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Innovation and technology for sustainable mining activity: A worldwide research assessment

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ABSTRACT

The analysis of innovations and technologies aimed at improving the sustainability of mining activity has become important in recent decades. The main objective of this article is to evaluate the dynamics of this line of research worldwide between 1998 and 2017. A bibliometric analysis and a systematic review of a sample of 2,562 articles was developed along with an analytical framework based on the mine life cycle and the three areas of sustainability (economic, social and environmental). The results show that sustainability research has grown at a much higher rate than that of mining and minerals research. The three journals that have published the most articles on this line of research are *Journal of Cleaner Production, Environmental Science and Technology,* and *Gornyi Zhurnal*, and the three countries with the highest number of published articles are the USA, China, and Germany. Some 60.9%, 30.9%, and 8.2% of the analysed mining innovations impact environmental, economic, and social sustainability, respectively, and some 7.1% affect the exploration phase, 84.8% the exploitation phase, and 8.1% the closure phase. The analysis of issues related to environmental sustainability becomes more relevant as the exploration phase moves on to exploitation and closure. The primary challenges and future lines of research are in reducing energy use and increasing the use of renewable sources, analysing the social sustainability of current mining activities, and achieving clean production in the development of new mining activity environments (ice-covered areas and the ocean floor). This work provides new perspectives on the analysis and integral assessment of innovations and technologies aimed at making mining activity more sustainable, particularly where the contributions to the environmental, economic, and social fields are valued.

1. Introduction

The Brundtland Commission (WCED, 1987) report provided the broadest definition of sustainable development as "… development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This document is considered the primary driver of the current research on sustainability (Gorman and Dzombak, 2018). Sustainability goals were not adopted by the mining industry until 1998 with the Global Mining Initiative, which introduced the term "sustainable mining" in the action plan following the 2002 World Summit on Sustainable Development (Whitmore, 2006). Thus, until a few decades ago, the primary and virtually only objective in mining was to reduce costs; however, in recent years, social requirements to minimize negative externalities and improve sustainability have been incorporated (Bakken, 2007; Chabukdhara and Singh, 2016). Currently, mining activities face important challenges regarding sustainability in the sector that are based on three aspects (Reichl et al., 2016; British Geological Survey, 2018; US Geological Survey, 2018): first, the limited nature of these resources and thus the problem of depletion; second, the demand for economic efficiency; and third, the environmental impact and social rejection of this activity (Tilton, 2002; Sinding-Larsen and Wellmer, 2012; Gómez-Ros et al., 2013).

Given the nature of extractive activities, "sustainable mining involves the adoption of practices in the phase of mining operations that result in environmental and social improvements over

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traditional resource development methods, as well as negative impacts, while maintaining the health and safety of mine workers and the interests of stakeholders and affected communities" (Gorman and Dzombak, 2018). Therefore, the primary challenge for the sector is to demonstrate that it contributes to the welfare and well-being of the current generation, without compromising the potential of future generations for a better quality of life, which requires an approach that is capable of balancing economic, environmental, and social concerns (Azapagic, 2004). According to Jenkins and Yakovleva (2006), sustainable development within the mining industry must pursue economic development, through the investment of profits obtained from plans for future local development that ensure the long-term support of communities; environmental protection, by minimizing the impacts of exploitation and rehabilitating the land to ensure its subsequent use; and social cohesion, by establishing dialogue with the different stakeholders, ensuring transparency of operations, and minimizing social and cultural impacts.

The industry's efforts to implement sustainability measures are reflected in the publication of corporate social responsibility and sustainability reports. By the end of the 1980s and beginning of the 1990s, companies in the petrochemical sector were the first to prepare independent environmental reports within the extractive sector (Davis-Walling and Batterman, 1997; Scott, 2000). Two of the pioneer mining companies in the preparation of reports with environmental and social information on their operations were Rio Tinto and BHP (Jenkins and Yakovleva, 2006). Such documents reflect the industry's commitments to sustainability in the form of corporate policies. Thus, policies covering health and safety, employee welfare, and the environment were the first to be developed, whereas general sustainability policies did not appear until 2003 (Jenkins and Yakovleva, 2006). Currently, companies in the mining industry are in a leadership position in the dissemination of social and environmental information (Kemp et al., 2012). Confronted by challenges within the sector, the industry argues that technological development, the discovery of new deposits, and recent developments enables them to be optimistic. Thus, companies emphasize innovation and technological development as the primary drivers of sustainability (Mudd, 2013). For example, we cite some of Rio Tinto's efforts to utilize innovation and technology to promote sustainability in their mining activities, such as deploying the world's largest wind-diesel hybrid power plant at the Diavik diamond mine, adding solar power to its Weipa bauxite operation in Australia to reduce diesel usage, obtaining most of its electricity from hydro and nuclear power, and developing a more efficient way to produce aluminium (Dougherty, 2017).

Many studies analyse innovation, technology, and sustainability in mining activities from different perspectives including: support models for decision-making (Bai et al., 2017), accounting and sustainability reports of mining activities (Lodhia and Hess, 2014), lifecycle applications to analyse the sustainability of mining activities (Gorman and Dzombak, 2018), use of renewable energy sources to improve the sustainability of mining activities (Choi and Song, 2017), empirical research for adopting technology innovation in coalbed gas mining (Jun-Ju and Li-Jie, 2017), barriers impeding technology adoption (Kuan et al., 2015), innovation in the value chain of mining activities (Pietrobelli et al., 2018), disruptive innovation in digital mining (Sganzerla et al., 2016), treatment techniques of mining waste (Careddu et al., 2018), sustainable management of mining waste (Aznar-Sánchez et al., 2018a), sustainable design approaches in the mineral industry (Corder, 2015) and crushed stone mining sector (Barbosa-Reis-Monteiro et al., 2018), and the sustainable management of metals (Aznar-Sánchez et al., 2018b).

In the current context of a sector that must respond to the growing demand for minerals and metals while facing critical social and environmental problems (Lodhia, 2007; Lodhia and Hess, 2014), improved understanding on the progress of sustainability efforts within the mining industry is needed. Therefore, the purpose of this work is to analyse the existing literature regarding innovation and technology, with an approach directed at increasing the sustainability of mining activities. The general objective is to evaluate the existing literature to show what has been accomplished thus far and use the results as a basis for identifying areas that require further research. Here, the primary contribution compared to previous studies is that innovation and technology are analysed with respect to the three areas of sustainability (economic, social, and environmental), considering an analytical framework that is based on a mine's lifecycle. This contribution is important because it helps detect gaps in technology research with respect to certain phases of mining activities and the different areas of sustainability, as well as reveal future lines of work for improving clean production, energy savings, reuse of materials, or the rehabilitation of closed mines. Thus, this study presents a general perspective on the evolution of applying sustainable practices in the mining industry; the primary drivers of research in this area; the most relevant lines of research; and the most outstanding innovative and technological contributions in the economic, environmental, and social fields of the sustainability of mining activities in each phase.

2. Innovation, technology, and sustainability

The three aspects that compose the concept of sustainability are environmental, economic, and social. Therefore, sustainability implies attempting to preserve the ecological processes necessary for the development of the environmental functions of the ecosystems that result in the flow of services; it must be based on economically viable development to maximize revenues based on available resources; and it requires agreement among all interested parties and the generation of equally distributed social benefits (Aznar-Sánchez et al., 2018c). Thus, from the perspective of sustainability, companies and administrations should pursue objectives that include economic, human, and natural capital (Schoolman et al., 2012).

Sustainability, from an economic perspective, implies the generation of results for the industry, provided that the final objective of every company is generating a profit, and for the other parties involved, especially affected local communities (Fan et al., 2017). From the company's perspective, achievement of this objective is determined by the continuous search for cost reduction, the improvement of productivity, and the overall efficiency of the system. For other stakeholders, the generation of wealth can materialize in the form of local job creation, payment of taxes, and contribution to the GDP for the entire country (Ouoba, 2017). Attraction of foreign capital via investments is another form of contribution to the generation of wealth for the country where mining operations are located (Kuan et al., 2015). Aspects of the creation and distribution of wealth within the mining sector are determined from an economic perspective, to ensure a fair and equitable return for the affected regions that suffer from the negative impacts of mining activities and the reduction of resource reserves (Azapagic, 2004).

The environmental factors of the sustainability of mining activities are the most developed (Vintró et al., 2014). These factors can be divided into two groups. On the one hand, there are the issues related to the inputs of the activity. In the development of mining activities, a surface area is destroyed and scarce water resources, fundamental for ecosystems and economic activities, are consumed; furthermore, as technological development of the sector advances, energy consumption increases with the development of the activity (Bai et al., 2017; Zharan and Bongaerts, 2017). On the other hand, the activity generates waste, both solid and liquid, and noise, in addition to the impacts on soil, water, and air that often are irreversible (Azapagic, 2004; Mudd, 2010a).

In the social sphere, issues related to sustainability differ depending on the stakeholders. Mine workers are the most affected by the impacts of mining activity. Appropriate payment systems for the performance and hazards of the activity performed are required, as well as guarantees of a healthy and safe environment (Maier et al., 2014). Similarly, these guarantees must be extended to the local communities where a mine operates. Air, water, and soil pollution can generate diseases via inhalation, and direct or indirect poisoning through food production (Martinat et al., 2016). Accidents can also be a risk factor for the safety of populations adjacent to a mine (Laurence, 2005). Training mining personnel influences sustainability, not only for the professional career of each worker, but in the form of social capital for mining regions. In general, the adoption of ethical management and corporate social responsibility principles, which ensures the participation of all interested parties, equal opportunities, and a fair and equitable distribution of the wealth produced, are a fundamental part of achieving the objectives of sustainability in the mining sector (Azapagic, 2004; O'Faircheallaigh, 2013; Tiainen, 2016). Table 1 presents a list of the primary aspects related to the sustainability of mining activities, classified according to economic, environmental, and social components (Azapagic, 2004). The table also includes the positive or negative nature of each aspect. For example, the contribution to the creation of wealth and employment always has a positive nature (+), whereas biodiversity loss or noise emission always have a negative nature (−). Aspects such as the distribution of wealth or the management of solid waste predominantly depend on the application of ethical principles and social responsibility (±).

