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Mapping the problems and challenges of intertwines between recycling and technology

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ABSTRACT

The article maps the interface between technology and recycling, considering the advances and task management. The theme is important because of the environmental problems caused by waste, irregular disposal, and the low recycling rates in the world, around 45%. The first round of academic production analysis through the Scopus database shows that the word challenge is strongly associated with technology and recycling. The hypothesis from this first cluster organization is that recycling is an unresolved challenge regarding cost, management, and technology. To analyze the recycling system, we use the affirmatives of circular economy in line with sustainable principles. Using data mining, we searched to collect, organize, and analyze the literature on recycling and technology. Beginning with 84.542 records and making six coupling analyses, we found that challenge, process, material, environment, and management are more closely associated with recycling and technology. There is a dominance of laboratory experiments. Researchers have offered small contributions to action alternatives to recycling. In short, we looked for the intertwining between recycling and technology in academic production and did not find this connection. The article highlights the superficial stage of knowledge, analysis, management, and recycling technology use.

1. Introduction

Recycling is one process of the circular economy. The expression means the return of part of the material used in production back into the production chain either as raw material, through the decomposition of products, or as reuse, as in the case of batteries (Huang et al., 2022).

Circularity becomes important as raw materials are increasingly scarce and resources must be reused (Horváth, 2023). In addition, the Global Agenda 2030 program pressures countries to review the production, disposal, and reuse models (Annesi et al., 2021).

In this production cycle that evolves from a linear model to a circular model, the use of technologies in the chain becomes relevant (Stallkamp et al., 2022). The initial bibliographic review indicated relevant technological progress at the production stage, with initiatives for clean production (Frau et al., 2022) and sustainable packaging (Wu, 2022).

However, the same technological effort does not seem to exist at the recycling stage. Data from articles and reports indicates that the world average material recycling rate is around 40% (Boubellouta and Kusch-Brandt, 2022; Mager et al., 2022). In Latin America,

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the number drops to 11%. One reason for this is using low-tech equipment, such as conveyor belts with manual separation. In the case of electronic waste, rates are 30% worldwide and 3% in Latin America (Forti et al., 2020), using old and polluting methods of separating materials, such as fire. Regarding plastic, 9% is recycled, and 69% is incinerated (Zhumadilova et al., 2024).

The rates show gaps and problems at the system's tip, where circularity starts its way back. Authors report the governments' difficulty in developing an efficient material collection chain—for example, in the field of civil construction (Chen and Liao, 2022) or the existence of an informal chain of sale and purchase of noble material, with the challenge of integrating it into the formal chain (Ferronato et al., 2019; Sengupta et al., 2022), or low awareness of the population about the importance of recycling (Dinu et al., 2020), and use of obsolete technologies for identifying, separating, and organizing waste, which causes damage to the environment (Cornelio et al., 2017).

In addition to these gaps and problems, there are variations in the recycling rate numbers. Real numbers are challenging due to informal chains whose quantities cannot be accurately estimated. That occurs, for instance, in the plastic recycling chain (UN Environment Programme, 2018). One solution is creating partnerships at all levels and points to capture quality information (Recycling Partnership, 2020).

The data shows that recycling is not resolved, with management, technology, and information challenges. Some questions arise from this context: Why does the recycling rate remain near 45% worldwide if there is technological development? Is it a question of increasing waste production versus recycling capacity? Are technologies more present in countries with higher recycling rates, in a relationship between developed countries, technology, and results? Could it be that despite the existence of technologies, their implementation is slow and costly? Is it a management problem of the organizations involved? Is it a problem of practice culture in the sense of a lack of environmental awareness in the population?

These questions call for a deep investigation of technology applied to recycling. Recycling technology means the organized and systematized use of equipment, software, and processes applied to the disposal, collection, transport, separation, packaging, and transformation (into energy, for example) of materials to recycle. Data from the initial review by the authors indicated the presence of more than 50 frequently cited technologies, each of which can be aimed at a specific material, such as metal, plastic, or electronic. Internet addresses group technologies into classes such as chemical, mechanical, thermal, biological, dissolution, and solvolysis (for example, https://www.google.com/search?client=firefox-b-d&q=types+of+technology+in+recycling). A mechanized plant uses several of these technologies simultaneously, according to its objective of reusing or burning the material to generate energy.

Fig. 1 shows the steps of recycling and an initial group of technologies associated with each.

It appears there is a field of study on technological variations and their successes and failures in recycling, but that is not the focus of this article. Here, we intend to investigate the discourses and examples of problems and challenges in general of technology applicable to recycling.

2. Literature review

The theme of technology applied to recycling management is important, considering the environmental problems caused by waste, irregular disposal, and the low recycling rates in the world of around 45% (Forti et al., 2020). To select and analyze the theme, we use the Scopus database, one of the most complete regarding quality and quantity (Baas et al., 2020).

The academic production of the expressions *recycling* and *technology* in Scopus indicates numbers around 222.000 and 4.000.000,

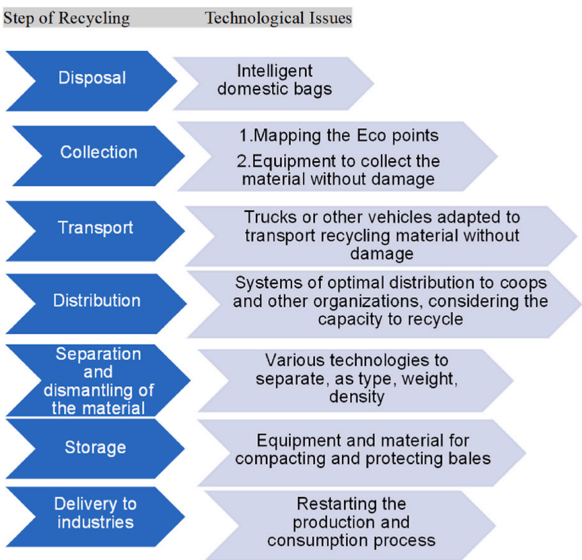

Fig. 1. The steps of recycling and examples of technologies associated.
Source: the authors

respectively. Crossing the two expressions results in 81.530 nominations distributed in various areas of Engineering, Social, and Biological Sciences, according to the frequency distribution shown by the portal.

