market strategy of companies and Governments.

On the other hand, climate change has been our major challenge as a society (Rogelj et al., 2016; Bui et al., 2018), where carbon capture and storage and fewer emissions can stop the dramatic ecological responses to climate change (Walther et al., 2002). According to Engelke, climate change is driving an innovation revolution in the energy and other carbon-intensive sectors to reduce emissions and mitigate the environmental impact (Engelke et al., 2021). The authors uncover how green techs, cleantech, and cleaner techs are being developed in various innovative ecosystems to face climate change with disruptive technologies and state-of-the-art business models.

2.2. Emerging Trends and Market Barriers in Disruptive and Sustainable Technologies

Research on disruptive technologies has shown that it is not even that advanced or emergent technologies become disruptive (Christensen, 1997; Rogelj et al., 2016). That is the list of (possible) disruptive and emergent technologies that can face market barriers to effectively change the value networks and be preponderant. New product development is leveraged by disruptive technologies in every market (Zheng et al., 2021), and sustainability has been incorporated as a fundamental driver for innovation (Ferrari et al., 2023). Innovation ecosystems are being set to explore disruptive technologies with the support of universities in some technical areas (Amaral et al., 2022; Barbalho et al., 2018; Ghesti et al., 2018). Duarte et al. (2020) demonstrated how disruptive digital technologies have been incorporated to transform conventional production into industry 4.0 manufacturing. Despite being studied in recent years, incorporating disruptive technologies when sustainability is the theme has not been clear with limited references encompassing technology disruption created by cleantechs, green techs, and cleaner techs.

Global leading consultancies, such as McKinsey Co., Price Waterhouse Coopers, and Accenture Inc., have researched technology trends to identify hotspots for technology and innovation consultancy. From these studies, pivotal research was performed by McKinsey Institute in 2013, and according to it, there are 12 disruptive technologies considered potential until 2025 (McKinsey Global Institute, 2013):

- Mobile Internet: Technology that enables access to the Internet on mobile devices, promotes global connectivity, and facilitates access to information anywhere.
- Knowledge-based Work Automation: Using artificial intelligence and advanced algorithms to automate tasks that require human intervention, enhancing efficiency and reducing costs.
- Internet of Things (IoT): Integrating electronic devices and sensors with the internet, enabling communication between objects and real-time data collection to optimize processes and improve decision-making.
- Cloud Technology: Data is stored and processed on remote servers, offering flexibility, scalability, and accessibility to computational resources.
- Advanced Robotics: The development of robots with advanced interaction capabilities, enabling the automation of complex tasks across various sectors.
- Autonomous and Semi-autonomous Vehicles: Utilization of technology to enable vehicles to operate independently or with assistance, aiming to enhance transportation safety and efficiency.
- Next-Generation Genomics: Advances in DNA analysis and manipulation, enabling more precise diagnostics, personalized treatments, and advancements in genetic medicine.
- Energy Storage: Development of technologies to efficiently and sustainably store energy, contributing to the expansion of renewable sources and the stability of power grids.
- 3D Printing is an additive manufacturing process that allows the production of three-dimensional objects directly from digital models, offering flexibility and customization in producing various items.
- Advanced Materials: The development of new materials with superior properties, such as increased strength, lightweightness, or conductivity, for applications across various industries.
- Advanced Exploration and Recovery of Oil and Gas: Utilizing innovative technologies to identify and extract resources more efficiently and sustainably, reducing the oil and Gas industry's environmental impact.
- Renewable Energy: Sustainable energy sources such as solar, wind, and hydroelectric power offer a clean and renewable alternative to fossil fuels, contributing to the reduction of carbon emissions and the mitigation of climate change.

For a broader visualization of bibliometrics, the article will adopt the broad concept of sustainable technologies, encompassing both green techs and cleantech, without delving deeply into each of the aforementioned technologies. The general meaning is that sustainable companies use these tech trends to provide green solutions. Therefore, some of them and their applications will be presented based on the literature analysis.

2.3. Cleantechs and Greentechs

The term cleantech originated in the 2000s within the venture capital (VC) investment community. The financial sector began using the term to refer to sustainable technology companies as the sector was growing and receiving significant investments. A few years later, the term was notably popularized by Nick Parker and Keith Raab, who founded the Cleantech Group in 2002, a research and consulting company based in San Francisco that now serves as the coordinating body for sector activities. The United Nations also uses the term in its initiatives (Per Nick, 2007).

It is worth noting that 2007 the book "The Cleantech Revolution" was published, which popularized the term and provided some theoretical basis for it. The American consultancy Clean Edge defined cleantech by three characteristics (Per Nick, 2007):

- Utilizing natural resources, energy, water, and raw materials to enhance efficiency and productivity significantly.
- Systematically creating less waste and associated toxic materials.
- Ensuring identical or superior performance to desired outcomes compared to traditional technologies, resulting in better user results.

In another study titled "Mapping Green Innovation Ecosystems" (Engelke et al., 2021), the diversity of terminologies used to group sustainable technologies is addressed. Terms like "climate tech," "cleantech," and "Greentech" are common but often used interchangeably. While "green energy" and "clean energy" are used in the energy sector, the transportation field presents an extensive list of terms such as "electric vehicles" and "hydrogen-powered vehicles." Terms like "FoodTech" and "AgTech" emerge in the food and agriculture sector. Additionally, there is an overlap between technologies created to address environmental issues and those aimed at meeting other market needs, such as the development of autonomous vehicles.

According to the authors (Engelke et al., 2021), investment trends explain part of this confusion. Terms like "cleantech" and "Greentech" were common in the 2000s, but after the 2008 financial crisis, the term "climate tech" emerged as an attempt to restore investor confidence. However, the report chooses to use "Greentech" as an umbrella term to encompass specific energy sector technologies and those working to mitigate climate impacts in other sectors, which are considered the most inclusive among the mentioned terms.