However, in innovation and technology reside the fundamental elements to face these challenges and contribute to achieving greater sustainability in mining, both in terms of resource depletion and the socioeconomic and environmental dimensions (Tilton and Guzmán, 2016). In this study, innovation includes a new method, process, idea, product, etc., oriented to improve some or all areas of the sustainability of mining activities, whereas technology is defined as the application of scientific knowledge for practical purposes (Oxford English Dictionary, 2018). Innovation and technology offer the possibility of identifying and exploiting previously unavailable deposits, which can increase the efficiency of the production and subsequent treatment of minerals and their derivatives, develop substitutes, reduce the consumption of resources, and even enable recycling (Tilton, 2002). In an economic context, innovation and technology enable cost reductions and thus lead to increased profitability of the sector. Regarding improvements in production efficiency throughout the mining process, advances in technology have provided an increasing amount of information and data in real time about machinery, personnel, energy, and resources (Ge et al., 2018). Thus, in the extraction phase, remote monitoring systems are being developed to, for example, characterize the geotechnical properties of an area (Calas, 2017). Furthermore, the machinery being used is increasingly efficient and environmentally friendly (Kusiak, 2018). In drainage and calcination processes as well as in extraction and other phases, the application of renewable energies, arc-plasma generators or microwaves is suggested (European Commission, 2017).

In the mineral resource treatment phase, new materials and techniques are being used to improve the properties and applications of the extracted materials (Johnson, 2004). To achieve the objective of increasing the reuse of and revaluating mining resources, technologies are being developed to enable the use of low-quality ores; high-intensity flotation devices can increase product recovery; selective flocculation procedures can eliminate impurities; and processes are being developed to efficiently transform the energy level of waste for use in construction products (Hudson-Edwards and Dold, 2015; Zhang et al., 2017). Geochemically analogous metal recovery processes have also been proposed (Ou and Li, 2016) including thermo-chemical and liquid extraction techniques for recovery through composting (Mulchandani and Westerhoff, 2016). Currently, waste treatment in the mining sector is committed to remediation and waste recycling as well as enhancing mining areas for alternative uses. Current lines of research are oriented towards the implementation of biotechnological and microbial methods, algae bio-remediation and phytoremediation (Ghose, 2004; Lottermoser et al., 2011; Párraga-Aguado et al., 2016; Abbas et al., 2017). To reduce water pollution, sediments with nutrients are used to reduce metal acidity and increase pH, and engineering storage systems following ecological protocols has been proposed (Johnson, 2014). Regarding waste recycling, taking advantage of the link between the mining and construction sectors has been proposed to transform such waste into construction materials, and other researchers are focusing on the use of gangue materials and gases to produce electricity (Haibin and Zhenling, 2010).

Since the beginning of the millennium, different indicators have been developed for the evaluation of the sustainability of mining activities. Thus, Azapagic (2004) proposed a framework for sustainable development indicators within the mining and minerals industry, based on the different phases of the mine lifecycle and

Table 1
The key items for the mining and minerals sector sustainability.

Economic	Nature	Environmental	Nature	Social	Nature
Contribution to GDP and wealth creation	+	Biodiversity loss	−	Bribery and corruption	−
Costs, sales and profits	+	Emissions to air	−	Creation of employment	+
Distribution of revenues and wealth	+/−	Energy use	−	Employee education and skills development	+
Investments (capital, employees, communities, pollution prevention and mine closure)	+/−	Global warming and other environmental impacts	−	Equal opportunities and non-discrimination	+/−
Shareholder value	+/−	Land use, management and rehabilitation	+/−	Health and safety	+/−
Value added	+	Nuisance	−	Human rights and business ethics	+/−
		Product toxicity	−	Labour/management relationship	+/−
		Resource use and availability	+/−	Relationship with local communities	+/−
		Solid waste	+/−	Stakeholder involvement	+/−
		Water use, effluents and leachates (including acid mine drainage)	+/−	Wealth distribution	+/−

considering the different areas of sustainability. Lifecycle analysis has become a framework for evaluating the responsible management of mineral resources in recent years (Durucan et al., 2006; Gorman and Dzombak, 2018). In ISO 14040, the life cycle is defined as "a technique to determine the environmental aspects and potential associated with a product: compiling an inventory of the relevant inputs and outputs of the system, evaluating the potential environmental impacts associated with these inputs and outputs, and interpreting the results of the inventory and impact phases in relation to the objectives of the study " (ISO, 1997:iii). This analysis has been widely used to measure the consumption of natural resources and the accompanying environmental impacts in relation to production systems, energy systems, supply chains, etc. (Yin et al., 2018). The life cycle is useful when identifying the different phases of an economic activity and its connections with the environmental, economic, and social dimensions of sustainability. Van Zyl (2007) developed a life cycle model for a mine based on grouping the different phases of the mining activity into exploration, exploitation, and closure. The exploration phase includes all operations aimed at identifying and characterizing land to locate sites based on the availability of deposits, and it includes the stages of prospecting and exploration. The exploitation phase includes all stages from the design and planning of the mine to its development and exploitation throughout its useful life. The closure phase covers all the operations after the end of a mine's useful life, which is understood to be the operational life of a mine, including dismantlement, decontamination, and completion of a reclamation plan. This framework of general analysis has been used in this work to assess the contribution of innovation and technology to the sustainability of mining activities. The final part of the mining innovation analysis should include an assessment of the level of contribution to sustainability in each of the different aspects. Fig. 1 illustrates the framework for analysing innovation for mining sustainability.

3. Methodology

A quantitative and qualitative review of the selected sample of articles was carried out to achieve the proposed objectives. First, the quantitative analysis of the sample of selected articles was conducted by the bibliometric method, which aims to identify, organize, and analyse the main components of a specific area of research (Zhang et al., 2017a; Velasco-Muñoz et al., 2018a). The bibliometric analysis allows the evolution, gaps, and future research trends on a subject to be studied (Zapata-Sierra and Manzano-Agugliaro, 2017; Giménez et al., 2018) as well as the main driving forces of a field of study to be identified, namely, authors, journals, institutions and countries (Fernández-García et al., 2015; Montoya et al., 2016). This methodology was

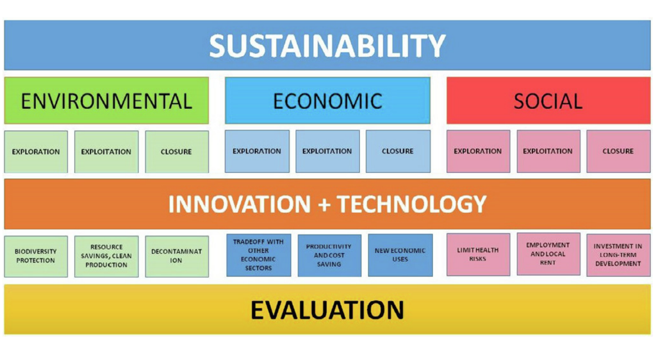

Fig. 1. Analytical framework of innovation and technology for sustainability mining activity.

introduced by Garfield in the mid-20th century; it uses mathematical tools and statistics to assess the relative importance of the output of a specific scientific area (Huang et al., 2014; Perea-Moreno et al., 2017). The main traditional approaches of the bibliometric method are co-occurrence, co-citation, and bibliographic coupling analyses (Velasco-Muñoz et al., 2018b), and the evolution of these approaches over the last decade has allowed diverse tools to be developed for the analysis of bibliometric data. Some of the most recent works in this field examine methods to identify and observe the evolution of specific scientific topics within a period of time (Novas et al., 2017; Zhang et al., 2017b), develop analytical frameworks to evaluate innovation (Robinson et al., 2013), use visualization tools for text and data extraction (Zhang et al., 2017c) such as overlapping maps to identify variable associations (Rafols et al., 2010), or develop automated tools based on common types of software (Suominen and Toivanen, 2016). As defined by Durieux and Gevenois (2010), three types of indicators can be used in bibliometric analysis: indicators of the relative productivity of the different agents involved in a specific topic; quality indicators of the relevance of the publications including the record of appointments, the H-index, and the impact factor, among others; and structural indicators of the links between the different agents. This last type of indicator is particularly interesting in areas of research with global repercussions and in which there is intense international cooperation.

Multiple bibliometric analytical studies use the Scopus database because it is considered the largest repository of citation data and the abstracts of arbitrated literature; it is readily available and offers the possibility of analysing and downloading content (Mugomeri et al., 2017). Compared to other databases, Scopus is ideal for this type of work due to its higher level of representation (Gavel and Iselid, 2008), higher volume of indexed publications (Mongeon and Paul-Hus, 2016), higher update frequency (Borrett et al., 2018), and greater facility related to debugging and processing data (Stirbu et al., 2015). The following parameters have been used to search for articles: [TITLE-ABS-KEY (mining OR mine OR mineral OR metal) AND TITLE-ABS-KEY (innovati* OR technolog* OR "processing technolog*" OR "processing innovation" OR "innovative technolog*" OR "technolog* innovati*" OR "innovati* producti*" OR "novel technolog*") AND TITLE-ABS-KEY (sustainable OR sustainability) AND DOCTYPE (ar) AND PUBYEAR > 1997 AND PUBYEAR < 2018]. In other investigations, similar parameters have been used. For example, in their analysis of the sustainability of mining activities, Gorman and Dzombak (2018) use: ["sustainable mining", "sustainable development AND mining", "sustainability and mining", "sustainab* AND mining"]. This search is broad enough to cover all the articles published on innovation and technology for the sustainability of mining activities. This search was performed during February 2018, and the study period covered 1998 to 2017; 2018 was excluded to analyse complete annual periods. Because the same studies may be published as different types of documents (presentations to governments, book chapters, working papers, etc.), only articles were included (De la Cruz-Lovera et al., 2017). The final sample of publications for this study consisted of 2,562 articles.

The variables under analysis in this phase of the work are the annual production of published articles, the number of authors involved in the production, the institutions and countries of affiliation of the different authors, the different subject areas according to the Scopus classification, the publishing journals, and the keywords. After downloading and processing the information, different tables and figures were elaborated to visualize and analyse the data using different software tools. The most frequent quality indicators were used to evaluate the relevance of the articles, such as the number of citations, the H-index, and the impact factor, i.e., the Scimago Journal Rank (SJR).

Second, a systematic review was carried out to qualitatively analyse the sample of selected articles, and a framework for analysing the contribution of innovation and technology to the sustainability of mining activity was developed to achieve this objective. To conduct a systematic review, only those works performed using a perspective of sustainability or sustainable development for mining that show a particular sustainability result or suggest specific actions to improve the sustainability of mining were considered. The variables were the theoretical or empirical nature of the articles, minerals and countries under study in the empirical works, lifecycle phase affected by innovation, and sustainability field to which the innovation contributes. The analytical framework relates the concepts of sustainability (based on its environmental, economic, and social dimensions) and the mining lifecycle as divided into the phases of exploration, exploitation, and closure.