The focus of this article is to map the interface between technology and recycling, considering advances and task management. In an initial survey, using the Scopus database, we apply selection criteria like area (business, management, and accounting areas) and the expression in the title, assuming that in this way, the article's content should focus on the words in the title, and the range from 2012 to 2023, which generated 88 indications. These articles are predominantly discussions on chemical processes (31), followed by items on carbon (5), plastic (5), and water (3).

Four works were found regarding managing the recycling task in its interface with technology, summarized here. Two articles discuss material collection technology issues and facilitating consumer donation, including payments for the amount donated (Kurniawan et al., 2022; Othman et al., 2020).

Cui et al. (2022) describe how the integrated use of market, public policy, enterprise, and technology factors increased the amount of recycled material in a region of China using integration technologies on the Internet. Rahmani et al. (2021) discuss the entrepreneurs' responsibility to choose production technologies, stating that governments leave industries free to decide on these issues when there should be closer work in the chain, based on the circular economy system.

The data from this initial panel, with the rarity of works on management models, raise the question of why technical themes are predominant—especially chemical ones—and if knowledge is evolving in this field, then why do annual reports continue to indicate that world rates are close to 45% and below 15% in Latin America (Forti et al., 2020)? Is knowledge and adoption of technologies not solving the situation?

Going one step further, we use BibCoupl, a free software, to observe the most frequent words used regarding technology and recycling. Primary evidence was the dominant presence of the word *challenge* associated with waste and recycling. Secondly, expressions of *management*, *cost*, *process*, and *intelligence* appear.

The hypothesis that emerged from this cluster organization is that recycling is an unresolved challenge with cost, management, and intelligence problems. Authors who investigated recycling state that the task must be managed from a network format that enables joint actions between organizations because of the task complexity, interdependence between actors, and governance requirements (Hou et al., 2022; Stallkamp et al., 2022).

The task complexity refers to specialties such as the logistics domain, product composition knowledge, product handling safety, and packaging composition knowledge. Due to this complexity, a field of interdependence arises, demanding the exchange of experiences and collective work. This is the case of collective work among city halls, malls for installing electronic waste collection points, residential collection companies, partnerships with warehouse owners to operate cooperatives, and knowledge and conscious action on the origin and destination of materials. Those processes and tasks are associated with management, cost, and challenges.

Another observation based on this first data organization is that recycling is at the point of consumption, where the waste starts back into the circular economy system. However, the intensive use of technologies is concentrated on the product's origin in supplying raw materials and production methods (Stallkamp et al., 2022). For example, this fact appears in the themes of journals specializing in sustainability and circular economy, such as the Journal of Cleaner Production (Neto et al., 2016). One of the most investigated topics is packaging technology—mainly plastic—which is the largest waste producer on the planet.

The third observation concerns the extensive range of material classification, whether due to danger or because of the origin (domestic, commercial, industrial, hospital, or oceanic activities). Each of them could be associated with distinct technologies.

Considering this primary analysis, we created the objective of conducting an in-depth search of the state of the art that unites the two expressions, *recycling,* and *technology*, searching to answer which ones are the problems and the challenges. We selected the theoretical foundations from this initial literature review to do the research.

2.1. Theoretical foundations

Circular economy refers to a system searching to optimize the production, consumption, reuse, and recycling of products to reduce solid waste and improve the recycling system, generating a sustainability effect on the planet (Geissdoerfer et al., 2020). The question of circular economy is not merely technical regarding which raw material to use and how to return it to the market. The challenge is to replace the linear economy model, based on production and sale, with a circular economy system, which values sustainability and reuse of material (Franzò et al., 2021).

Academic production on circular economy and business indicated that the expressions *business model*, *circular economy*, *circular business model*, and *transition* were the most frequent, suggesting a theoretical and empirical field in transition, with changes in the value chain and the business system (Ferasso et al., 2020).

As part of the circular economy model, recycling is not only a process of reusing material. It implies and requires a mindset of sustainability, detachment from pollutants such as plastic, and the personal cost of separating and cleaning recyclables and disseminating recycling ideas. It is a lifestyle based on correct consumption, use, and disposal. That is why some articles draw attention to the importance of the consumer in the circular economy and recycling (Khatami et al., 2023; Rabiu and Jaeger-Erben, 2022).

Recycling is a complex task that requires specific knowledge, sharing information and techniques, and working together (Hærem et al., 2015)—for example, knowledge and mastery of logistics (how to collect the material without contaminating it with other waste), material separation and classification into categories, compaction, supervised sale (for organizations that follow sustainability standards), and reuse of the material (for the same products or others).

It is a work in a network format (Larson and Starr, 2017), which requires group governance. Governance refers to the mechanisms, rules, practices, and norms that guide collective action (Fareed and Su, 2022; Lubell, 2015).

The literature on network management affirms the difficulty of obtaining results because of the challenges of collective work (Kickert et al., 2012; Klijn, E., & Koppenjan, 2012), especially the use of technologies, the challenges of network management, and the resistance of entrepreneurs and consumers to change the model of production and consumption.

Table 1 shows the theoretical foundations.

3. Methodology and analysis

The objective is to map, organize, and discuss the use of technologies in recycling, pointing out the problems, challenges, and impacts of adopting these technologies. Secondarily, the data may indicate solutions to a better association between technology and recycling to increase the rate in the world, which remains constant, around 45% of the waste produced.

According to the abduction methodology (Żyluk et al., 2021), we followed the path of the gradual construction of hypotheses and interpretations as the results appeared. We started with simple frequency analyses—especially with words—and the results of the words *waste* and *challenge* led to the construction of clusters, varying the central word. These variations indicated that the association between technology and recycling is a theoretical field still under construction. Then, we performed a step to check the articles that carried out a systematic review.

The result was that numerous experiments were conducted using recycling technologies, and some applications were done in restricted locations. However, the great challenge is the management, in the sense of changing a linear production system, where disposal and recycling are not important, for a circular economy system, where reuse and recycling are as important as production.

According to Grodal et al. (2021), abduction methodology begins with questions about prior context or research. In the present case, the questions raised from an initial review—described in the introduction—with items relating to results of managing the recycling task, the adequacy of public policies, the resistance of people's culture, including consumption and disposal habits; the low technological development for recycling processes, when compared to the application of technology in production; the economic situation of the countries; and the costs of implementing technologies.