In conclusion, in conducting a bibliometric analysis of the mentioned terms and disruptive technologies, examining how related literature datasets have been scientifically referenced over the past 20 years, we would like to contribute to mapping how different disruptive technologies are planned to be used in these environmental solutions. The study aims to provide insights into the evolution, trends, and intersections of cleantech, Greentech, and related concepts within scholarly discourse. A comprehensive understanding of the scholarly landscape surrounding sustainable technologies and their contributions to environmental preservation can be gained to offer valuable insights for researchers, policymakers, and practitioners.

3. Methodology

This article used quantitative and bibliographic methods to elaborate maps and identify clusters. So-called bibliographical research is widely used in exploratory studies. It consists of research based on materials already prepared, mainly books and scientific articles, to provide a broad view of studies already carried out on a subject (Gil, 2008).

Bibliometric studies are a quantitative method for investigating science, characterized by i) measuring author productivity based on a size-frequency distribution model of various researchers in a predefined set of documents, ii) measuring the frequency of keyword appearance to obtain a list of terms related to a specific discipline or subject, and iii) measuring journal productivity by establishing the core and dispersion areas on a particular topic across a set of journals (Vanz & Caregnato, 2003).

This protocol was put into practice in the study conducted by Faria and Barbalho (2023), "Mechatronics: a study on its scientific constitution and association with innovative products", which inspired this article. The method's following stages characterize it.

- Stage 1 - Study the databases and select which one will be used.

Several databases use bibliometric indicators to provide data analysis of scientific productions, the most used being the Web of Science, Elsevier's Scopus platform, and Google Scholar. The restricted choice to use Scopus in this study arose from a meticulous comparison between Scopus and Web of Science. During this evaluation, it was found that the articles identified in these two platforms were essentially the same for the selected research strings. Moreover, considering the Scopus platform, launched in 2004 and widely recognized in the academic community, the decision to exclusively use this database was made to ensure consistency and accuracy in collecting and analyzing bibliometric data.

- Stage 2 - Construct and test the appropriate keyword combination for the research.

For the search in this database, the strategy for using the keywords is shown in Table 1. In addition, Boolean markers (Boolee, 1854) such as: “*”, AND, and OR were used to bring results that included all the terms according to the constructed groups. This stage started with the previous step of choosing the database but was more in-depth.

Thus, global results were possible, allowing a comprehensive view of the topic of interest. The keywords were also combined to search the database better; therefore, some groups of keywords will appear showing merged words. The motivation for using these words is to reveal more information about the topic, not just its history but also its trends. After hundreds of tests to find the best results, the search found 140 publications related to the topic.

Table 1. Publication selection and classification protocol.

Keyword combinations	
Textual content	TITLE-ABS-KEY
Terms	"Sustainable Development", "Disruptive Technology", "Sustainability", "Environmental", "Technology", "Disruptive Innovation", "Disruptive Technologies"
Final combination	TITLE-ABS-KEY (((green OR clean OR sustainab*) AND (innovat* OR techs OR technolog* OR manufactur*) AND (disruptive AND technolog*))) AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (OA , "all")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (EXACTKEYWORD , "sustainable development") OR LIMIT-TO (EXACTKEYWORD , "disruptive technology") OR LIMIT-TO (EXACTKEYWORD , "sustainability") OR LIMIT-TO (EXACTKEYWORD , "innovation") OR LIMIT-TO (EXACTKEYWORD , "technology"))
Publications found and used in the quantitative analysis	140 results

3.1. Criteria for Selection and Inclusion

The articles included in this analysis were selected based on predefined criteria to ensure relevance and quality. First, the focus was on articles published in peer-reviewed journals to guarantee a high standard of scientific rigor. Only articles written in English and published within the last 20 years were considered to maintain the study's contemporary relevance. Moreover, publications needed to have keywords aligned with the themes of disruptive technologies, sustainability, and innovation. Articles were excluded if they lacked substantial discussion of the interplay between disruptive technologies and sustainability or if they were not accessible through the Scopus database.

To further refine the dataset, the 30 most-cited articles within the retrieved results were selected for detailed analysis. Additionally, preference was given to open-access articles to ensure broader accessibility and applicability of the research findings. This selection process ensured a comprehensive and focused dataset for analysis.

- Stage 3 — Spreadsheet the identified articles and filter the most relevant ones from the last 20 years to be analyzed in VOSviewer.

The articles were analyzed qualitatively using Microsoft Excel® software, such as subjects, technologies, and discussions, and the graphs generated by the journal database were also used.

- Stage 4 - Create maps in VOSviewer® software and analyze the results.

VOSviewer software was selected for bibliometric analysis due to its advanced capabilities in creating and visualizing bibliographic networks, which are essential for identifying and interpreting complex patterns within scientific literature. Developed by the University of Leiden, VOSviewer is specifically designed to handle large datasets from academic publications and provides various visualization options, making it a powerful tool for mapping and analyzing research fields.

In this study, VOSviewer was used to generate bibliometric networks that highlight the most frequent terms, prominent authors, and connections between keywords and authors. The results obtained from the Scopus database were downloaded and processed in VOSviewer to map the relationships and identify key trends within the selected articles. Specifically, the software's functionalities allowed the visualization of countries with the highest publication counts, leading authors in the field, and patterns of keyword co-occurrence, all of which are vital for understanding the landscape of disruptive and sustainable technologies research.

The analysis settings in VOSviewer were adjusted to perform a co-occurrence analysis of keywords and co-authorship analysis of authors, where the relationship between items was determined by the number of documents in which they appeared together. The analysis units were set as keywords and authors, using the full counting method, which means that the weight of each co-authorship or co-occurrence link was considered in its entirety without fractional adjustments. To ensure a more focused analysis, a minimum threshold of four occurrences for each keyword was set, allowing for the identification of core terms even in an emerging research area.

This approach enabled the study to identify clusters of related topics and influential contributors in the field, facilitating insights into the structure and trends within the body of literature on disruptive technologies and sustainability.

4. Results and discussions

The results presented in this section are closely aligned with the study's primary objective of providing a comprehensive bibliometric analysis of trends and the literature landscape related to Green Techs, Clean Techs, and disruptive technologies. By examining descriptive data, publication trends, thematic distributions, and geographical contributions, this analysis aims to map the academic discourse surrounding these technologies and their roles in sustainable development.

