UNIVERSIDADE FEDERAL DE SÃO CARLOS
DEPARTAMENTO DE CIÊNCIAS AMBIENTAIS
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS AMBIENTAIS

A BIBLIOMETRIA E A PESQUISA INTERDISCIPLINAR NAS CIÊNCIAS AMBIENTAIS

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São Carlos, fevereiro de 2019

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Quando chegamos ao final de um ciclo podemos perceber (ou não) a gratidão. É algo como escolher a postura do otimista ao invés do pessimista. Escolher ser grato é optar por um ato deliberado, e perceber a bondade e a bênção no mundo. A gratidão também é uma escolha moral porque quando a escolhemos fazemos uma declaração sobre o tipo de mundo em que acreditamos e que queremos viver. A gratidão é uma escolha!

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RESUMO

Nos últimos anos, os resultados de pesquisas nas Ciências Ambientais têm crescido em complexidade e proporção, e isso tem exigido dos cientistas a habilidade de sintetizar informações de diferentes fontes para apoiar análises holísticas e gerar novos conhecimentos. A análise bibliométrica surge nesse contexto como uma ferramenta analítica com alto potencial de apoiar a síntese sistemática da informação e a análise dos *outptus* da ciência. Nessa tese, buscamos avaliar como as ferramentas e os métodos bibliométricos podem contribuir para a geração de novos conhecimentos e análise da ciência, apresentando cinco artigos desenvolvidos a partir de tópicos das Ciências Ambientais e seus subcampos. Especificamente, no capítulo 1 foram exploradas diferentes formas de análises de redes e introduzimos uma metodologia inédita de análise de palavras-chave para detectar lacunas de pesquisa na área da Ecologia da Restauração. Essa mesma metodologia foi utilizada no capítulo 2, onde investigamos a pesquisa sobre a imobilização de enzimas. Introduzimos nesse estudo os recursos de análise espacial para complementar a discussão da análise de redes e analisamos a dinâmica dos indicadores bibliométricos em diferentes períodos (27, 10 e 5 anos). No capítulo 3, demos ênfase na pesquisa estratificada por países, e por meio do critério de co-ocorrência de palavras-chave apresentamos os principais tópicos de pesquisa sobre a gestão dos resíduos eletrônicos. No capítulo 4, foram apresentados dois focos distintos de estudo: uma pesquisa de caráter aplicado, relacionada à restauração de ecossistemas; e uma abordagem prática e teórica relacionada à química qualitativa, intermedidas pela técnica LIBS (Laser-Induced Breakdown Spectroscopy) e pela bibliometria, respectivamente. Nesse capítulo, revelamos uma nova perspectiva da utilização dos indicadores bibliométricos para apoiar a pesquisa. Por fim, no capítulo 5 tivemos a oportunidade de trabalhar com a menor base de dados entre os estudos dessa tese, o que gerou diversos *insights* sobre o desempenho dos indicadores bibliométricos em bases “estreitas. Nesse estudo tivemos como objetivo geral: discutir e sintetizar informações sobre a utilização dos indicadores bibliométricos na pesquisa de tópicos das Ciências Ambientais. Os resultados indicam, para uma grande diversidade de temas, que a aplicação de ferramentas bibliométricas é forma eficaz de revelar o estado atual da pesquisa e os seus direcionamentos, o que pode favorecer o desenvolvimento de novos estudos e a produção científica nas Ciências Ambientais.