The main question that encompasses all others is: If the causes are known, if there are proposals for integrated management, and if there is research on technologies applicable to solid waste, then why do the results of recycling rates remain at the global average of 45%?

The next step was to search deeply for academic production over 10 years. We utilize the Scopus database, a competent way to obtain quality and quantity information (Baas et al., 2020). We use data mining from the basic matrix of 81.530 references (Zhu and Ren, 2023) to collect, organize, and analyze the literature on recycling and technology. Then, we make variations and coupling analyses, creating new objectives following the data organization. The steps are described in Table 2.

The cloud map of words shows an extensive range of waste material types, depending on the danger, origin, specific recycling characteristics, and specific technologies to deal with. Our strategy was to organize the general data from the articles, leaving the comparative analysis to future research.

4. Results

Initial research shows that the absence of technologies applied to recycling is one of the main reasons for the global rate of around 45%. One evidence to sustain the affirmative is the concentration of studies and applications at the production step. It is possible to explain the fact due to a linear production paradigm that values production and sale, not material return.

The following paragraphs show the results according to the script established in Table 2. We started with a coupling requesting the top words around recycling and technology. The data led us to perform the second round of coupling, now with the word *waste*, the frequency champion in the first round. The first and second coupling results led us to conduct the third round, now requesting clusters around recycling and technology. Table 3 resumes the data of the three first couplings.

1. First round: Expressions related to recycling and technology.

Table 1
Theoretical foundations to analyze recycling and technology.

Expression	Concept	Reference
Networks	Actors with common challenges and objectives work together to increase results.	Larson and Starr (2017)
Task complexity	The task demands special knowledge and capacities. Because of that, actors need to share these abilities to do the task.	Hærem et al. (2015)
Governance	Mechanisms, rules, norms, and practices to drive collective actions.	Fareed and Su (2022); Lubell (2015)
Circular economy and recycling	The system searches to optimize the production, consumption, reuse, and recycling of products, reduce solid waste, and improve the recycling system, generating a sustainability effect on the planet.	Chen and Liao (2022); Geissdoerfer et al. (2020)
Technology	Use knowledge, equipment, and processes to develop, create, produce, and innovate products, processes, and services.	Hennen (2023)
Network management	Use the resources and capabilities of actors to get results.	Kickert, W.; Klijn, E., & Koppenjan, 2012

Table 2
The research steps to collect data about recycling and technology intertwining.

Action	Result
1 Survey of academic and managerial production with the expressions recycling and technology	Tables and graphs with the organization of relevant variables, considering criteria of most frequent words, authors, journals, and regions.
2 Survey and analysis of recurrent expressions associated with recycling and technology and their evolution over time	(a) Tables and graphs that allow the construction of hypotheses about links between the two keywords and the other expressions; (b) Analyze possible convergence of data over time.
3 Considering the results of items (1) and (2), the data are crossed searching for clusters	Graphs allow discussions about the meaning of the clusters, especially the link between recycling and technology and the clusters around the expressions.
4 Search for articles that carried out a bibliographical review on recycling and technology	A description of the tracks in development, the problems, and a comparison with the clusters found in item 3.
5 Organize a research conclusion	Present the research answer, considering the analysis.

Table 3
Resumption of three couplings using a matrix database of recycling and technology.

	Coupling 1 – Recycling and technology	Coupling 1 – Top countries with academic production	Coupling 2 – Associations with waste	Coupling 3 – Clusters around recycling and technology
Top expressions	waste (169.000 times), material, recycling, *process*, protein, cell, *system*, water, production, *management*, method, model, energy, treatment, product, metal, acid, property, carbon, activity, *development*, soil, technology, impact, *efficiency*, rate, application, reaction, cycle, temperature (33.922 times).	China United States Germany India United Kingdom France Japan Italy Australia Spain	waste management, solid waste, electronic waste, waste water, waste disposal, waste treatment, water recycling, plastic waste, environmental impact, municipal solid waste, life cycle, water treatment, waste recycling, sustainable development, protein transport, cell membrane, industrial waste, food waste, wastewater treatment, carbon dioxide	new recycling technology, advanced recycling technologies, waste recycling technologies, east Asian resources recycling technology, recycling technology, recycling technologies, new concrete recycling technology, effective recycling technologies, advanced recycling technology, cold recycling technology, current recycling technology, new environmental recycling technology, current recycling technologies, main recycling technologies, water recycling technologies, available recycling technologies, related recycling technology, sustainable recycling technology, water recycling technology, household waste recycling technologies
Words relate to problems, challenges, and solutions	The words *process*, *system*, *management*, *development*, and *efficiency* show the strategic field, not technology	There is no clear relation between authors, countries, and state of technology application to recycling	Growing awareness about sustainability and resource rarity, like water	Focus on technological solutions to e-waste and plastic

A sum of 81.530 records was obtained, considering the period from 2012 to 2023. The analysis of the top-frequency words shows a dominance of technical areas, like engineering and chemistry. The expressions in italics - process, system, production, management, and efficiency—show that recycling and technology are on the researchers' radar, meaning the challenges. Regarding technology, expressions such as system, method, energy, treatment, and application indicate researchers' and managers' interest in applying technologies in the production chain.

The top countries that present academic production are listed in Fig. 2. Chinese authors are the champions of valuing the technology applied to recycling. Still, it is not coherent to affirm a direct association between the number of articles and problems and challenges in the countries because countries like Germany and Japan have recycling rates above the average of 45% and use technologies for burning and generating energy from recyclable materials. Those technologies solve the problem of separating and remanufacturing the material.

The word *waste* caught our attention, as it is the frequency champion, so we decided to verify which expressions were associated with waste and the position of recycling and technology. Secondarily, we search for variations over time to determine whether waste is a growing and hot theme in academic production.

2. Survey and analysis of recurrent words associated with waste, recycling, and technology and their evolution over time.