4.1. Descriptive data analysis

It was chosen to cover twenty years of publication because we wanted to understand the evolution of the articles published on the subject over a considerable period.

4.1.1. Publications over the years

Figure 2 represents a timeline showing the number of publications per year over time.

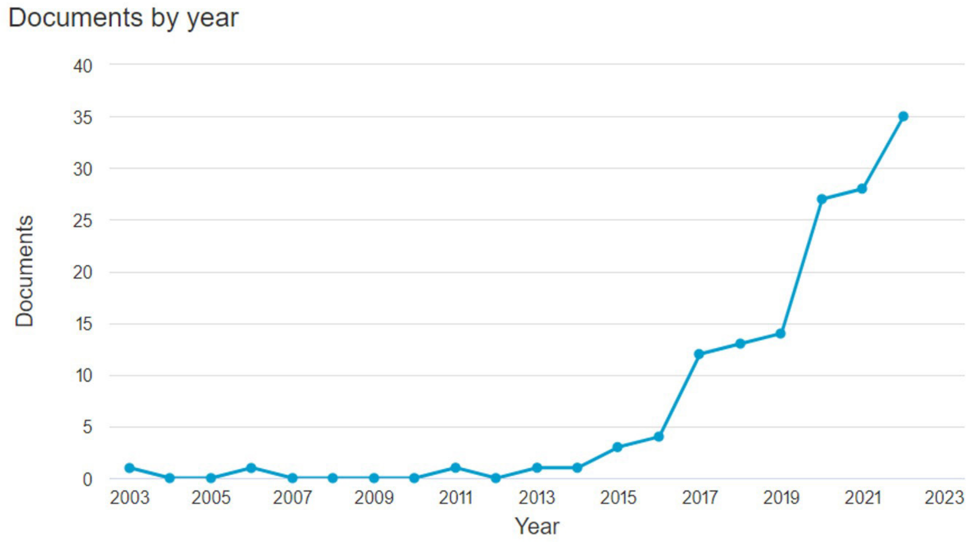

Figure 2. Number of publications from 2003 to 2022, using the keywords.

The first publication on disruptive technologies and sustainability was in 2003 in civil construction in the United Kingdom (Barrett, 2003). The Department of Environment, Transport, and Regions (DETR) funded a research and development study. It aimed to analyze three different hybrid concrete designs and their supply chains, identifying the advantages and disadvantages of each application. The research was carried out through snowballing interviews (Rojas-Drummond, 2007) that provided insight into the main problems of supply chain complexity and which positive characteristics of hybrid concrete can be maximized. Despite the author emphasizing the project's complexity at the time, he concluded with technical opportunities for developing mixed concrete. It suggests potential areas or ways to improve the development of mixed concrete, such as by introducing new materials, refining mixing processes, optimizing curing methods, or enhancing the overall performance of the concrete mixture. These opportunities may involve advancements in technology, research, or techniques that could lead to better quality, durability, sustainability, or cost-effectiveness in the production and use of mixed concrete. According to the author, hybrid concretes were, at that time, ‘disruptive technologies’, as discussed by Christensen (1997).

Only three studies with the indicated keywords (Table 1) were published in the next ten years. In 2006, a Californian Study published advances in nanowire synthesis, characterization, eventual applications, and relevant technical and scientific issues of electronic integrated circuits. The author briefly mentions that it is a disruptive, transformative technology of the 20th century (Pauzauskie, & Yang, 2006). The study, published in 2009 (Westbrook et al., 2009), was the first to deal with disruptive technologies. This study, run in Australia, investigated how to use technologies to create new, more effective service delivery models. New services can build capacity and provide fast, safe, effective operations, affordable health care, and sustainable resource utilization. Here, sustainability refers to something that can be maintained over the long term, not environmental sustainability. It is very common to identify the term sustainability being used in a financial sense in older research. The project of the article assessed the effects of integrating technology into healthcare services by conducting observations, gathering user feedback, and conducting interviews. It explored the perception of these technologies within the healthcare sector. The findings suggest that consumers often embrace these technologies despite concerns expressed by industry representatives. Critics outside the healthcare sector argue that such technologies are necessary to disrupt traditional learning models and enable less costly professionals to perform increasingly complex tasks in more cost-effective settings.

The third article, from 2003 to 2013, explores the phenomenon of local economic restructuring in rural areas affected by disruptive technologies (Matthias et al., 2013). Employing an institutionalist framework, a systematic, theory-informed case study analysis of two rural communities in Austria was conducted. The investigation identifies practices crucial for sustainable development within these communities, emphasizing the necessity for social innovations accompanying disruptive technologies. These innovations should consider the capacities and needs of the local community while establishing vertical linkages to regional and national policies. By presenting a practical framework for contextual analysis of economic restructuring, the study contributes to theoretical discourse. Additionally, it demonstrates how this institutionalist perspective can offer valuable insights to entrepreneurs and policymakers in formulating strategies and policies to navigate disruptive technologies within rural contexts.

Only from 2014 onwards did the studies begin to present the indexed strings more consistently. In 2014, Pinkse et al. (2014) opened the growth of research on the topic with a study on alternative low-carbon vehicles. In partnership with the University of Holland, the French author identifies the need for and challenges associated with alternative technologies for internal combustion vehicles, particularly electric and hybrid vehicles. The article explores how private and public protective measures impact business strategies to enhance products' appeal to conventional customers. Through multiple case studies, the authors empirically explored the emergence of low-carbon vehicles at three car manufacturers in the context of European, Japanese, and US policies. As main conclusions, Pinkse et al. (2014) identifies regulation, fiscal incentives, and public-private partnerships as public protection levers that impose or encourage "new" performance metrics, such as fuel economy and vehicle emissions. The paper concludes that the private-sector trajectory has gained momentum. In contrast, the public investment trajectory has stalled due to systemic and socially embedded technological impediments to electric and fuel-cell vehicles in that time.