The methodology used in this work may present some limitations. The selection of keywords directly affects the results; therefore, a broad search has been conducted to avoid excluding relevant documents. The selection of the database can represent another limitation, by conditioning the sample of works for the analysis. In addition, provided the high volume of articles that compose the sample, a systematic review has been conducted in successive stages, initially classifying based on titles, words, and abstracts.

4. Results and discussion

In this section, the primary results of this work are presented and discussed.

4.1. Evolution of scientific production

The evolution of the main characteristics of the articles published on innovation and technology for the sustainability of mining activity (ITSM) during the last twenty years is shown in Table 2; the number of published articles increased from 18 in 1998 to 405 in 2017. Fig. 2 shows the growth trend throughout the analysed

Table 2
Characteristics of the articles on ITSM research from 1998 to 2017.

Year	A	AU	AU/A	NR	NR/A	J	TC	CTC/CA	C
1998	18	29	1.6	550	30.6	17	4	0.2	10
1999	26	47	1.8	808	31.1	25	12	0.4	11
2000	31	55	1.8	1,063	34.3	26	30	0.6	11
2001	36	74	2.1	773	21.5	32	36	0.7	20
2002	32	64	2.0	1,052	32.9	30	88	1.2	12
2003	33	102	3.1	700	21.2	26	138	1.8	17
2004	36	108	3.0	711	19.8	3.4	153	2.2	25
2005	60	172	2.9	1,378	23.0	49	245	2.6	25
2006	72	147	2.0	1,663	23.1	61	391	3.2	21
2007	98	268	2.7	2,014	20.6	79	462	3.5	28
2008	110	325	3.0	2,976	27.1	97	669	4.0	32
2009	129	366	2.8	3,971	30.8	108	994	4.7	37
2010	117	371	3.2	3,357	28.7	107	1,328	5.7	35
2011	144	443	3.1	4,636	32.2	119	1,879	6.8	44
2012	145	536	3.7	4,937	34.0	119	2,425	8.1	43
2013	214	776	3.6	8,687	40.6	170	3,205	9.3	46
2014	237	807	3.4	9,822	41.4	184	4,260	10.6	53
2015	283	1,129	4.0	13,946	49.3	205	5,389	11.9	52
2016	335	1,338	4.0	15,444	46.1	233	6,981	13.3	66
2017	405	1,640	4.0	17,619	43.5	252	9,294	14.8	74

A: total number of articles; AU: annual number of authors; AU/A: average number of authors per article; NR: total number of references in all articles; NR/A: annual number of references per article; J: annual number of journals; TC: cumulative annual number of citations in all articles; CTC/CA: annual total citations per cumulative article; C: annual number of countries.

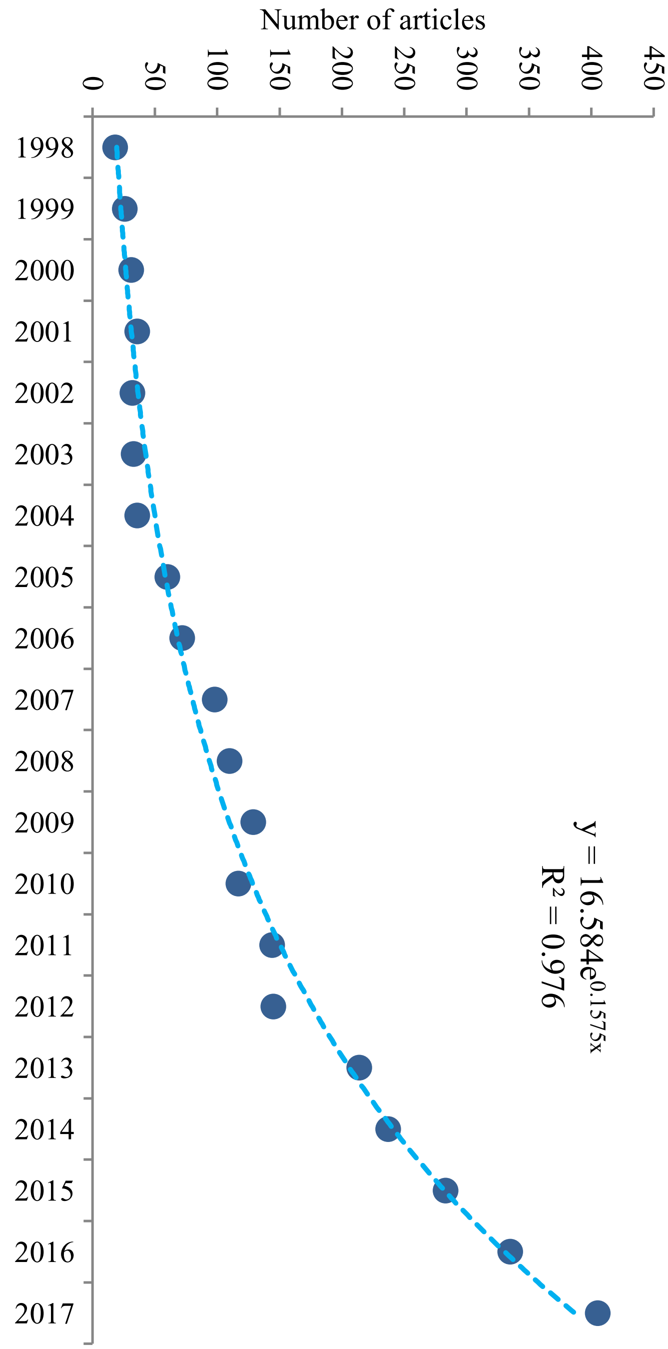

Fig. 2. Trend in the number of articles on ITSM research from 1998 to 2017.

period, and the results demonstrate that this line of research has recently experienced a surge in development, given that 57.56% of the articles were published in the last five years (2013–2017). This same tendency is verified in other works on mining. In their article on the crushed stone mining sector during 2007–2016, Barbosa-Reis-Monteiro et al. (2018) indicate that most of the research was published between 2013 and 2016, and an analysis of those articles published on the sustainable management of mining waste during 1988–2017 by Aznar-Sánchez et al. (2018a) shows that more than 50% of the works were published during the last seven years. To verify the relevance of this line of mining and mineral research, the trends in the number of published articles were comparatively analysed. As shown in Fig. 3, the accumulated annual growth rate in

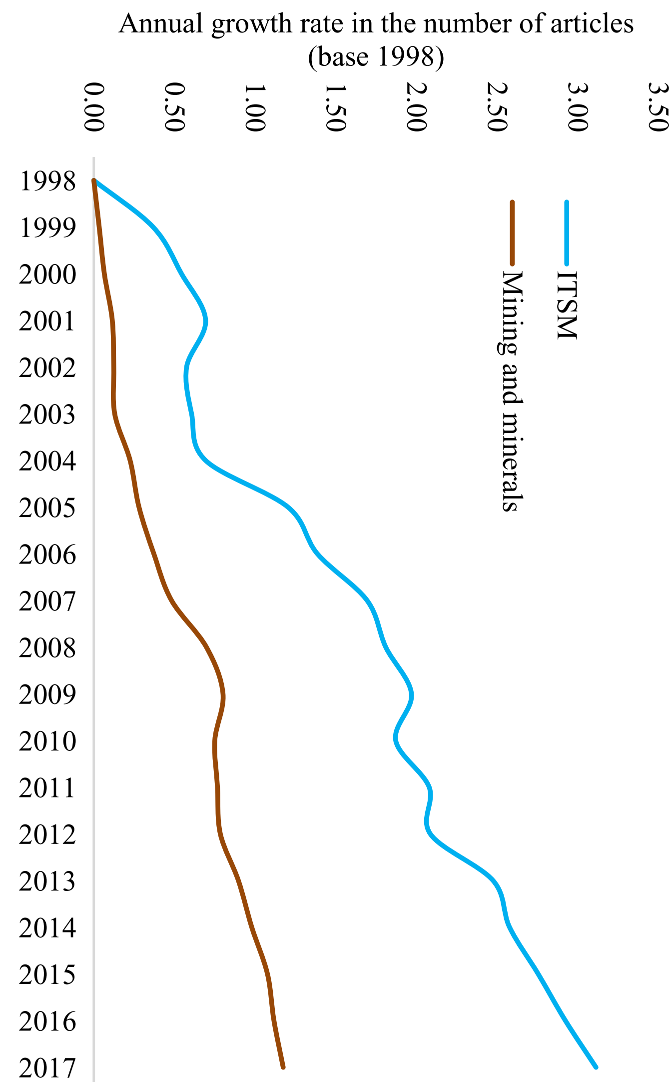

Fig. 3. Comparative trends in the number of articles on ITSM and mining and minerals research from 1998 to 2017.

the number of articles published on mining and minerals is 6.38% while that of articles on ITSM is 17.81%, indicating that although ITSM studies are recent, they are experiencing strong development while attracting increasing attention within the field of mining and mineral research. In their work analysing the highly cited knowledge base of sustainability science, Buter and Van Raan (2013) found that the growth rate of articles on sustainability was 11.77% during the 1999–2008 period, but that of articles on ITSM was 17.38% for the same period. This means that compared to the evolution of the research on sustainability, works on ITSM have also exhibited more accelerated development.

This growth trend is consistent with the changes in the other variables related to scientific production in this research area. The number of authors involved in the production of articles on ITSM increased from 29 in 1998 to 1,640 in 2017, and the average number of authors per article increased from 1.6 in 1998 to 4.1 in 2017. The average number of references included in the articles has also grown from 30.6 in 1998 to 43.5 in 2017, and the number of journals that published the articles on ITSM increased from 17 in 1998 to 252 in 2017, which reflects the growing interest on this line of research. The average number of citations of articles on ITSM increased from 0.2 in 1998 to 14.8 in 2017, demonstrating a notable increase in the impact of publications on ITSM. Furthermore, the number of countries contributing to this research has also grown significantly, from 10 in 1998 to 74 in 2017, indicating the increasing international expansion of this line of investigation. Other works on the institutional analysis of sustainability sciences, such as those by Yarime et al. (2010) and Aznar-Sánchez et al. (2018a), point to this same trend.