The result of the previous item suggests that the expression *waste* is more related to processes and production systems than recycling, logistics, and separation technologies. The data supports researchers' affirmative of greater attention to production

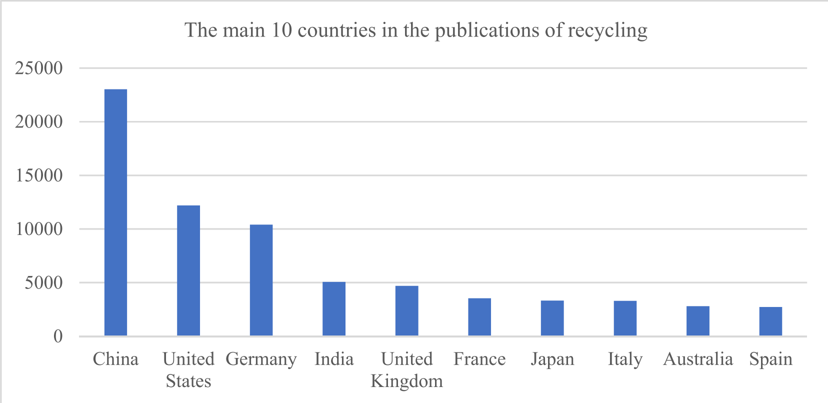

Fig. 2. The main 10 countries in the number of recycling publications.
Source: the authors

processes at the beginning of the circular economy chain.

We associated the word *waste* with others, considering its evolution over time. The result shows an increasing concern with resources, such as water, and materials that generate waste, such as plastic. Over time, data showed the growing importance of sustainability associated with solid waste. Analyzing the titles, keywords, and abstracts of a sample of the articles referring to those top 20, we found that the data indicates more attention to the production step. Technology is rarely present in expressions such as *waste treatment*.

Considering this result—especially the low presence of technology—we decided to search for the obligatory presence of recycling and technology, seeking associations with other expressions.

3. Considering the results of items (1) and (2), data were crossed searching for clusters.

Analyzing the titles, keywords, and abstracts of a sample of the articles referring to the top 20 shown in Table 3, we realize that the primary subject is technical issues for specific materials, such as plastic, water, and electronic waste.

Table 4
Description of 10 articles about recycling and technology literature review.

Year	Author	Title and content	Conclusion
(1) 2014	Bouzon et al. (2014)	Managing end of life products: A review of the literature on reverse logistics in Brazil. The authors analyzed 34 articles.	Brazil has technological, information, inventory control, and performance measurement gaps.
(2) 2017	De Almeida and Borsato (2017)	Exegetics analysis as an agile approach to recycling processes: A literature review	The paradox is that the available recycling technology requires raw materials and energy, thus contributing to the depletion of resources.
(3) 2018	Li et al. (2018)	Bibliometric analysis of research trends on solid waste reuse and recycling during 1992–2016. Authors were searching for hot topics about waste and recycling.	There is a lack of knowledge and technology between developed and developing countries.
(4) 2019	Margallo et al. (2019)	Enhancing waste management strategies in Latin America under a holistic environmental assessment perspective: A Review for Policy support.	Recycling public policy—including adopting new technologies—does not work in Latin America. The authors propose using Life Cycle Assessment (LCA) to understand potential alternative waste management.
(5) 2019	Gao et al. (2019)	Global trends and future scenarios of e-waste research: a bibliometric analysis. The authors were investigating the hot topics.	The main problem is the management of e-waste recycling.
(6) 2019	De Almeida and Borsato (2019)	They are assessing the efficiency of end-of-life technology in waste treatment. The authors show the number of processes to increase recycling.	Sustainability is the challenge. Products continue increasing. Technology for recycling requires material and energy. Disruptive technologies are promising solutions.
(7) 2019	Zhang et al. (2019)	A bibliometric analysis on waste electrical and electronic equipment research, trends, and features of e-waste.	One hot topic is that of the treatment technologies applied to recycling.
(8) 2021	Anandh et al. (2021)	Reuse assessment of WEEE: Systematic review of emerging themes and research directions—331 articles selected.	The central theme is consumer behavior. The authors suggest regulation of purchase, use, and disposal.
(9) 2022	Concari et al. (2022)	Bibliographical review and text mining of 2061 articles about recycling behavior.	The authors suggested research themes, some of which were related to technology: smart city design and sensor network systems.
(10) 2023	Zhu and Ren (2023)	The evolution of research in resources, conservation & recycling revealed by Word2vec-enhanced data mining.	The technique shows nine trends covering industrial management, waste typology, sustainability, climate change, and methodologies—nothing about recycling and technology.

Table 3 shows an important association between *recycling* and *technology* with *challenge*, indicating a field demanding deep analysis and solutions. Complementing this result, the words *new* and *advanced* indicate a field under development associated with frequent expressions about sustainability. However, there is no deep discussion about the challenges to adopting technologies in recycling, and the predominant discourse is about lab tests.

Considering this result, indicating a new and challenging field, we searched for articles that organized scientific and managerial production; that is, they conducted reviews of the knowledge up to that point.

4. (a) Search for articles that carried out a bibliographical review on recycling and technology; (b) conclusions.

From the initial database spreadsheet, the selection criterion of a bibliographic review on recycling and technology resulted in 40 nominations. A detailed analysis of titles, keywords, abstracts, and indexed keywords resulted in the selection of 10 articles, described in Table 4.

A primary observation is about the range of themes without concentration. This means that the issue of recycling technology does not present valid and convergent knowledge, which leads to a focus on public policy, consumer, management, region, or general sustainability. Another point is that the articles are presented in a descriptive pattern, emphasizing the list of authors, universities, and countries without discussing the meaning of the numbers. For example, what does it mean that China has more articles? Are they more developed in recycling? The same discussion is absent when articles show lists of expressions obtained. There is no analysis of why these expressions appear. Are they pictures of reality or simply authors' selections?

This evidence - i.e., the range of themes and lists of words, regions, and authors—occurs when a field is in the early stages of scientific development (Zhu, 2022). Researchers collect pieces of evidence and select many variables but without integration.

One significant piece of evidence raises a central question: The academic production is convergent to affirm that technologies applied to recycling exist and are positively tested in labs. So, why can we not go to the next step, implementation? Considering all variables cited in this last coupling matrix, is it possible to affirm one of them as central? Discussing e-waste, Gao and collaborators (Gao et al., 2019) affirm that management is the central point - i.e., entrepreneurs are not capable and are not committed to focusing on recycling because this effort demands a change to the circular economy model. It is a response to be considered.