The numbers are impressive when calculating the average of publications over the years. The average number of publications between 2008 and 2015 is 0.4 per year. However, in the following seven years, between 2015 and 2022, the average number of publications per year was 19.2, i.e., an increase of more than 4000%.

4.1.2. Publications by theme

Social sciences dominate the theme with publications on the Internet of Things (IoT), 3D printing, automation, and other disruptive technologies from the point of view of their applications, social impacts, public incentives, and protection policies. Figure 3 presents a chart of publications by subject.

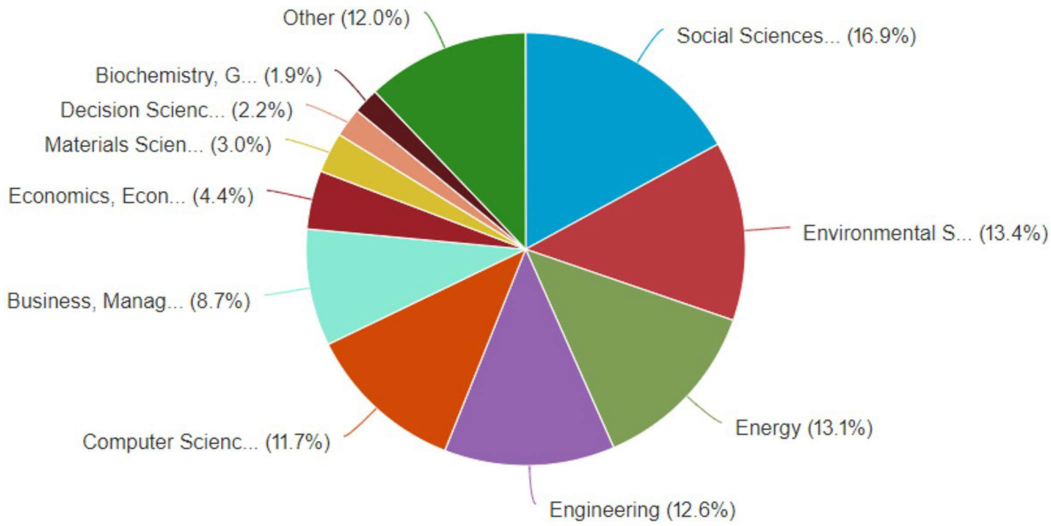

Figure 3. Subjects with the most papers published using the keywords.

Amongst the indexed words, it is possible to identify that social sciences, environmental, energy, and engineering add up to more than 50% of the publications.

4.1.3. Publications by Country

Figure 4 displays the countries with the most publications on the subject. Leading the list is the United Kingdom, which contributed 30 articles out of 138. Among them is the most cited article in the selection, which aims to broaden the discussion within the literature on technology, innovation, and public policies. Thus, the study proposes a new conceptual framework for public policies and sustainability transitions and presents this framework as an "engine of creative destruction" (Kivimaa & Kern, 2016).

The top three countries with the most publications are amongst the most economically and technologically advanced nations globally. The United Kingdom ranks as the 7th largest economy, followed by the United States, which holds the top position, and China, the second richest country (World Bank, 2021). Moreover, both the United States and China are recognized as leading countries in terms of research and development (R&D) expenditures, as reported by the National Science Board (NSB, 2021) and the National Bureau of Statistics of China (National Bureau of Statistics of China, 2019), respectively.

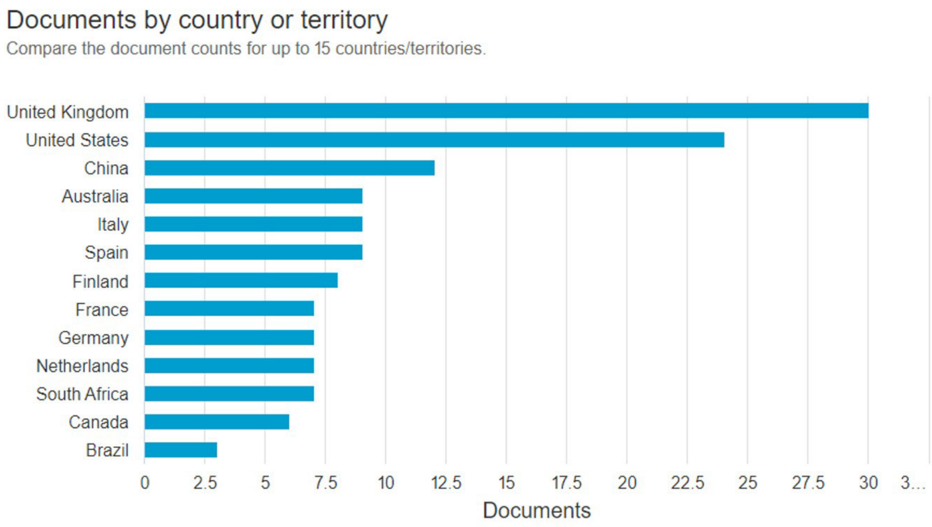

Figure 4. Papers published by country.

All three countries have set ambitious targets to reduce greenhouse gas emissions and mitigate the effects of climate change (Krug, 2008; Sun et al., 2022). The UK has committed to net zero emissions by 2050 (Krug, 2008), and the US has set a target to reduce emissions by 26-28% below 2005 levels by 2025, as announced by the Environmental Protection Agency (EPA, 2021). China has also set an ambitious target to peak its carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060 (Sun et al., 2022), as reported by the National Energy Administration of China (2021).

It can also be seen in Figure 4 that Brazil had only two publications (Valenti et al., 2021; Yigitcanlar et al., 2019) on the subject between 2003 and 2022. The first, published in 2019, aims to provide a status of autonomous vehicles (AVs), advances, and potential impacts of the adoption of AV and proposes actions for planners and public policymakers in the age of smart urbanism and mobility (Yigitcanlar et al., 2019). The other Brazilian publication, Valenti et al. from 2021, is about Aquaculture. The author argues that disruptive technologies are needed to exploit the Brazilian potential for producing aquatic organisms and generate a true-blue revolution. In addition, it states that one should consider consumers' general tendency to prefer natural food produced by local farmers, known not to affect the environment negatively, respect the rural population, and commit to animal welfare.