4.2. Distribution of scientific output in thematic categories and journals

Fig. 4 shows the evolution of the main thematic areas in which publications on ITSM are classified, and the results of the review indicate that most articles have an environmental or technical focus. According to the Scopus classification, the main thematic category is that of Environmental Science with approximately 40% of the total articles in the sample. Next is Engineering with 28.5% of the total articles, Materials Science with 18.24%, Energy with 18.12%, Earth and Planetary Sciences with 16.17%, Chemistry with 15.42%, and Chemical Engineering with 11.21%. It must be noted that the same article can be simultaneously included in more than one category, and the remaining categories do not account for 10% of the published articles. Environmental Science, Earth and Planetary Sciences, Engineering, and Chemistry are also among the five main categories of the research on the sustainable use of mining waste (Aznar-Sánchez et al., 2018a). These thematic areas are related to the different lines of research on ITSM. Under the categories of Environmental, Earth, and Planetary Sciences, all works are oriented towards environmental sustainability that study the pollution and remediation of ecosystems, and the rehabilitation of soils. In the category Materials Science, all the studies focus on the recovery, recycling, and reuse of minerals and metals. In addition, in this group are studies on the distribution chain, lifecycle of materials, and the circular economy, which extend beyond the mining scope, analysing the sustainability of the sector. The Energy category includes an important group of articles that analyse improvements in the energy consumption of the activity, which is one of the sector's primary problems due to high costs and the emission of greenhouse gases. The Engineering and Chemistry categories represent two fundamental collateral disciplines in the vast majority of works on sustainable innovation and technology. In these categories we find works that range from the development of machinery to processes of bioremediation.

The concept of sustainability includes environmental, economic, and social dimensions that have led to the development of the so-called "tripartite model" of sustainability, which conceives sustainability as consisting of equitable economic growth as well as the search for social welfare and sustainable ecological systems (Galdeano-Gómez et al., 2017). According to this model, sustainability research must therefore rely on three areas of knowledge: environmental sciences, social sciences, and economic sciences (Kajikawa, 2008). The Social Sciences category included 8.98% of the articles in the sample, while 4.49% were in the Economics, Econometrics, and Finance categories. Therefore, the social and economic aspects are little developed in the work on ITSM, indicating that only a partial vision of sustainability is offered in most of the published articles. Aznar-Sánchez et al. (2018a) and Schoolman et al. (2012) reached the same conclusion concerning the interdisciplinarity of studies on sustainability, with the latter authors concluding that there is a smaller number of economic studies, although the articles taking this approach are the most interdisciplinary. Barbosa-Reis-Monteiro et al. (2018) indicate that 23% of articles focus exclusively on environmental and social approaches to the detriment of the economic approach.

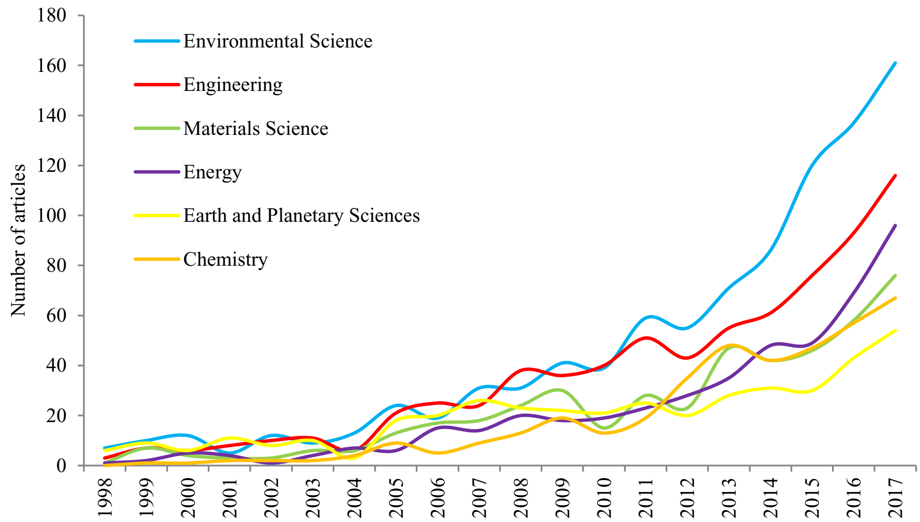

Fig. 4. Articles on ITSM research by subject category from 1998 to 2017.

Table 3 shows the main characteristics of the journals with the largest number of articles published on ITSM during 1998–2017. *Journal of Cleaner Production* published the most articles in this line of research with a total of 87, and it published its first article on ITSM in 2003 while ranking as the most productive journal in 2006. In addition, this publication had the highest number of citations with a total of 1,875 and ranked third on the SJR index with a score of 1.615. According to Lodhia and Hess (2014), this magazine has contributed extensively to the research of mining sustainability. *Environmental Science and Technology* ranked second with 35 articles as well as second in terms of the number of citations, 1,122; it also ranked second in the average number of citations per article with 32.1. *Gornyi Zhurnal* has recently incorporated this line of research with its first article published in 2013, but in five years, it has managed to become the third most productive journal. The publication with the highest average citations per article was *ChemSusChem* with 46.8, and the journal with the oldest publication is *Resources Policy* with an article published in 1999. Yarime et al. (2010) offer a list of the 100 most prolific journals in sustainability research including *Journal of Cleaner Production* (position 5), *Journal of Environmental Management* (position 10), *Environmental Science and Technology* (position 28), and *Resources Conservation and Recycling* (position 34). *Environmental Science and Technology* and *Journal of Environmental Management* are also among the 10 most productive in terms of research on the sustainable management of mining waste (Aznar-Sánchez et al., 2018a).

The most prolific journals in the publication of ITSM articles are of high quality based on their SJR ranking because all except two are in the first quartile. In addition, all these journals actively publish articles on this subject, given that all published articles in 2017. However, these ten journals accounted for only 12.61% of the total articles in the sample, meaning that the scientific literature on ITSM is published in a very wide range of journals. Although the social and economic aspects of sustainability were not well represented in terms of thematic categories, some of the most productive journals were form this area of research such as *Resources Policy*, *Waste Management* and *Journal of Environmental Management*. The set of articles classified within one of the different thematic areas corresponding to Social Sciences and Economics accounted for 19.17% of the sample, and when evaluating the ten most productive journals in these thematic categories, this set of journals accounted for 42.16% of the total number of articles with a social or economic focus. This indicates that while the publication of articles with a technical approach is very fragmented, those with a social and economic focus are highly concentrated in a few journals.

4.3. Main countries, institutions and authors driving research on ITSM

Table 4 shows the main variables for the ITSM articles from the 10 most productive countries in this topic during 1998–2017 that include some of the main consumers of minerals and metals such as the USA, China, and countries in Europe as well as some of the main

Table 3
The 10 most productive journals for ITSM research from 1998 to 2017.

Journal	A	SJR	H index [a]	C	TC	TC/A	1st A	Last A
Journal of Cleaner Production	87	1.61(Q1)	25	Netherlands	1,875	21.6	2003	2017
Environmental Science and Technology	35	2.53(Q1)	20	USA	1,122	32.1	2003	2017
Gornyi Zhurnal	30	0.22(Q3)	3	Russia	33	1.1	2013	2017
Resources Policy	29	1.11(Q1)	13	UK	882	30.4	1999	2017
Waste Management	29	1.35(Q1)	13	UK	405	14.0	2004	2017
Resources Conservation and Recycling	28	1.16(Q1)	12	Netherlands	648	23.1	2001	2017
Environmental Science and Pollution Research	2.3	0.81(Q2)	9	Germany	339	14.7	2007	2017
Minerals Engineering	22	1.13(Q1)	9	Netherlands	320	14.5	2007	2017
ChemSusChem	20	2.38(Q1)	13	Germany	936	46.8	2009	2017
Journal of Environmental Management	20	1.14(Q1)	9	USA	326	16.3	2002	2017

[a] Only ITSM articles. A: total number of articles; SJR: Scimago Journal Rank; C: country; TC: total number of citations in ITSM articles; TC/A: number of citations by article; 1st A: first ITSM research article; Last A: last ITSM research article.

Table 4
The 10 most productive countries for ITSM research from 1998 to 2017.

Country	A	APC	TC	TC/A	H index [a]	1st A	Last A
USA	431	1.334	11,629	27.0	57	1998	2017
China	395	0.287	4,947	12.5	36	2000	2017
Germany	197	2.388	3,118	15.8	25	1998	2017
UK	183	2.790	4,223	23.1	3.4	1999	2017
India	156	0.118	2,043	13.1	2.3	1999	2017
Australia	152	6.278	3,163	20.8	31	1999	2017
Italy	134	2.210	1,878	14.0	24	1998	2017
Canada	102	2.813	2,420	23.7	20	1998	2017
France	89	1.330	1,835	20.6	20	2002	2017
Spain	87	1.872	914	10.5	16	2005	2017

[a] Only ITSM articles. A: total number of articles; APC: number of articles per 1 mill. inhabitants; TC: total number of citations in ITSM articles; TC/A: number of citations by article; 1st A: first ITSM research article; Last A: last ITSM research article.

producers such as Canada, China, and India. The USA ranked first with 431 articles, followed by China with 395, Germany with 197, the UK with 183, and India with 156. The USA ranked first up to 2014, the year in which China reached its position of leadership in consumption and production that it holds today. The countries in the table were also the most productive in research on the sustainable management of mining waste, with the exception of Italy and France (Aznar-Sánchez et al., 2018a). The table also shows the number of articles published per million inhabitants (APC), and considering this variable, the most productive country was Australia followed by Canada, the UK, Germany, and Italy. Regarding the relevance of the literature output, the USA presented the highest number of citations followed by China, the UK, Australia, and Germany. Regarding the average number of citations per article, the USA remained in first place with 27 citations followed by Canada with 23.7, the UK with 23.1, Australia with 20.8, and France with 20.6. Fig. 5 shows the relationship between the H-index and the total number of articles. A model was used to simulate the increase in the H-index with the increase in the total number of articles per country during the 20-year period analysed.

Among this group of countries are some of the world's leading producers and consumers of minerals and metals. In the last decade, China has been in the top position in the production of a large variety of minerals (Aznar-Sánchez et al., 2018b). With more than 10,000 mines, China is the world's largest producer of coal, gold, and rare earth minerals. The United States (US) is among the primary producers of gold, copper, molybdenum, bauxite, lead, phosphates, sulfur, and zinc, among others (US Geological Survey, 2018). Australia is prominent in the export of gold, copper, silver, coal, uranium, natural gas, and oil. In addition, Australia is the primary producer of precious stones, such as diamonds and opals. India is one of the leading exporters of diamonds and also produces iron, zinc, and lead. Canada produces silver, copper, zinc, and gold. In addition, Canada is prominent in the energy extractive sector, being the third largest producer of natural gas and one of the primary exporters of crude oil (British Geological Survey, 2018; US Geological Survey, 2018). The group of European countries composed of Germany, the United Kingdom (UK), Italy, France, and Spain have a long mining tradition. Despite the fact that during the last century these countries have reduced their mining activities, currently, in Europe, mineral production continues to be an important part of the economy. According to a 2018 PwC report on mining, 30 of the 40 most important mining companies are based in the top ten countries (five in Australia, ten in China, six in the UK, three in the US, two in India, and six in Canada) (Botas et al., 2018).