Considering the results until this last step-mainly the frequency of the word *challenge* and the superficial knowledge from review articles-we turn to force the database to connect recycling, technology, and challenge.

5. Data organization adding the expression *challenge.*

We started organizing the combination of recycling and technology to deeply understand the results from Steps 1 and 3, and we are now looking for clusters. Fig. 3 shows the result obtained from the bibliographical coupling technique using the free software Bib-Coupl.[1] There are nine clusters around the expressions *impact*, *electronic*, *process*, *economic*, *waste*, *recycling*, *material*, *resource*, and *property*. The word *technology* does not appear but is implicit in derived expressions such as *separation*, *equipment*, and *treatment*. The word *challenge* presents a degree of similarity of 0.27 with recycling, indicating a low relationship. The highest recycling index is with *product* (0.35). The words *waste*, *process*, and *material* present indices around 0.38, and the highest waste ratio is with *management* (0.48).

The cluster analysis indicates that the academic and managerial production raises a series of items around some central expressions, such as *waste* and *recycling*, but without significant associations, even within each cluster. In scientific and managerial terms, it is possible to affirm that there are still no established paradigms and models regarding recycling, technology, and management. This situation may be the reason for the expressive frequency of the word *challenge*.

Next, the data were organized around the expression *challenge*, shown in Fig. 4. The first observation is that the word *challenge* appears more strongly associated with waste, recycling, material, and management. The expressions *sustainable*, *application*, and *use* appear in the second line. Compared to Fig. 3, the degree of disaggregation is more remarkable, with clusters that do not communicate with each other, such as the one centered on consumption and the one on costs.

The interpretation is that the challenges refer to creating a sustainability practice in organizations and society and developing management models on the recycling problem reality. In this hierarchy distribution, technology would be secondary in terms of application and equipment. In other words, the key challenge is preparing people and organizations to think about and act on sustainability and then use technologies.

To test the hypothesis that researchers value behavior and entrepreneur practices as a challenge and solution to apply technology in recycling, we organize the data around the expressions *challenge,* asking the software to force associations with recycling and technology.

6. Data organization around the expression *challenge* associated with technology and recycling.

Fig. 5 presents the results. The expression *challenge* is strongly associated with awareness and disposal related to consumer behavior. There is a connection between disposal and management. The awareness line has a connection with infrastructure related to

[1] Accessible in Bibliographic Coupling of Authors (leydesdorff.net).

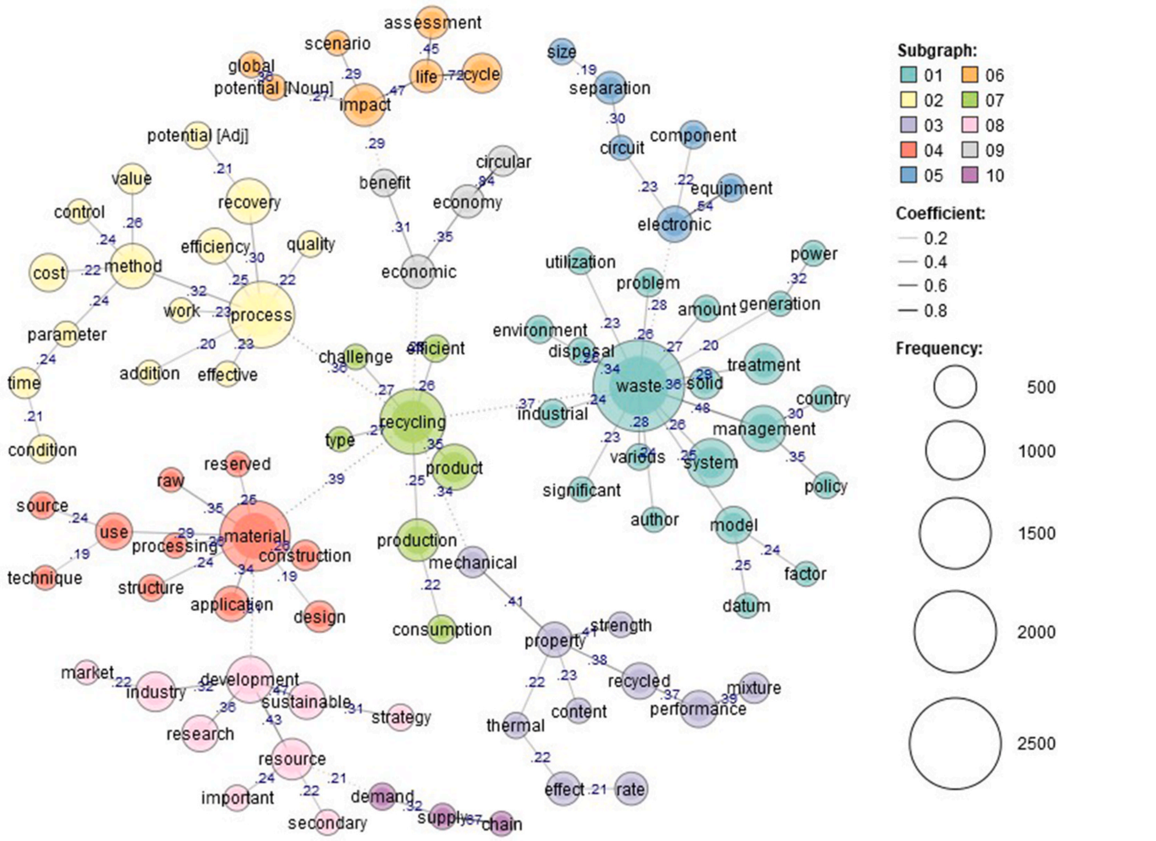

Fig. 3. Expressions coupling of recycling technology network*.
* Criteria: Coef. Cos: 0.18, N/Adj, Min T/f: 150, spanning tree).
Source: constructed by the authors

political sustainability decisions. This infrastructure appears connected with another cluster (yellow), which presents some known expressions of challenges in the supply chain, like cost, focus, and industrial participation. Disposal connects with a cluster related to process optimization.

The expression *technology* is rare. It appears isolated, down on the right. Discussions about the word *technology* show similar expressions, such as *tool*, *technical*, and *conversion* (Hennen, 2023), presented in Fig. 5.