4.1.4. Discussion per journals

The database of journals and the number of publications that used the keywords chosen for this article over the last 20 years found 38 journals published in different areas. For the most part, the average publication of journals was 1.9 per year. Alternatively, Figure 5 shows the top 5 journals with the most publications. These journals have published articles from 2017 to 2022.

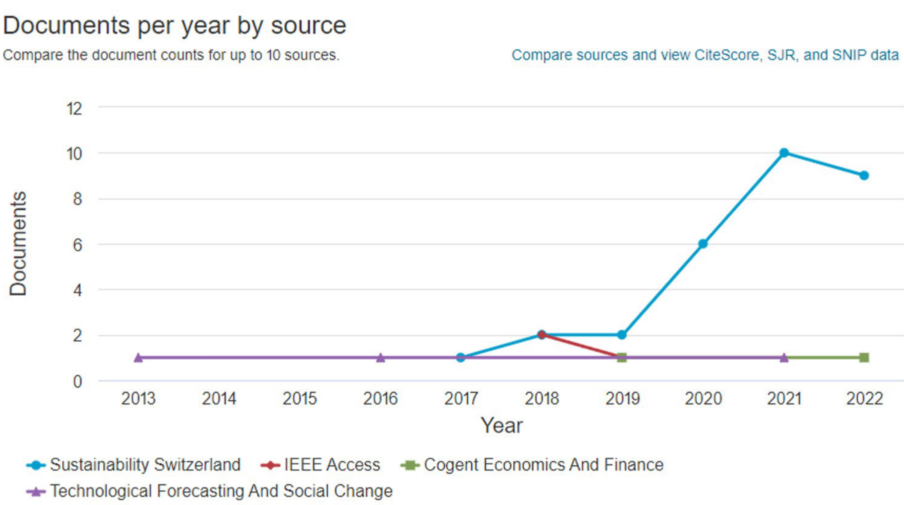

Figure 5. Main Journals.

In this study, Technology Forecasting and Social Change, Energy Policy, Computers and Industrial Engineering, IEEE Access, and Sustainability Switzerland had the highest impact factors in 2021. Sustainability Switzerland magazine had the most publications, with 30 articles.

Generally, these data can validate the thesis that this subject offers great publication possibilities in top-cited journals.

4.1.5. Most cited articles

Following our analysis, Table 2 presents a set representing 44% of citations in our sample. These data also corroborate the findings related to the top-cited journals.

Table 2. Most cited articles and their respective authors.

Authors/Year	Title	Journal	Cited by
Kivimaa & Kern (2016)	Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions	Research Policy	654
Bai et al. (2020)	Industry 4.0 technologies assessment: A sustainability perspective	International Journal of Production Economics	603
Pauzauskie & Yang (2006)	Nanowire photonics	Materials Today	450
Barnes & Mattsson (2016)	Understanding current and future issues in collaborative consumption: A four-stage Delphi study	Technological Forecasting and Social Change	266
Middleton et al. (2017)	The shale gas revolution: Barriers, sustainability, and emerging opportunities	Applied Energy	239
Sedlmeir et al. (2020)	The Energy Consumption of Blockchain Technology: Beyond Myth	Business and Information Systems Engineering	213
Hannan et al. (2018)	A review of internet of energy based building energy management systems: Issues and recommendations	IEEE Access	191
Nicholson et al. (2021)	Manufacturing energy and greenhouse gas emissions associated with plastics consumption	Joule	150
Valenti et al. (2021)	Aquaculture in Brazil: past, present and future	Aquaculture Reports	143
Shen & Pena-Mora (2018)	Blockchain for Cities - A Systematic Literature Review	IEEE Access	136

The study by Kivimaa & Kern (2016) explores policy mixes in the innovation domain, particularly focusing on their significance in sustainability transitions. The study aims to unveil the composition and effectiveness of policy combinations by analyzing policy mixes in energy efficiency and demand reduction in Finland and the UK. It introduces the concept of 'creative destruction' in policy mixes, suggesting that ideal mixes encompass policies that foster innovation and disrupt established practices. The study's novel approach broadens the understanding of policy instruments beyond traditional technology push and demand pull strategies, shedding light on their role in sustainability transitions.

Although the study does not explicitly focus on disruptive technologies, it discusses the need for policies that promote innovation and change of established practices, which may imply the use of disruptive technologies as part of these policies. However, compared to other studies focusing on disruptive technologies and their role in sustainability, this study may be considered more comprehensive and general in its approach.

The study by Kivimaa & Kern (2016) offers valuable insights into understanding innovation policies and their relation to sustainability. However, suppose the aim is a deeper analysis of disruptive technologies and their impact on sustainability. In that case, it may be necessary to complement this study with more specific research in that area.

Chunguang et al. (2020) study is significant in assessing the sustainability dimensions of Industry 4.0 technologies. It addresses the pressing need for organizations to understand the sustainability implications of adopting these technologies and offers a structured approach for evaluating their sustainability performance.

While the study does not delve deeply into the disruptive nature of these technologies, it emphasizes the importance of considering sustainability alongside technological advancements.

The study's findings highlight the crucial role of mobile technology in driving sustainability across various industries, indicating the potential for significant environmental, social, and economic benefits. However, the study also emphasizes the importance of careful evaluation and prioritized investment in these technologies to ensure sustainable adoption.

Regarding its contribution to understanding the sustainability aspects of Industry 4.0 technologies, Chunguang et al. (2020) study provides valuable insights and a practical framework for organizations to assess and prioritize their technology investments.

The Nanowire Photonics study (Pauzauskie & Yang, 2006) highlights advances in nanophotonics and their scientific and technical applications, offering a promising view for developing advanced photonic circuits. On the other hand, the research on Collaborative Consumption (Barnes & Mattsson, 2016) focuses on identifying drivers, inhibitors, and future trends in this domain, providing insights into their social, economic, and environmental impacts. However, neither study directly explores the relationship between disruptive technologies and sustainability, leaving a gap in understanding these interconnected themes.