In addition, within this group of countries are the primary industrial regions of the world; therefore, they are also the primary consumers of minerals. China and India have supported their recent economic growth in sectors concentrated in raw mineral and metal materials (Fan et al., 2017). The primary industrial countries of the European Union (EU) are Germany, the UK, France, Italy, and Spain, which includes among them the main consumers of mineral resources, alongside the United States, Canada, and Australia (Carvalho, 2017). The EU imports more than 90% of the basic metals it uses, such as copper, zinc, lead, iron, etc. Within Horizon-2020, the EU has identified several priority areas for specific investment in research and innovation, among which is the "efficiency of mineral resources."

Table 5 shows a series of indicators of the level of international collaboration in generating articles on ITSM by the most prolific countries. France produced the highest percentage of articles through international collaboration with 56.18% of the total and was followed by Spain with 51.72%, Canada with 45.10%, and Australia with 42.76%. The USA exhibited the largest network of collaborators with a total of 52, with China, the UK, South Korea, Australia, and Canada the most outstanding partners. France,

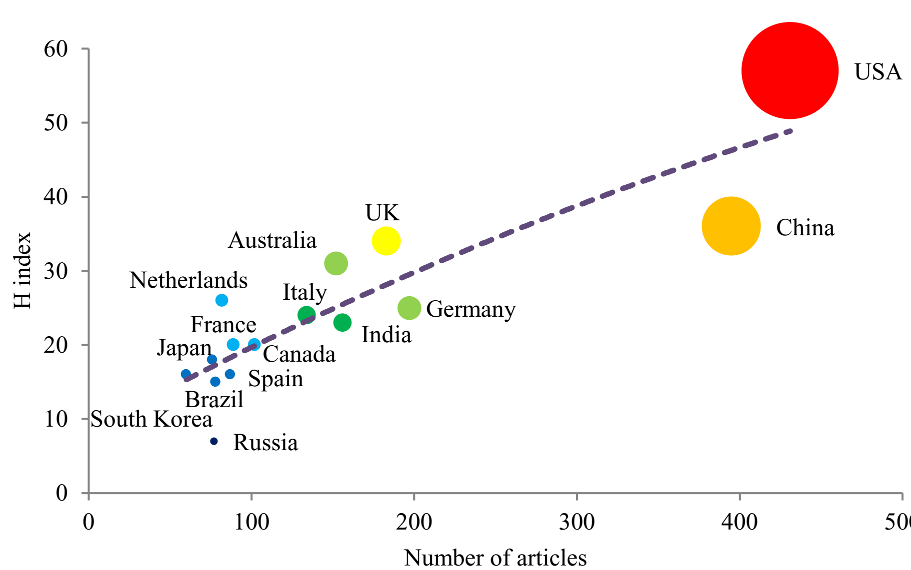

Fig. 5. H Index and total number of ITSM research articles by country from 1998 to 2017.

Table 5
International collaboration among countries in ITSM research from 1998 to 2017.

Country	IC (%)	NC	Main collaborators	TC/A	
				IC	NIC
USA	39.91	52	China, UK, South Korea, Australia, Canada	22.9	29.7
China	25.06	35	USA, Australia, Japan, UK, Germany	15.4	11.6
Germany	37.56	35	France, Switzerland, USA, Austria, UK	26.6	9.3
UK	39.89	43	USA, Italy, France, Germany, Australia	22.2	23.7
India	27.56	31	USA, South Korea, Australia, Canada, China	11.8	13.6
Australia	42.76	29	China, USA, UK, Switzerland, Japan	23.6	18.7
Italy	31.34	39	UK, USA, France, Germany, Spain	16.5	12.9
Canada	45.10	2.3	USA, Brazil, China, Australia, France	21.9	25.3
France	56.18	37	Germany, Spain, Switzerland, Belgium, UK	31.2	7.0
Spain	51.72	31	France, Germany, Italy, UK, Netherlands	11.8	9.1

IC: international collaborations; NC: total number of international collaborators; TC/A: total citations per article; NIC: no international collaborations.

Germany, and Australia presented the greatest positive difference between the citations obtained by articles produced with international collaboration versus those produced independently.

Through a network map of co-authorship collaborations, Fig. 6 illustrates the main collaboration linkages between the different countries that published articles on ITSM. The size of each circle represents the number of articles published on the subject, while the different colours indicate the possible groupings based on the number of collaborations between the different countries. In Fig. 6, three clusters stand out: green consists of the US, India, Australia, Canada, and Brazil; red highlights Germany, the UK, France, Spain, and Italy, among others; and blue shows China as the leading partner with Japan, Malaysia, and Taiwan.

Table 6 presents the main characteristics of the institutions with the most articles on ITSM. Within this group, China was represented by the largest number of institutions with the Chinese Academy of Sciences, Tsinghua University, and the Ministry of Education. The Chinese Academy of Sciences published the largest number of articles on ITSM with 58 followed by Tsinghua University with 31, the University of Queensland with 28, the Ministry of Education of China with 23, and Eidgenoessische Technische Hochschule (ETH) Zurich with 19. The Chinese Academy of Sciences, Tsinghua University, ETH Zurich, and Monash University were represented by the greatest number of citations, and in terms of the average number of citations per article, Monash University produced most of the relevant publications with 40.8 citations per article followed by ETH Zurich with 39.4, the University of Cambridge with 31.2, and the Delft University of Technology with 29.1. The Chinese Academy of Sciences and the University of Queensland were also among the 10 most productive institutions in research on the sustainable management of mining waste (Aznar-Sánchez et al., 2018a).

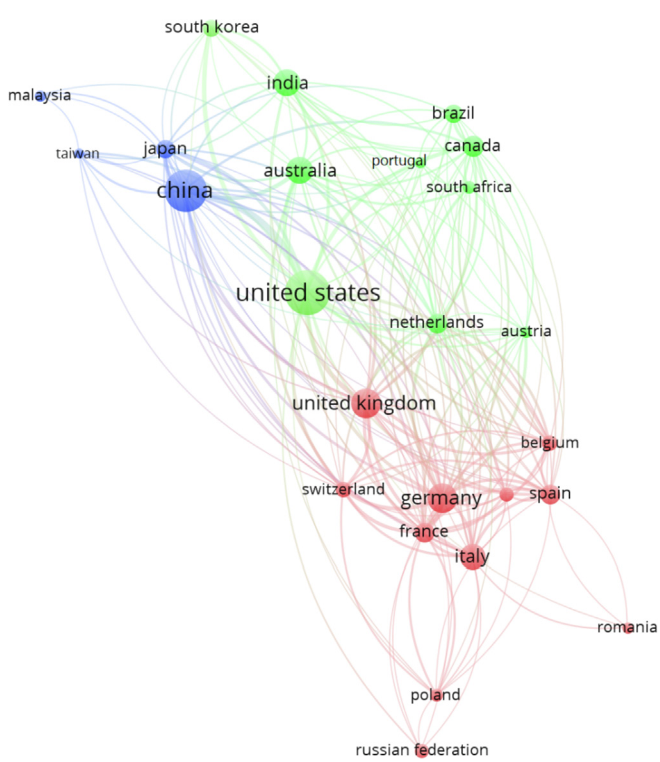

Fig. 6. Cooperation among countries based on co-authorship from 1998 to 2017*.
* Grouping of the main countries investing in ITSM research based on co-authorship relationships of the articles published during the 1998–2017 period. The colours represent the different groups of countries with the highest degree of cooperation.

Regarding the production of articles through international collaboration with other institutions as a percentage of the total, the order was as follows: the University of Cambridge with 77.78%, ETH Zurich with 73.68%, the Centre National de la Recherche Scientifique with 62.50%, and the Delft University of Technology with 55.56%. Regarding the average number of citations of articles produced with and without international collaboration, Monash University, the Russian Academy of Sciences, the University of Cambridge, and ETH Zurich exhibited the greatest degree of international collaboration.

Table 7 presents the main characteristics of the authors with the most published articles on ITSM. The author with the most articles was Gavin M. Mudd of the Royal Melbourne Institute of Technology University, who focuses on the evaluation of mining sustainability in Australia (Mudd, 2010a-b; Prior et al., 2012). Likewise, this author was the most cited and thus had the highest H-index for ITSM articles. The following authors stand out in terms of production: Damien P. Giurco of the University of Technology of Sydney and Thomas E. Graedel from Yale University with the highest average number of citations per article (48.5); his most relevant paper addresses metal recycling (Graedel et al., 2011). The author with the oldest publication is Marcelo M. Veiga of the University of British Columbia with an article published in 1999. Based on the analysis, this author had a total of seven articles published on ITSM and had accumulated a total of 199 citations; his most relevant article focuses on clean artisanal gold mining (Hinton et al., 2003). Jinhui Li, from Tsinghua University, was the author who had most recently incorporated this topic into his research with his first article published in 2015. However, in just two years, he has managed to become one of the most prolific authors, and his works address the sustainable processing of lead, cobalt, and rare and precious metals, among other topics, and mainly focus on China. His most recent work is a review of metal recovery in urban mines (Wang et al., 2017).

Table 6
The 10 most productive institutions for ITSM research from 1998 to 2017.

Institution	C	A	TC	TC/A	H index [a]	IC (%)	TC/A	
							IC	NIC
Chinese Academy of Sciences	China	58	930	16.0	19	37.93	20.7	13.2
Tsinghua University	China	31	879	28.4	14	29.03	24.3	30.0
University of Queensland	Australia	28	403	14.4	13	42.86	11.5	16.6
Ministry of Education, China	China	2.3	314	13.7	10	47.83	10.1	16.9
ETH Zurich	Switzerland	19	749	39.4	11	73.68	43.4	28.4
Delft University of Technology	Netherlands	18	523	29.1	10	55.56	29.6	28.4
Russian Academy of Sciences	Russia	18	111	6.2	4	11.11	25.0	3.8
University of Cambridge	UK	18	562	31.2	11	77.78	35.2	17.3
Consiglio Nazionale delle Ricerche	Italy	17	229	13.5	10	23.53	12.5	13.8
Centre National de la Recherche Scientifique (CNRS)	France	16	185	11.6	8	62.50	15.2	5.5
Monash University	Australia	16	652	40.8	11	31.25	67.0	28.8

[a] Only ITSM articles. C: country; A: total number of articles; TC: total number of citations in ITSM articles; TC/A: number of citations by article; IC: international collaborations; NIC: no international collaborations.