What do these clusters reveal? The main challenge in applying technology in recycling is management, and one of the tasks of this management is determining consumers' disposal behavior. The clusters to the right of the word *management* and above to the left (in blue) show some of the necessary management tasks, such as scale, process optimization, and partnerships (simultaneous).

The clusters in yellow and red indicate the chain infrastructure factors (industry, supply) and socio-economic challenges for using technologies (social, economic, difficult, technical). Our interpretation is that technologies exist but do not constitute a challenge because they appear as an isolated cluster (dark blue, on the right). The problem is the lack of knowledge and commitment to using them.

At this point, we decided to finish the analyses because we found enough convergence to present the answer to the question about recycling technologies. Considering all analyses, it appears that recycling is a field with challenges—especially regarding management—but with little information regarding the use of technology. However, the academic and managerial data indicated many laboratory types of research, like the waste separation process. Yet, the impact of these works does not change the recycling rates.

A possible cause of this situation, with much lab research but a rare impact on waste recycling management, is the supply complexity. There is a long way to go for waste, starting in the production systems, going to consumer disposal, and initiating the return in logistics to collect, distribute, and separate the material.

The answer is that recycling technologies exist—especially dismantling and separating products. However, that is only one point in a chain of many points, including consumer practices, entrepreneurs' commitment, and public policy. The recycling rates of around 45% worldwide result from the absence of competent management models (in the literature) and limits of public policy actions.

We quickly searched the Internet for recycling technologies and found hundreds of news items, videos, and enterprises offering equipment, supporting the affirmative that technologies exist. Some of them are low-cost, like intelligent trash cans, which cost around $20.00.

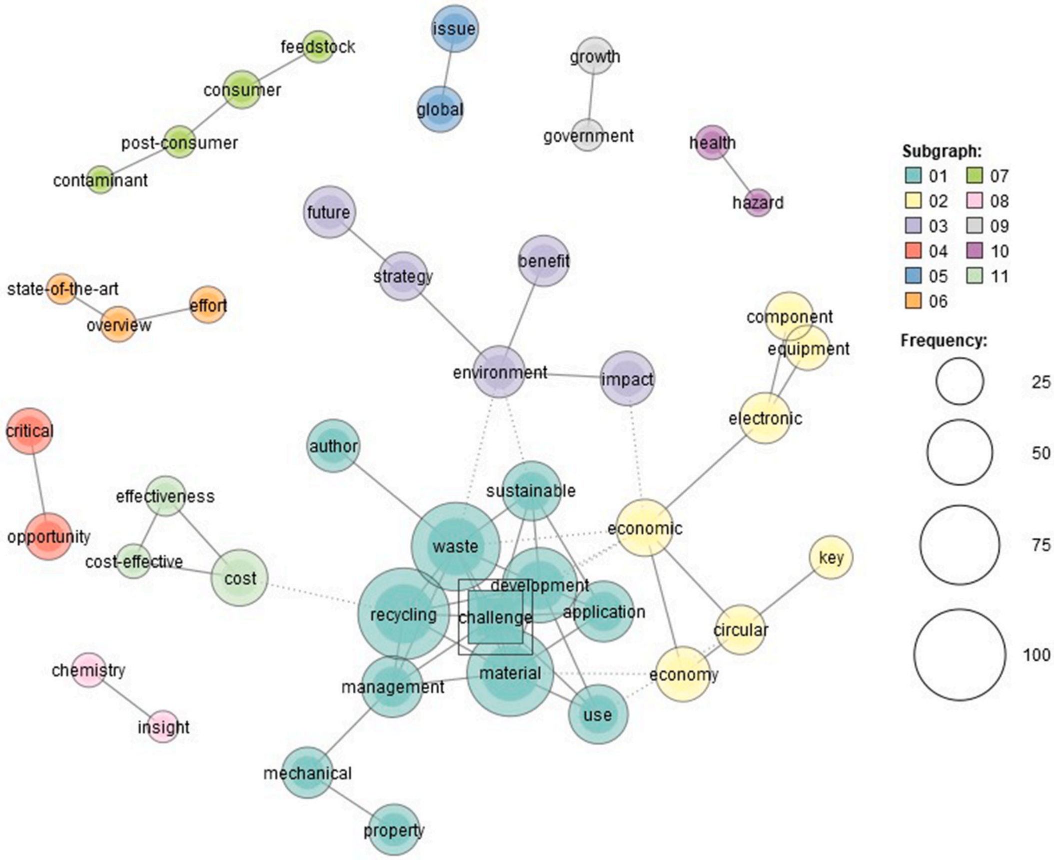

Fig. 4. Expressions coupling around *challenge**.
* Criteria: top 100, N/Adj, Differential, hits: 141-H5).
Source: the authors

The challenge remains for administrators and specialists in related areas. It is necessary to keep up with technological advances in the separation and reuse of material in the sense of a logistical network capable of handling waste collection, transport, and distribution. Works that describe temporary projects organized by local groups reveal results above the local averages in the collection and distribution of material (Rigillo et al., 2020; Särkilahti et al., 2017). Regular local projects can be a solution. They would be small sub-networks within the broader recycling network, with a degree of independence for their organization and management.

5. Discussion

The academic production of the last 12 years on the relationship between technology and recycling shows a diversity of technologies, material classification, countless laboratory tests, technical, political, and management problems associated with implementation, challenges presented generically, such as consumer education, and some cases of temporary local actions that were successful.

After carrying out six coupling analyses, based on reflections and hypotheses for each new group found, it was possible to construct four converging points, helping us to construct the answer about recycling and technology.

a. Few researchers are focusing on recycling, technology, and management. The hot theme is production technologies.
b. Researchers did not consider recycling to be a lucrative and growing business. Articles that discuss strategy, competition, market, cost, and profits are rare. However, recycling handled about $61B in 2022 (https://www.amcsgroup.com/blogs/global-waste-and-recycling-market-trends/).
c. Regarding technology applied to recycling, there is a dominance of chemical experiments of material separation. We assert that the network of organizations participating in the task poses management, logistical, and consumer behavior challenges. Articles about these three factors are rare and without efficient models tested. This absence could be the reason why recycling rates remain around 45%.