Two notable articles in the table highlight blockchain technology, each bringing a unique perspective. The first (Sedlmeir et al., 2020), published in Business and Information Systems Engineering, has amassed 213 citations since its publication in 2020. This study critically analyzes the energy consumption associated with blockchain technology, debunking common misconceptions and providing insights into its true environmental impact. On the other hand, the second article (Shen & Pena-Mora, 2018) has garnered 136 citations since its publication in 2018. In this study, the authors conduct a systematic review of blockchain applications in urban contexts, providing a comprehensive overview of the opportunities and challenges this technology presents for urban management. While both articles address blockchain technology, they do so from different angles, with Sedlmeir et al. (2020) focusing on energy consumption and sustainability. At the same time, Shen and Pena-Mora (2018) explore its urban applications. The two-year difference between the publications highlights the evolution of the field and the growing relevance of blockchain technology in different research areas with positive environmental impact.

On the other hand, Nicholson et al. (2021) stand out by directly addressing the intersection between disruptive technology and sustainability. This study examines the energy emissions and greenhouse gases associated with plastics consumption in manufacturing, showcasing how disruptive technologies in the manufacturing field can significantly impact environmental sustainability. By highlighting the environmental implications of plastics production and exploring more sustainable alternatives, this article provides crucial insights into how technological innovation can be directed toward promoting more environmentally responsible practices.

The other articles (Valenti et al., 2021; Hannan et al., 2018; Pauzauskie & Yang, 2006) follow a similar reasoning, presenting how a certain technology contributes to a specific field of operation. Some highlight disruptive technologies, while others take a broader approach, but all involve the theme to some extent. Each offers a unique perspective on how technology can drive changes and improvements in various sectors, contributing to innovation and, often, to sustainability. Although they do not directly address the relationship between disruptive technologies and sustainability, these studies provide insights into how technology can influence and transform different areas, from energy production to plastic consumption, reinforcing the use of cleantech and green techs in a search for more efficient and sustainable manufacturing and consumption practices.

4.2. Networks

4.2.1. Authors and co-authorships

The relationship between authors and co-authorship was visualized using the VOSviewer software. There are 524 authors involved with at least two co-authored documents. The three researchers with the most publications and co-authorships in red in Figure 6 are from Portugal. They are researchers in Energy, Engineering, Environmental Sciences, and Management. When analyzing a single country, the map shows no large collaborative network, only independent studies.

The visualization map in Figure 6 reveals a low incidence of co-authored publications, indicating ample opportunities in the subject area that authors can explore individually or collaboratively. It also indicates no strong connection between authors in the theme, which is common in emerging research areas.

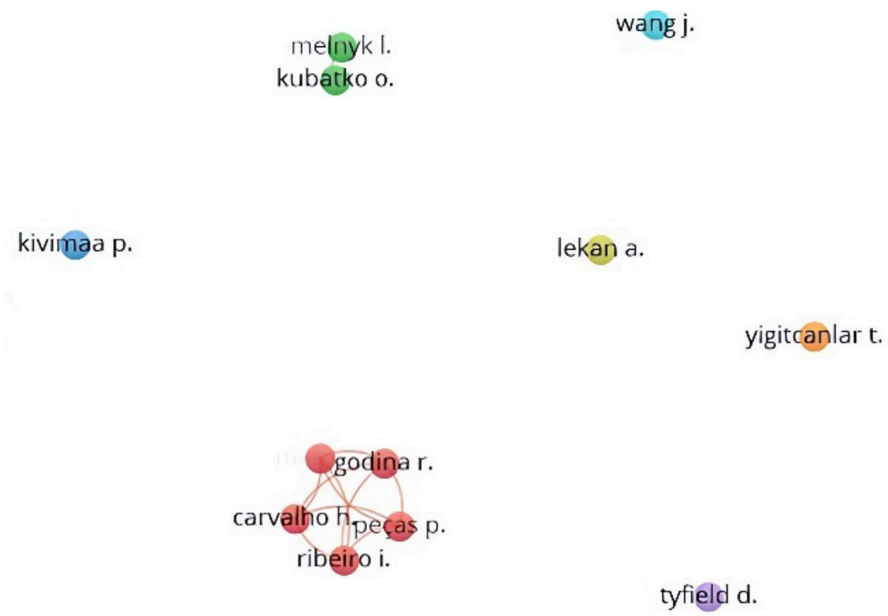

Figure 6. Co-authorship visualization map.

4.2.2. Keywords analysis

The keyword map (Figure 7) was developed based on more than 1000 keywords. Each word's minimum number of citations was configured as 4 to allow more effective visualization and analysis. Thus, 39 keywords were separated into 4 clusters, which will be discussed next.