Table 7
The 15 most productive authors in ITSM research from 1998 to 2017.

Author	A	TC	TC/A	H index [a]	C	Affiliation	1st A	Last A
Mudd, Gavin M.	13	624	48.0	10	Australia	Royal Melbourne Institute of Technology University	2006	2014
Giurco, Damien P.	10	208	20.8	7	Australia	University of Technology Sydney	2011	2014
Graedel, Thomas E.	10	485	48.5	8	USA	Yale University	2006	2016
Meers, Erik	8	266	33.3	8	Belgium	Universiteit Gent	2010	2016
Li, Jinhui	7	31	4.4	4	China	Tsinghua University	2015	2017
Vangronsveld, Jaco	7	254	36.3	7	Belgium	Universiteit Hasselt	2005	2016
Veiga, Marcello M.	7	199	28.4	6	Canada	The University of British Columbia	1999	2015
Hilson, Gavin	6	270	45.0	5	UK	University of Surrey	2000	2005
Prior, Timothy	6	135	22.5	4	Switzerland	Ecoles Polytechniques Federales	2011	2014
Tack, Filip MG	6	175	29.2	6	Belgium	Universiteit Gent	2010	2016
Witters, Nele	6	228	38.0	6	Belgium	Universiteit Hasselt	2010	2016

[a] Only ITSM articles. A: total number of articles; TC: total number of citations in ITSM articles; TC/A: number of citations by article; C: country; 1st A: first ITSM research article; Last A: last ITSM research article.

Fig. 7 presents a network map of co-authorship collaborations on ITSM articles; the size of each circle represents the number of articles published on this subject while the different colours indicate the possible groupings according to the number of collaborations. A quite complex network of collaborations can be observed that emphasizes a central nucleus through which different groups are interrelated that are mainly composed by the set of Chinese authors. However, three other relevant groups stand out. The first (colour yellow) includes authors such as Mudd and Giurco, with the largest production of articles, as well as Mason, Nakajima, Prior, Stamp, Cooper, and Daly. Graedel leads the second group (blue colour), which is composed of authors such as Matsubae, Nuss, Reck, and Harper among others. The third prominent group (dark green) includes authors such as Meers, Vangronsveld, Vaneeckhaute, Van Slycken, Tack, and Witters.

Fig. 7. Cooperation among authors based on co-authorship from 1998 to 2017*.
* Grouping of the main authors in ITSM research based on co-authorship relationships of the articles published during the 1998–2017 period. The colours represent the different groups of countries with the highest degree of cooperation.

4.4. Keywords

Table 8 shows the evolution of the 20 most used keywords in the sample of articles throughout the analysed period; these keywords represent the "hot spots" of ITSM research. The terms used in the search have been included to monitor their evolution throughout the period. In total, 18,629 different key terms were identified from the set of articles in the sample. *Sustainable Development* was the most-used term, but it only appears in 30.42% of the articles in the sample. It is noteworthy that 159 different terms containing the word sustainable were found among the set of keywords, and all were regrouped if necessary and accounted for separately. The term *Sustainability* was used in 13.86% of the total number of the articles in the sample, and the rest of the keywords appeared in less than 10% of the articles. This means that there is great atomicity in the

Table 8
The 20 most frequently used keywords in ITSM research from 1998 to 2017.

Keywords	1998–2017		1998–2002		2003–2007		2008–2012		2013–2017	
	A	%	R(A)	%	R(A)	%	R(A)	%	R(A)	%
Sustainable-Development	779	30.42	1(64)	44.76	1(139)	46.49	1(382)	59.22	1(385)	26.12
Sustainability	355	13.86	2(20)	13.99	5(28)	9.36	2(176)	27.29	2(219)	14.86
Recycling	245	9.57	12(9)	6.29	3(32)	10.70	4(122)	18.91	4(143)	9.70
Metals	216	8.43	14(7)	4.90	11(17)	5.69	8(92)	14.26	3(146)	9.91
Environmental-Impact	212	8.28	4(13)	9.09	4(31)	10.37	7(96)	14.88	5(120)	8.14
Mining	207	8.08	2(20)	13.99	2(38)	12.71	3(136)	21.09	9(81)	5.50
Heavy-Metals	180	7.03	17(5)	3.50	19(13)	4.35	6(102)	15.81	6(117)	7.94
Waste-Management	144	5.62	17(5)	3.50	7(19)	6.35	10(86)	13.33	11(77)	5.22
Carbon-Dioxide	136	5.31	193(1)	0.70	49(7)	2.34	16(20)	3.10	8(99)	6.72
Chemistry	131	5.12	76(2)	1.40	166(3)	1.00	38(42)	6.51	7(105)	7.12
Life-Cycle	122	4.76	17(5)	3.50	24(11)	3.68	22(52)	8.06	10(80)	5.43
Environmental Protection	122	4.76	9(10)	6.99	8(18)	6.02	9(88)	13.64	35(50)	3.39
Technology	110	4.30	9(10)	6.99	14(15)	5.02	5(106)	16.43	86(32)	2.17
Innovation	109	4.26	41(3)	2.10	30(9)	3.01	13(68)	10.54	19(63)	4.27
Economics	103	4.02	17(5)	3.50	49(7)	2.34	15(58)	8.99	20(62)	4.21
Catalysts	101	3.94	0	0.00	113(4)	1.34	42(40)	6.20	11(77)	5.22
Mineral-Resources	95	3.71	13(8)	5.59	8(18)	6.02	22(52)	8.06	50(43)	2.92
Environmental-Management	93	3.63	7(11)	7.69	166(3)	1.00	36(44)	6.82	26(57)	3.87
Catalysis	92	3.59	0	0.00	166(3)	1.00	19(54)	8.37	20(62)	4.21
Nanoparticles	89	3.48	0	0.00	80(5)	1.67	8(28)	4.34	15(70)	4.75

A: total number of ITSM articles; R: rank.

use of keywords with high variation over time, which makes it difficult to identify clear trends in ITSM research throughout the study period.

During the 1998–2002 period, the most used key terms were related to the economic and environmental fields (Economic-and-Social-Effects, Industrial-Economics, Cost, Economics, Environmental-Impact, Environmental-Management, Environmental-Protection) and to the processes of regulation and planning (Strategic-Planning, Laws-and-Legislation, Societies-and-Institutions), and the most commonly used reference terms in this period were Africa, Germany, and Australia. Therefore, the technology was focused on increasing productivity, waste management, and recycling. At the end of the 20th century, the impact of mining activities on the environment and on human health was recognized, primarily due to tailing and acid drainage, which led to a legislative development with the purpose of restoring and decontaminating the affected areas (Carvalho, 2017). This trend took place mainly in developed countries such as the United States and European countries. During this period, the first attempts to introduce the concept of sustainability into the mining sector occurred. These attempts consisted of the development of mining projects based on sustainability criteria. In this initial phase, the primary efforts to achieve sustainability focused on reducing environmental impacts and improving the efficiency of operations (Hilson and Basu, 2003). In this period, the first indicators to evaluate the sustainability of the mining industry were also developed (Azapagic, 2004).

In the 2003–2007 period, specific metals, such as copper, appeared, compared to the previous period in which there were only general discussions of heavy metals, metals, or minerals. Terms such as Marketing, Life-Cycle, Project-Management, Strategic-Planning, and Waste-Management, all of which represent a change in the trend from the previous period, acquired special relevance, and in the environmental field, terms related to ecology and air and water pollution arose. In this period, the terms *recycling* and *waste management* reached their greatest use, and terms related the geographical area (regions and countries) became relevant. The incidence of appearance of China and Australia in the published articles was greatest, and Eurasia stood out as a region. In 2003, the Extractive Industries Transparency Initiative was created with the aim of promoting the accountability of industries and governments to the public (EITI, 2016). In this period, the Mines and Communities Organization conducted an assessment on the evolution of the social sustainability of mining with unsatisfactory results (Whitmore, 2006).

In the 2008–2012 period, the innovation was focused on cadmium, zinc, lead, iron and coal, and the main objectives were managing for energy efficiency, recovering metals, and reducing greenhouse gas emissions. For the first time, the catalysis process for treating metals was highlighted, and China was the focus of the greatest number of articles. In 2010, the Responsible Mineral Development Initiative was published by the World Economic Forum, which established a framework for responsible mineral development, where knowledge-sharing, transparency, stakeholder engagement, dispute management, and the monitoring and enforcement of commitments were encouraged (WEF, 2010). In the same year, the Natural Resource Governance Institute published the Natural Resources Charter, where a framework was established on the economic and environmental responsibility of extractive industries for future generations (Natural Resource Governance Iniciative, 2014).

Finally, the greatest production of articles occurred in the 2013–2017 period. The technological advances applied to metal processing related to nanotechnology and catalysts stood out, and the focus on pollution changed from air and water to the soil. However, China continued to appear in the greatest number of articles. In this period, new scenarios arose that presented future research trends. These include the expansion of mining activities to previously inaccessible environments such as ice-covered areas and the ocean floor in search of new deposits (Carvalho, 2017). The development of mining activities in this new type of environment presents new challenges for the sector that should be the subject of research, especially regarding the protection of ecosystems (Weaver et al., 2018).