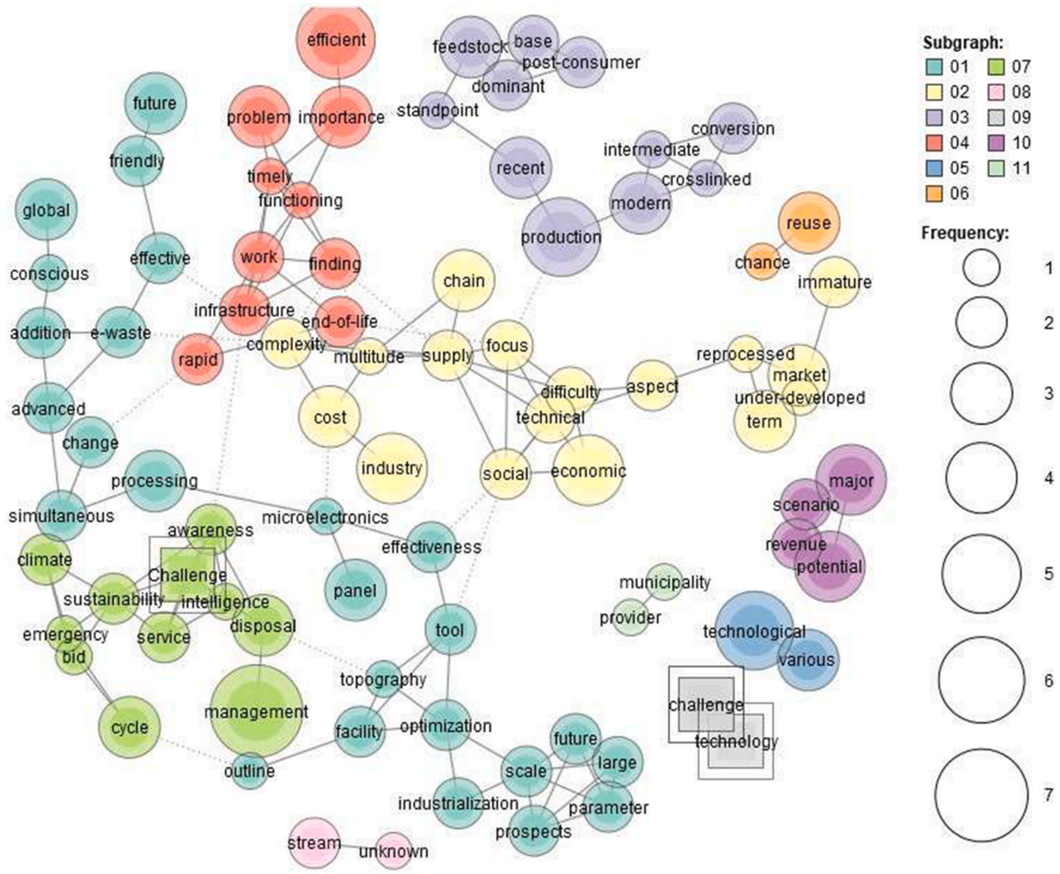

Fig. 5. Data organization around the expressions challenge and technology.
Source: the authors

d. Technology adoption and recycling capacity grow slower than waste production. The growing quantity of plastic and electronics waste is an example compared with the recycling rates. Articles value the production technology, but waste—like plastic—continues to flood land and oceans.

Considering those points, we affirm that until now, researchers have offered little contribution of solutions to recycling, as pointed out in an article by Yang et al. (2023). Our analyses show that researchers present generic comments about management models, consumer behavior, and public policy without empirical evidence or critical success factors. Even the articles with cases show generic conclusions about success factors.

Another point is that technology is not a hot topic in recycling, but it is in production. It could be an intelligent way to cut the sustainable problem in origin, as presented in the mission of various journals dedicated to the sustainable cause. However, it is a fact that clean production does not reduce waste or even achieve a growing recycling rate, and thus, something is wrong with this clean production.

Another fact is that Latin American recycling rates are lower than in Europe and the United States. Articles that show this situation did not create deep and integrated analyses about the economy, public policy plans, technological development, and consumer cultural practices.

We think these aspects are all integrated. The argument is that the volume and nature of the waste result from the lifestyle of social groups inserted in an economic and social system. For example, Latin America lacks social, political, and economic development and sustainability education. Then, the waste recycling rate is low when compared to developed countries. It is possible to infer that recycling is connected to social and political systems, which could (or could not) value technologies for solving the waste problem.

To sustain this affirmative concerning the absence of models trying to integrate the factors, our analysis shows that articles focused on revisions about recycling and technology use descriptive techniques without connection to the significant categories of social issues. Literature values the frequency of authors, regions, and words but fails to create deep analysis and develop propositions and hypotheses.

It is worth emphasizing that local projects—organized by the actors who generate, collect, or separate and pack the waste—could be a solution. These small networks of temporary local projects achieve collection and disposal results that the traditional local system cannot. The problem is the time limit since temporary networks do not achieve a level of interrelation between the actors and the necessary commitment of government and enterprises that allows the permanence of actions.

6. Conclusions and future works

The article discusses the intertwining between recycling and technology in academic production. The effort is justified because the worldwide recycling rate of domestic solid waste is around 45%, but the waste volume increases yearly. Electronic waste is an example of this (Forti et al., 2020). This situation raises the question of how technology is (or is not) helping to increase this rate.

Six bibliographic couplings of data on recycling and technology in academic production were obtained from an initial selection of 81.530 articles from 2012 to 2023. We found that research contributes little to management solutions for increasing the rates of recycled material. In general, attention focuses on the use of technology in production or laboratory research on the physical-chemical separation of materials.

The expressions *recycling* and *technology* present the highest proximity indexes with the expressions *challenge*, *management*, *consumers*, and *public policies*. The interpretation is that researchers perceive the phenomenon of technology applied to recycling as secondary since other challenges of public policies, management, and consumption practices are more urgent.

However, the situation is the opposite regarding the production stage. Articles are supposed to deal with recycling, but they actually deal with clean production, defined strategies, management oriented towards the gradual change of industrial equipment, and government support, offering tax incentives for each success in cleaner and more sustainable production.