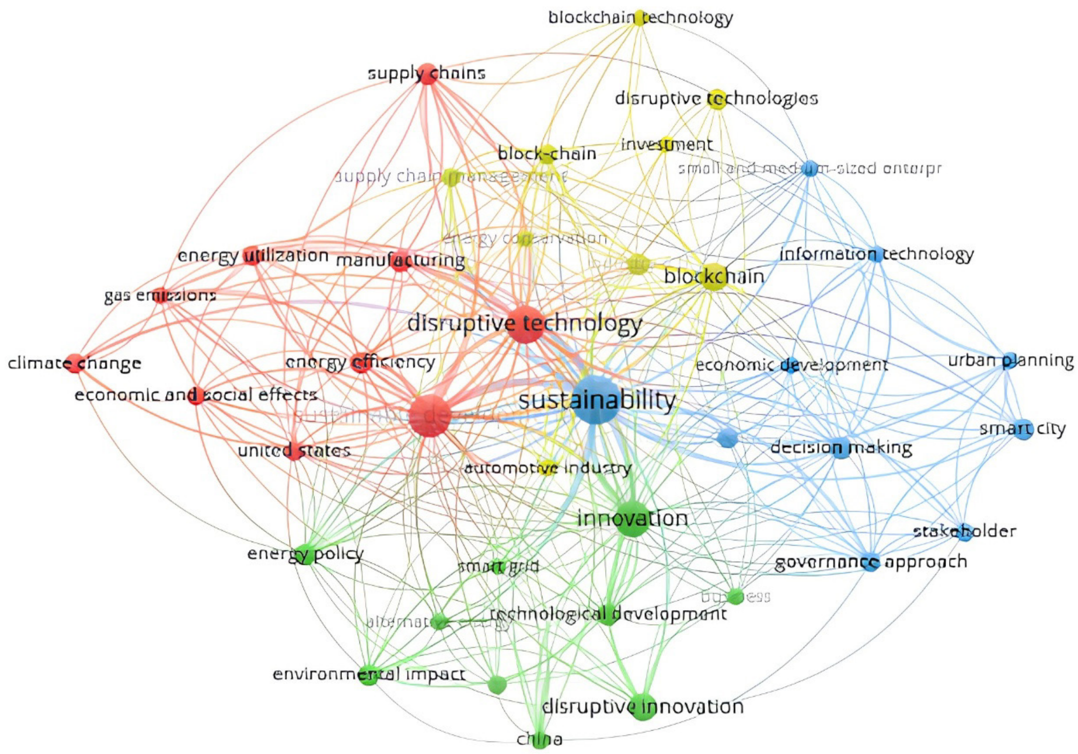

Figure 7. Keywords map with cluster separated by colors.

- **Cluster 1—Red. The dominant keywords in the Red Cluster are " disruptive technology" and "sustainable development."**

The dominant keywords in the Red Cluster are "disruptive technology" and "sustainable development." This cluster emphasizes the intersection of technological advancements and their role in promoting sustainability.

One of the key studies in this cluster (Hannan et al., 2018) critically reviews the potential of building energy management systems, such as energy routers, storage materials, renewable sources, and plug-and-play interfaces. The study anticipates that energy security will become a central issue in sustainable economic development. This insight aligns with existing literature that highlights energy efficiency as a cornerstone of sustainability (e.g., Juran, 1988; Ohno, 1988).

The focus on additive and lean manufacturing, industry 4.0, and zero-energy buildings illustrates the practical implications of these technologies in reducing emissions and waste. By connecting these findings to global sustainability goals, such as the United Nations Sustainable Development Goals (SDGs), this cluster underscores how innovative manufacturing techniques contribute to sustainable practices. Future research can expand on this by exploring policy frameworks that incentivize the adoption of such technologies.

- **Cluster 2 - Green. The Green Cluster features “innovation” as a prominent keyword.**

The Green Cluster is dominated by the keyword “innovation,” highlighting the transformative role of technological breakthroughs in the energy sector. Key studies (Jia et al., 2018; Wang et al., 2018) explore smart electricity systems, future power grids, and hybrid grids, providing insights into the transition to a sustainable energy sector.

The emphasis on China's role as a case study reflects the country's significant investments in renewable energy, such as solar and wind, and electric vehicles. These studies contribute to understanding how national policies and global collaboration can accelerate the adoption of sustainable technologies. For policymakers, this cluster provides valuable lessons on how innovation ecosystems can drive large-scale transitions in energy sectors worldwide.

- **Cluster 3 - Blue. The word “sustainability” is the most prominent in the cluster.**

“Sustainability” is the most prominent keyword in the Blue Cluster, which connects infrastructure, governance, and the economy. This cluster links urban planning with smart cities, presenting them as complementary approaches to achieving sustainable development (Woodruff & BenDor, 2016).

The overlap with blockchain (from the Yellow Cluster) emphasizes the potential of decentralized technology in enhancing transparency and governance in urban settings. Studies in this cluster propose that integrating technology into governance can lead to more effective decision-making, particularly in urban planning. The findings suggest that technology-enabled urban systems, such as smart cities, are critical for fostering sustainable economic development while addressing governance challenges.

Future research could investigate the scalability of these solutions and their adaptability to varying economic and governance contexts. Theoretical implications include the need for interdisciplinary approaches combining urban studies, governance, and technology to address sustainability challenges holistically.

- **Cluster 4 - Yellow. The word “blockchain” is the most prominent.**

The Yellow Cluster, characterized by the prominence of “blockchain” and “investment,” represents an emerging area of study. Blockchain is highlighted for its potential to improve transparency and efficiency in energy investments (Sedlmeir et al., 2020; Shen & Pena-Mora, 2018).

The integration of blockchain into energy systems also connects to public policies and end-user involvement. For instance, studies suggest that blockchain can enhance energy efficiency and consumer participation in energy management. While this cluster is less robust in terms of publication volume, it provides a foundation for future studies to explore the intersection of blockchain, sustainability, and investment. Policymakers could leverage these findings to design transparent, decentralized energy policies that encourage sustainable practices.

4.2.2.1. Discussing implications and trends

Each cluster contributes unique insights into the broader understanding of sustainable technologies and their applications:

- Practical Implications: The findings highlight the potential for technological innovation to address critical sustainability challenges, such as energy security, governance, and urban development.
- Theoretical Implications: The analysis underscores the importance of interdisciplinary research to explore the synergies between technology, policy, and sustainability.
- Future Research Directions: This study lays the groundwork for exploring the scalability and adaptability of sustainable technologies across diverse contexts, emphasizing the need for global collaboration to advance research in these areas.

By linking these findings to the objectives of the study, this discussion positions the clusters not only as thematic groups but as pathways to guide future research and policymaking in sustainable and disruptive technologies.

4.3. Discussions on Clean Techs and Greentechs on the literature dataset

After thoroughly analyzing the literature on greentech and cleantech, it is apparent that the reality seems to differ despite an intuitive association between these concepts and the phenomenon of startups. Most of the reviewed and relevant studies on the subject tend to emphasize the role of large companies in generating and implementing sustainable technologies at the expense of startups. This suggests that sustainable innovation initiatives are primarily led by established companies and not necessarily by emerging startups, at least not those found in the literature, corroborating the disruptive innovation concept presented by Christensen (1997). The presence of keywords such as "startups" and "spin-off" is relatively scarce in the most cited articles, reinforcing this observation.