Fig. 8 presents a network map of the co-occurrence of keywords. The size of each circle represents the number of articles in which each word appears, and the different colours represent groupings of keywords based on the number of co-occurrence linkages between them. The parameters used in the search were excluded from the elaboration of this map to avoid distorting the results,

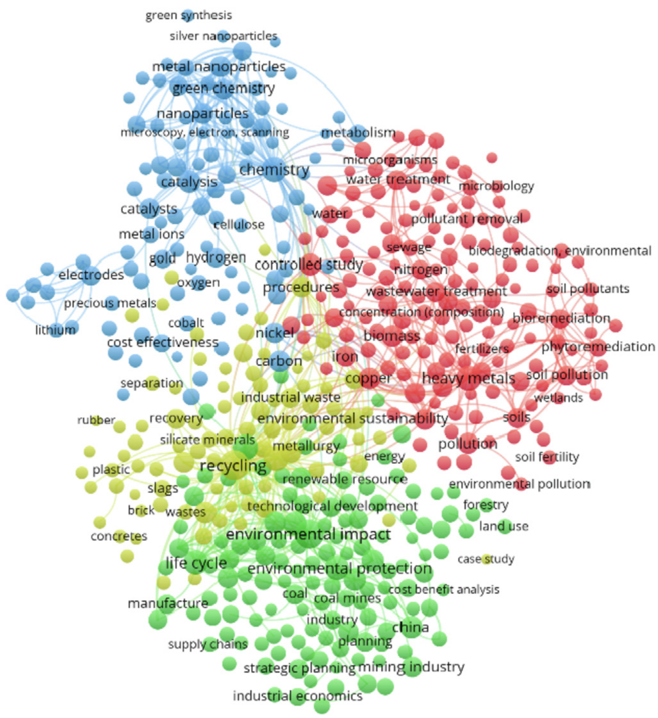

Fig. 8. Mean co-occurrence network of keywords in ITSM research from 1998 to 2017*.
* Primary lines of research based on the co-occurrence relationships of the main keywords in the literature on ITSM during the 1998–2017 period. The colours represent the different lines of research.

which generated four large groups or clusters. The first cluster (in blue) is framed under the term *Technological innovation*, and this cluster presents a technical perspective. Terms such as Chemistry, Catalyst, Nanoparticle, and Electrodes stand out, but terms related to technical efficiency also appear in this cluster. Most of these terms are related to the development and exploitation phase of the mine; carbon, cobalt, gold, lithium, nickel, palladium, and silver are some of the minerals included in this group. Some examples of innovations and technological advances along these lines could be improvements that are capable of achieving a net energy-use reduction of 21% by means of best practices. For example, the optimization of blasting and energy efficient milling, such as high-pressure rollers, waste heat recovery, and advanced casting technology. An additional reduction of 40% is theoretically possible based on minimum practical estimates (Norgate and Haque, 2010; Parameswaran, 2016). In addition, a vision of the lifecycle of mining operations has revealed other potential opportunities for energy reduction: crushing in the well would reduce loading and hauling requirements and the adoption of new sensor technology could reduce excavation and exploratory drilling (Norgate and Haque, 2010). The adoption of renewable energy in mining sites is also a great opportunity to reduce fossil fuel energy use and greenhouse gas emissions (Parameswaran, 2016). The restoration and stabilization of disturbed areas have been recognized as being important for the environmental and social management of mining lands (Allan, 1995; Miranda et al., 2005; Laurence, 2011). This line of research is among the most consolidated. Technological development and innovation in the mining sector have been constant for centuries. Improvements in technical efficiency, reductions in the consumption of inputs, and cost reductions in general have been traditional objectives. The introduction of the sustainability concept in the mining industry has diversified these traditional objectives in the field of innovation towards the development of cleaner production technologies and safer production processes. However, there are aspects that still require more effort. For example, little has been accomplished to link technological development and innovation in the sector with social objectives. One of the most significant advances in the industry has been the development of open-pit mines; however, this type of exploitation generates a strong adverse reaction by a large sector of the local population due to its severe visual impact, the surface area affected, and air and sound pollution. One of the great challenges that this line of research must face is the expansion of mining activities to ice-covered environments and the ocean floor. Initial experiences reveal that significant technical improvement is necessary to perform mineral extraction in these environments.

The second cluster (in green), Environmental management, is focused on risk control and the planning and management of environmental impacts. It includes terms applicable to different industries related to the treatment of minerals and metals and covers the different links of the supply chain. This group would address all phases of the mining life cycle and also considers factors related to the economic and social dimensions of management and decision making. The protection of soil, water, and air are priorities in this line of work. To protect water resources, mining waste should not be released directly into rivers or other surface waters, acid-generating waste must be isolated, and mine dewatering should be avoided (Miranda et al., 2005; Parameswaran, 2016; Gorman and Dzombak, 2018). In the Framework for Responsible Mining, Miranda et al. (2005) present potential opportunities for improving sustainable land management, including public access to information on exploration, environmental impact analysis, and responsible waste management. This line of research developed primarily due to the inclusion of sustainability criteria in mining activities at the end of the last century. This line of work has also been one of the central research axes on sustainability within the sector, along with innovation and technology. Traditionally, water and soil pollution, produced by tailings and leaching, have been the main objects of study. Open-pit mining represents a new and important source of air pollution, and noise pollution is another challenge to confront. Technological improvements in the sector have resulted in an increase in energy consumption from mining operations. This increased use of energy produces a greater amount of greenhouse gas emissions. The management of toxic waste is the another major concern in achieving environmental sustainability in the sector. These two aspects are subjects that remain to be examined in this line of research, despite previous efforts. Regarding innovation and technology, future challenges for environmental management within the sector include the protection of ecosystems and their biodiversity from the expansion of mining activities (into the ice and ocean).

The third cluster (in red), *Decontamination*, includes terms such as Bioremediation, Phytoremediation, Biodegradation, and Water Treatment. Innovation in this cluster is mainly linked to the closure and post-closure phase of the life cycle of the mine, specifically the biophysical dimension. Restoration approaches include the replacement of topsoil, revegetation, and landfilling, as well as financial guarantees from companies that have the capacity to remediate and monitor depleted mined lands (Allan, 1995; Pasariello et al., 2002). This research, along with recycling, is one of the most recent areas of investigation. After many decades of mining activity without landfill and waste storage controls, the extent of affected ecosystems is troubling. This research is closely related to environmental management. The main difference between the two is the reactive nature of the decontamination line of interest, as opposed to the preventive nature of the environmental management line. Lacking in the literature in this line of study are investigations of the interrelations between the different types of ecosystems and the pathways of polluting substances. A future challenge is the globalization of pollution from mining activities because of the diversity of affected ecosystems and the new types of mining exploitation. Open-pit mining has led to increased air pollution as harmful particles are easily transported by wind across great distances. Exploitation of the ocean floor can result in pollution over a large area, due to the transport of harmful substances by marine currents.

The last cluster (in yellow), *Recycling,* includes all the technological advances related to reuse and recycling. Miranda et al. (2005) identified several approaches to improving waste management, such as covered tailing dams and rock waste landfills. These types of methods are among the most recently implemented; however, they are one of the best prospects in improving sustainability in the supply of minerals and metals. These approaches extend beyond the frontiers of a mine's activity and are considered new trends in the circular economy. The recycling and reuse of materials can meet a significant portion of the demand for resources. Among the main developments in this area of practice is the conversion of waste materials from mines into by-products that can be used in the construction sector. However, there is a large amount of waste deposits from mining activities that represent a potential source of resources. Future research in this area must pursue the objective of zero untapped waste.

4.5. Type of article, countries and minerals under study

It should first be noted that most of the articles on ITSM focus on the technical aspects with few works conducted from an economic or social perspective. To evaluate the different aspects of innovation, it is necessary to use multidisciplinary approaches that not only analyse the levels of productive efficiency and resource consumption but the implications for the entire process and exploitation and the environmental, economic, and social impacts as well.

Theoretical articles represented 37.4% of the sample. Approximately all the articles describe technologies that involve improvements to production processes tested in the laboratory, decontamination procedures, or material testing. Empirical studies predominated, accounting for 62.6% of the sample. China, Australia, Canada, Russia, South Africa, India, the USA, and Chile (Fig. 9) were where most of the studies have been carried out, and coal, gold, zinc, copper, nickel, petrol, lead, and iron were the most analysed resources (Fig. 10). Mining activities occur in a small number of countries. Currently, there are more than 20 million mines, including artisanal and small-scale mining, which are concentrated in 30 countries (Que et al., 2018). Some of the most important mines in the world are located in these countries. The world's largest underwater gold mine, owned by Laizhou Ruihai Mining Ltd., is located in China. In Australia, the Cannington and Kalgoorlie mines are located in the Queensland and Esperance regions, where silver, lead, zinc, and gold are extracted, operated by BHP Billiton, Barrick Gold, and Newmont Mining Corporation, respectively. In Canada, the Diavik and Highland Valley Copper mines produce diamonds, copper, molybdenum, silver, and gold, operated by Rio Tinto and Teck Resources. In Russia, the Udachnanya diamond mine is run by Alrosa. Located in South Africa, the Tau Tona gold mine is the world's deepest at approximately 4 km depth. Prominent in the

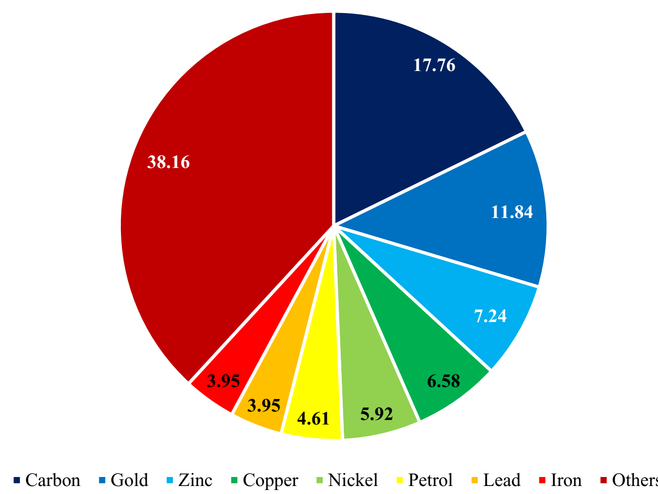

Fig. 10. Mine resources in ITSM research.