For us, there is a distortion of research and practice because the valorization of production seeks to create new packaging and manufacturing processes that are less polluting, but the amount of waste generated continues to increase. In the case of plastic, for example, manufacturers strive to use alternative materials to those derived from petroleum, such as biodegradable materials, but plastic packaging constitutes the highest volume of solid waste.

We concluded that this valuation of production, following the principles of linear production, does not help solve the problem of the growing volume of waste and the tight recycling capacity, which consistently stands at around 45%. If we take the circular economy system as a principle (Hou et al., 2022), the conclusion is that the chain system is unbalanced.

From the results and discussion, it is possible to present some converging points.

(a) The academic production on the relationship between technology and recycling shows a diversity of technologies, material classification, laboratory tests, technical, political, and management problems associated with implementation, challenges presented generically, and cases of successful temporary local actions. There is no clear direction of the literature, showing that it is a field still in progress, with methodological procedures, which are characteristics of exploratory research.

(b) Congresses and forums worldwide discuss the need to modify production technologies to solve the industrial problem, encouraging governments and support organizations to drive funding for production-oriented research. The other supply point, recycling, does not receive impassioned speeches of attention. Those discourses become articles in academic journals, reinforcing the value of production and the secondary place of recycling.

(c) The circular economy—a system that values eco-efficiency—has not yet been able to position itself as a capable and necessary alternative to the linear economy, nor for entrepreneurs, public programs, and consumption practices, as can be inferred from some articles discussing the theme (Ababio and Lu, 2023; Davis et al., 2023; Kyriakopoulos, 2021). According to our analyses, the adoption of the circular economy is not simply a change of production plant because it refers to different uses of materials and energy, and its adoption requires coexistence between modes of production, regional ways of applying its principles (of reuse and recycling), and the social level of environmental education of producers and consumers (Kyriakopoulos et al., 2019).

The business model that uses the circular economy format presents different characteristics from the linear production model, including the need for integrated work, education, and control over the act of consumer disposal, regulations that extend from sustainable supplier certifications for raw materials to control of waste distribution, and the need for collaborative governance, seeking cohesion and efficiency of collective actions.

(d) Without pressure speeches for giving attention to recycling—and without an established strategy and practice of circular economy—research on technologies in recycling remains at the laboratory stage, still without connection to the routine of people’s lives. However, a quick look at the Internet shows various tools and equipment for recycling, including low-cost items like intelligent trash cans. There seems to be a distance between the reality of the market offering technologies and the portrait of academic production.

(e) The recycling task is complex in the sense of specialists who must act together. The analysis shows that we do not have a legal and operational system that facilitates the entry of organizations capable of collecting, organizing, buying, and properly disposing of waste; a consumer education and information system to separate material; a collection and delivery logistics system that supplies the cooperatives; a system of financial assistance and management for the operation of cooperatives; and a price regulation system for material to be recycled, today operating at the whim of the market. Each country, region, state, or municipality constructs its own system to deal with waste, resulting in a different average recycling rate, like 11% in Brazil and 69% in Germany[2].

(f) An area of academic production emphasizes the growing problem of electronic waste, with worldwide rates of around 11% below the general domestic waste of around 45%. The articles report the presence of an informal chain collecting e-waste, including online purchases, and prohibited technical resources, such as material burning, to separate the noble material from the electronic boards (Giglio et al., 2023), masking the valid rates. E-waste is profitable; some countries, like Belgium, accept e-waste worldwide. As with solid waste in general, the e-waste challenge is the network's complexity, with so many distinct interests and supply chain structures.

(g) A few articles described local actions aimed at recycling, which achieved better results than ordinary collection—for example, Majale et al. (2024). The interesting thing to note in these cases is that some of the challenges mentioned in the previous paragraphs are solved. For example, consumers strive to separate material and participate in the project; local retail enterprises assist with communication and offering bags for collection; local influencers, such as religious figures, communicate the action and request adherence; the local government does not put up bureaucratic obstacles; local industries offer bags and trucks to transport the collected material; cooperatives are willing to work special hours during the event.

Even without theoretical and technical knowledge, participants in these local projects avoid and solve the problems cited in the literature. It is an alternative that deserves more attention. For example, industries could finance regular events of these local projects (not just one-off events) and adopt cooperatives, which are important in receiving waste but are not valued in political and commercial negotiations.

In short, we looked for the intertwining of recycling and technology in academic production and did not find a deep and organized connection. Our research highlights the superficial stage of knowledge, analysis, management, and use of technology in recycling when we focus on urban solids, with more attention on plastic and e-waste. The technology is being tested in laboratories in several countries, but these efforts are disconnected from the countries' economic, social, and political realities. At present, the dominance of technology practice is at the production stage, which does not help with the recycling stage.

A limitation of our analysis is the lack of discussion about dividing waste into various categories. A more detailed study of this division and the technologies applied to each—for example, liquid or hospital waste—could provide a more realistic picture of the theme. We found divisions of technologies from the initial matrix but realized that was not our focus.

Another limit, only glimpsed during the academic research, is that there perhaps exists a gap between the absence of academic reports of technologies applied to recycling and the business reality of using technologies. We did not conduct a deep search, but we verified the presence of a large amount of news in the media about hundreds of experiences using technologies to collect, store, separate, and reuse solid waste. Even waste in the oceans—a subject that is practically absent in academia—appears with examples of projects, especially in journals of the nautical sector, such as Marine Policy and world events like Ocean Literacy Dialogues (https://www.oceanliteracydialogues.com/).

The final point is about management. We affirm that our article shows the problems and challenges and a few comments and examples of management. It seems that researchers related to management could not present generic management models that could serve as a guide for adapting to each material and technology. This task could generate a new article that is exclusively focused on management.

We hope that this article impacts researchers' awareness of the importance of recycling because of the theme's importance, solutions' social role, and the alignment with global programs like the 2030 Agenda that aim to realize a clean world.

CRediT authorship contribution statement

Ernesto Michelangelo Giglio: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Natalia Matui:** Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Aline Lima:** Writing – review & editing, Visualization, Validation, Project administration, Investigation, Formal analysis. **Ana Paula Lima:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization.

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.

Data availability

Data will be made available on request.

[2] Source: https://www.statista.com/statistics/1219551/municipal-waste-recycling-eu-by-country/

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