Although a more restricted selection of the term "startup" in the articles has presented some technologies, such as blockchain, it is important to note that this is not necessarily considered emerging by McKinsey (McKinsey Global Institute, 2013). On the other hand, renewable energy, which is also related to "startups" in the narrower selection, aligns with technologies identified as disruptive by McKinsey. However, although McKinsey does not mention other areas, such as legal technology and fintechs, they are also explored in the literature (Darbellay, 2022) on startups and small and medium-sized enterprises.

Meanwhile, the remaining analyzed articles on 'startups' focus on various topics such as healthcare systems, smart cities, food systems, and entrepreneurship, with less emphasis on sustainability, which is the main theme of this study alongside disruptive technologies. In summary, these results indicate the need for a deeper analysis of the role of startups in sustainable innovation in the literature. This underscores the importance of further exploration in this specific field, as previously noted, it is a critical area that lacks attention in literature. Additionally, it highlights the urgency to advance literary studies to align with the current reality, where sustainability concerns are increasingly prominent.

The collected data allows us to suggest how disruptive technologies are going on in incorporating new product development in sustainable solutions. It sounds like blockchain (Accenture, 2023), smart grids powered by IoT technology (Barbalho et al., 2018), and alternative energy sources (Barbalho et al., 2018) are the main technical drivers for greentechs and cleantechs nowadays. In general, the main keywords identified suggest that these companies do not experiment with many advanced technologies, and there is an avenue to explore.

The fact that social sciences and environmental issues are more present in the literature than business and economics suggests that the kind of company analyzed here is not yet making enough money to be studied in these areas or that large companies are not exploring these sustainable solutions as the business mainstream but as responses to environmental and social pressure. Environmental-based solutions and companies need to make money to be attractive, as stated in Sun et al (2023). On the other hand, Europe is the main place to discuss these technologies, and Brazil is the only Latin American country in our sample. China and the United States are the main source of these studies. The collected data also suggest that small clusters of authors characterize our theme, suggesting again that this subject is not widespread and mature. Only a limited but promising amount of innovation ecosystems (Engelke et al., 2021) have been created in this area for a while.

New product development is not a highlighted subject in our analysis, nor is it driven by disruptive technologies leveraged by sustainability issues (Ferrari et al., 2023), even being the main business process to boost innovation from companies to market (Barbalho & Rozenfeld, 2008). Also, investment analysis and decision-making are treated in the researched literature, which can be understood once all issues are new and hard to understand. It must appropriately balance climate change, disruptive technologies, innovation, and how to make money in this context (Sun et al., 2023).

When discussing innovative issues, the technological development processes are highlighted. Clausing (1994) and Kurumoto et al. (2012) discuss that developing technologies is not the same process as developing new products. The first focuses on design-build-test cycles to increase technology robustness, while the latter puts robust technologies into the new product development pipeline as the final product, architectural, or component solution (Ulrich & Eppinger, 1995; Barbalho & Rozenfeld, 2008; Cook & Mo, 2022).

Cleantech, green techs, and cleantech are endeavors with high potential to contribute to climate change, and they also have the potential to face social injustice (Souza Piao et al., 2023) that is already known as a phenomenon that reinforces the linear paradigm. Circular paradigms can be built in the innovation ecosystems far from industry applications, embracing services and agricultural practices, such as organic production, as demonstrated by Ferrari et al. (2023). Despite this, our research demonstrated that those technologies are far from being incorporated into new products with effective market appeal, according to the lack found in our literature analysis.

5. Conclusion

The findings of this research provide both theoretical and practical contributions to the scientific literature on disruptive and sustainable technologies. The bibliometric analysis reveals a substantial gap in studies that practically connect the concepts of disruptive technologies and sustainability, emphasizing the need for effective applications in these fields. This research highlights that some publications still use the term "sustainability" primarily in a financial context, indicating a disconnect between sustainable goals and technological advancements.

Our analysis shows that the United States and China lead in publications on disruptive technologies, as evident in the keyword maps. In contrast, European countries collectively demonstrate a stronger focus on greentechs and cleantechs, aligning more with sustainability goals. This regional distinction may stem from sustainability's multidisciplinary nature (Brundtland, 1987), which often requires integrated approaches across various sectors. Disruptive technologies, however, tend to concentrate on specific domains, such as information technology (IT), energy, and transportation, where sustainability is not always prioritized in development and implementation (Denkena et al., 2020).

Notably, while new product development is underrepresented, the literature frequently emphasizes technology development in areas like supply chain and manufacturing, particularly in light of the Industry 4.0 revolution. This focus positions sustainability as an evolving characteristic of modern industrial practices.

A significant finding suggests that, contrary to popular belief, established companies, rather than startups or spin-offs, are more frequently reported in the scientific literature as the primary drivers of cleantech, greentech, and cleaner techs. This trend points to an ongoing effort among established corporations to meet environmental standards and contribute to sustainable innovation.

6. Implications and recommendations

These results offer valuable insights into the emerging trends and intersections within disruptive and sustainable technologies. A key gap in the literature is the limited exploration of how these technologies are practically integrated. Future research should examine the role of startups in advancing sustainable innovation and explore how disruptive technologies can be more effectively incorporated into greentech and cleantech solutions. Additionally, there is a need for more studies on integrating these technologies into architectural and component solutions within sustainability frameworks.

7. Limitations and future research directions

This study faced limitations in analyzing complex concepts such as sustainability and technological disruption, potentially introducing biases in data interpretation. Future research should adopt diverse methodologies to better understand how disruptive technologies contribute to sustainability and develop frameworks for their practical application in greentech and cleantech. Additionally, as terms like climate tech, cleantech, and greentech are often used interchangeably, future studies could critically examine their distinctions in practical contexts and explore other terms used for similar concepts, clarifying nuances and overlaps to enhance academic and practical understanding.

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