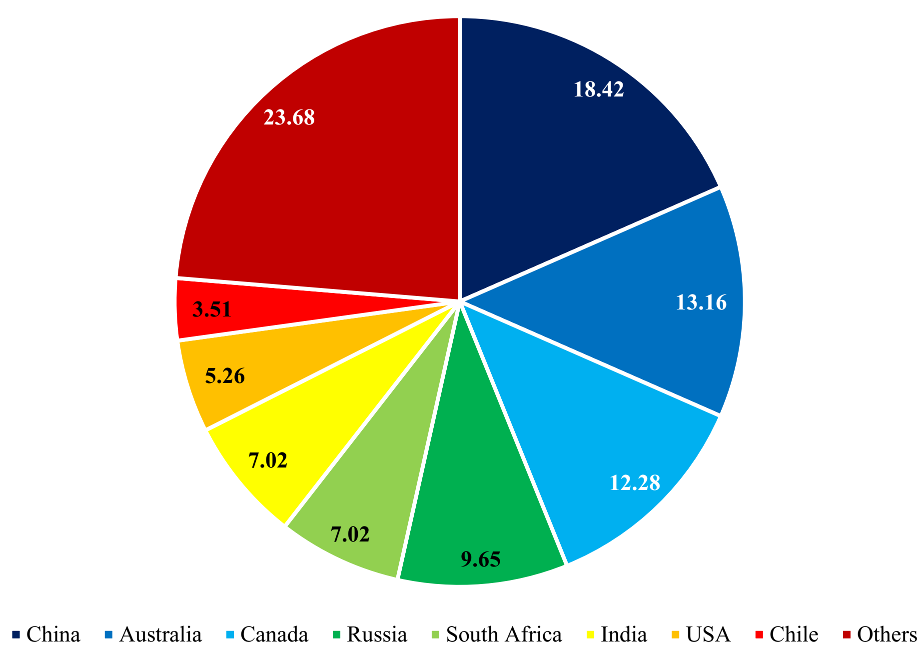

Fig. 9. Mining countries in ITSM research.

past, the Kolar Gold Fields in India are currently engaged in intense exploration activities. In the US, the Bingham Canyon and Goldstrike mine produce copper and gold and are operated by Rio Tinto and Barrick Goldstrike, respectively. With the development of the Chuquicamata and Escondida mines, Chile became the first copper producer in the world. These mines are operated by Codelco, BHP Billiton, and Rio Tinto.

4.6. Sustainability scope and life-cycle phases

Regarding the scope at which innovation contributes to sustainability, 60.9% of mining innovations impact the ecological dimension, 30.9% the economic, and only 8.2% the social. This result agrees with Gorman and Dzombak (2018) who state that environmental mining impacts have received the greatest attention in the development of the current framework for sustainable mining. Therefore, the social field of sustainability is the least analysed when assessing innovation processes related to mining activity, and this is also due to the evolutionary trajectory of the mining sector. Until two decades ago, climate change and global warming was not considered a threat in either the business or political environments, so the sustainability of the sector was exclusively considered from the economic perspective. From the late 1990s, environmental issues began to attract more attention (Severo et al., 2018). The social pressure for different economic sectors to adopt clean production processes has been growing, and the mining industry has not been slow to adapt (Aznar-Sánchez et al., 2018a). The major pending issue is the social field as few companies have programmes aimed at corporate social responsibility or cooperation for social development (Govindan et al., 2014).

No article has been found that analyses the contribution of innovation in the three sustainability areas together, indicating that research on innovations for the sustainability of mining activity provides only partial data. In addition, there is the possibility of trade-offs and synergies in the execution of innovations among the different sustainability areas that should be analysed before implementation. The findings of this review are consistent with those of Aznar-Sánchez et al. (2018a), who analysed the sustainable management of mining waste and did not find any article addressing the social field of sustainability, so no studies address the three areas as a whole. Hahn and Kühnen (2013), in their reports on sustainability for the 1999–2011 period, conclude that there is a lack of comprehensive sustainability reports and only 7% of the samples analysed explicitly address social aspects. Mining is one type of economic activity with the greatest amount of social opposition. Several non-governmental organizations around the world are battling the negative externalities derived from mining activities in areas such as Mount Quilish, Peru and the uranium mine in Jabiluka, Australia (Jenkins and Yakovleva, 2006). This opposition reflects the need for the sector to establish communication bridges and reach an agreement with local communities. The primary reasons for the opposition among local populations to mining development, and therefore where mining companies should focus their efforts, are the non-transparent procurement of licenses and concessions, lack of community involvement, impacts with other economic activities such as agriculture and tourism, pollution and its impacts on animal and human health, and the arrival of immigrants attracted to employment opportunities (Jenkins and Yakovleva, 2006).

Regarding the life-cycle phases, 7.1% of innovations affect the exploration phase, 84.8% the exploitation phase, and 8.1% the closure phase. This result coincides with the work of Gorman and Dzombak (2018), which indicates that a limitation of the current framework of sustainable mining is that most efforts focus on the exploitation phase of a mine. Therefore, innovation in mining activity focuses on the exploitation phase of the mineral, and the vast majority of projects focus on technological development aimed at improving the economic productivity of mines or the development of more environmentally friendly production processes. In the closure phase, the central subjects have been the development of innovations aimed at the decontamination and rehabilitation of closed sites for different purposes, such as reopening, installation of fish farms, recreational uses, etc.

Fig. 11 illustrates the repercussions of innovation in the different areas of sustainability for each of the mine life-cycle phases. In the exploration phase, 29.4% of innovations affect the environmental dimension, 64.7% the economic, and 5.9% the social. Most innovations in this phase focus on improvements in efficiency that affect the probability of success and reduce the time and labour requirements during exploration, thus improving the economic outcome. The contribution to environmental sustainability in this phase is mainly focused on energy savings during operations, and the contribution to the social dimension is limited to considering the possible risks of contaminating ecosystems in the initial phases of the exploration and characterization of the land. The most noteworthy innovations in this phase during the entire study period have been the high-frequency downhole sparker sound source for crosswell seismic surveying, 3D seismic sensing, hyperspectral remote sensing, geochemical exploration applications, narrow-beam and SSS mapping, and geomagnetic exploration by extremely low-frequency/audio frequency magnetics, among others.

In the exploitation phase, 49.7%, 36.8%, and 13.5% of the innovations impacted the environmental, economic, and social fields, respectively. The contribution of innovation in the ecological field is fundamentally based on processes and technologies that involve lower energy consumption, reductions in the emission of greenhouse gases that contribute to global warming, and minimization of waste and pollution. In the economic field, innovation contributes technologies that improve productive efficiency, increase the use of minerals, and reduce resource and maintenance costs. The contribution in the social field includes the development of new participatory approaches that involve corporate social responsibility, cooperation in the field of environmental education and sustainable development, and regional development programmes involving training centres as well as research institutions and local administrations and other stakeholders. The innovations in this phase of the mining activity are broad and include improvements in high-fidelity mathematical simulation tools such as discrete element modelling, computational fluid dynamics, discrete grain breakage, and population-balance modelling; the use of virtual

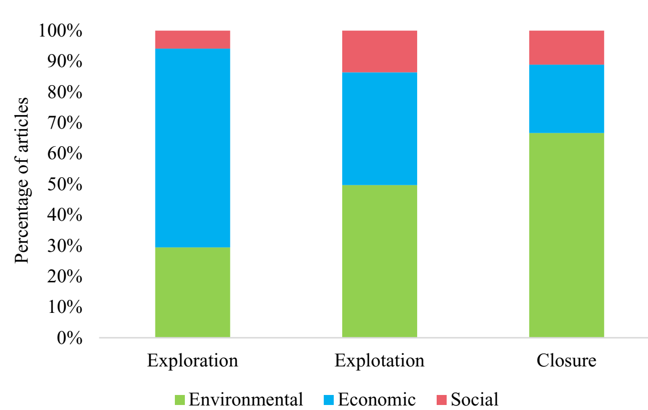

Fig. 11. Distribution of sustainability aspects between the different life-cycle phases of mining activity.

reality in mine design and planning by multidisciplinary teams; the development of autonomous and highly mobile equipment, such as the conception of a fully mobile crushing plant to enhance mining operations in large open pit mines; and programmes to continuously improve equipment and processes such as diamond cutting, crushers with jaws, or flotation technology.

In the closure phase, 66.7%, 22.2%, and 11.1% of innovations impacted the environmental, economic, and social areas, respectively. In this phase of the mining activity, practically all the innovations focus on the decontamination of polluted soils and waters, and the main advances involve so-called "Green Technology" such as bioremediation and phytoremediation. In the post-closure stage, innovations aimed at developing activities with economic and social repercussions include aquaculture and recreation.

Fig. 11 also demonstrates how the analysis of environmental issues is increasingly relevant when moving from the exploration phase to the exploitation phase to the closure phase. In contrast, issues that affect the economic dimension lose relevance with the progression of the life cycle.

5. Conclusions

This article analysed the evolution of global research on ITSM between 1998 and 2017. In total, 2,562 articles were reviewed. The results indicate that there was a sharp increase in the number of articles in the last five years that account for more than 57% of all the analysed articles. The research on ITSM exhibits a much higher growth rate than that of mining and minerals research and research on sustainability. Furthermore, the publication of articles related to this field involves an increasingly large number of journals and countries, indicating that ITSM is increasingly capturing international attention. The most important subject category and journal were Environmental Science and *Journal of Cleaner Production*, and the US produced the most published articles. The Chinese Academy of Sciences was the top research institution. The network map of the co-occurrence of keywords revealed four large clusters centred on technological innovation, environmental management, decontamination, and recycling. Implementation of the analytical framework found that 60.9%, 30.9%, and 8.2% of mining activity innovations impact the environmental, economic, and social areas of sustainability, respectively. Analysis of the issues related to the environmental segment are increasingly relevant when advancing from the exploration phase to the exploitation phase to the closing phase, whereas issues affecting the economic segment lose relevance.

Due to the nature of resource consumption from mining activity operations, the sustainability objective that should be pursued in this sector is zero-negative impact to the environment, along with a return of benefits for all interested parties. Achieving these objectives primarily depends on technological developments, identifying production methods that are increasingly cleaner and safer. Despite all the progress realized, open-pit mining generates increasingly significant impacts on the landscape, mining accidents continue to occur with consequences for both the environment and human lives, and environmental recovery is ongoing. Therefore, innovation efforts in clean production should focus on minimizing the amount of waste generated and ensuring it is non-toxic; reducing greenhouse gas emissions, through processes involving lower energy consumption and renewable energy production systems; and operations that imply a better use of minerals to increase the input-output ratio and guarantee workers' safety. These objectives can establish future lines of research in this area.

Future trends in mining include expanding activities to previously inaccessible environments such as ice-covered areas and the ocean floor in search of new deposits. Research on underwater mining remains in the early stages, and first attempts have resulted in severe incidences of pollution. The exploitation of deposits in these new environments presents new challenges in research, especially for clean production. It is essential to develop productive processes that preserve these ecosystems, which are of great importance for their biodiversity and are severely threatened by the effects of global climate change. Future lines of research also include the development of specific sustainability indicators for the development of innovation and technology, based on each phase of a mine's lifecycle, which includes different social, environmental, and economic aspects. These indicators should serve to evaluate the effectiveness in achieving sustainability objectives within the sector and to guide the planning and design process of innovation and technology.

Finally, ITSM research is increasingly capturing international attention, but it is necessary to develop a comprehensive framework through which to analyse and evaluate the contribution of innovation in the environmental, economic, and social fields. The analytical framework presented in this paper may represent a useful tool in its development.

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