Palavras-chave: pesquisa interdisciplinar; interdisciplinaridade; análise bibliométric; bibliometria; Ciências Ambientais

ABSTRACT

In recent years, research results on Environmental Sciences have grown in complexity and proportion, and this has required from the scientists the capacity to synthesize information from different sources to support holistic analyzes and generate new knowledge. Bibliometric analysis appears in this context as an analytical tool with high potential to support the systematic synthesis of information and the analysis of the outptus of science. In this thesis, we seek to evaluate how bibliometric tools and methods can contribute to the generation of new knowledge and analysis of science, presenting five articles developed from topics of Environmental Sciences and its subfields. Specifically, in Chapter 1 we explored different forms of network analysis and introduced an unprecedented methodology of keyword analysis to detect research gaps in the area of Restoration Ecology. This same methodology was used in Chapter 2, where we investigated the research on the enzymes immobilization. We introduced spatial analysis resources to complement the discussion of network analysis and analyzed the dynamics of bibliometric indicators in different periods (27, 10 and 5 years). In Chapter 3, we emphasized country-stratified research, and through the co-occurrence criterion of keywords we present the main research topics on electronic waste management. In Chapter 4, two distinct focuses of study were presented: an applied research related to the restoration of ecosystems; and a practical and theoretical approach related to qualitative chemistry, intermediated by the Laser-Induced Breakdown Spectroscopy (LIBS) technique and by bibliometrics, respectively. In this chapter, we present a new perspective on the use of bibliometric indicators to support research. Finally, in chapter 5 we had the opportunity to work with the smallest database among the studies of this thesis, which generated several insights on the performance of the bibliometric indicators in "narrow" bases; which was analyzed under Ostrom's precepts on common forest management. From the perspective of bibliometrics scholars related to the non-LIS community (Library and Informations Science), we had as general objective: to discuss and synthesize information on the use of bibliometric indicators in the research of Environmental Science topics. The results indicate, for a great diversity of subjects, that the application of bibliometric tools is an effective way of revealing the current state of the research and its directions, which can favor the development of new studies and scientific production in Environmental Sciences.

Keywords: interdisciplinary research; interdisciplinarity; bibliometric analysis; bibliometrics; Environmental Sciences.

SUMÁRIO

APRESENTAÇÃO GERAL

Esta tese é composta por uma Introdução geral, seguida por cinco artigos, os quais compõem os capítulos do trabalho, e as Considerações Finais. Na Introdução Geral busquei abordar o assunto central que une todos os capítulos: o desenvolvimento e a análise de indicadores bibliométricos para sistematizar a pesquisa e gerar novos conhecimentos, com ênfase nas Ciências Ambientais e seus subcampos. Ressalto na introdução a importância da bibliometria em análises sistemáticas da literatura e situo o trabalho em relação à comunidade científica que trata da Ciência da Informação. Quanto aos cinco artigos, apesar de abordarem temas independentes, trazem em comum a utilização da análise bibliométrica para conduzir a pesquisa. Esses trabalhos estão apresentados na ordem em que foram produzidos. Dessa forma, é possível que o leitor acompanhe a evolução das metodologias empregadas e o desfecho da experiência dos autores com a utilização dos indicadores bibliométricos. Os capítulos foram formatados visando sua submissão em periódicos científicos e, por isso, elementos textuais como figuras, tabelas e materiais suplementares podem estar inseridos diretamente no texto ou ao final dele, para facilitar a leitura. Os dois primeiros capítulos já foram publicados nos periódicos *Ecological Engineering* e *Process Biochemistry*, respectivamente. O terceiro artigo está submetido no periódico *Environmental Science and Pollution Research*, e os dois últimos serão submetidos nos periódicos *Science of the Total Environment* e *Forest Policy and Economics*, respectivamente. Encerro a tese com as Considerações Finais, apresentando *insights* gerais sobre a utilização de indicadores bibliométricos na pesquisa interdisciplinar nas Ciências Ambientais. Espero que com esse trabalho outros pesquisadores sejam motivados a utilizar os recursos bibliométricos em seus tópicos de estudo, principalmente no âmbito das Ciências Ambientais, onde esse recurso é relativamente pouco explorado.

INTRODUÇÃO

To steal ideas from one person is plagiarism, to steal ideas from many is research. — Anonymous.

Abordagem geral

As mudanças ambientais globais têm proporcionado desafios científicos sem precedentes para a humanidade (Hicks et al., 2010; De Laender, 2018). Nos últimos anos, a necessidade do desenvolvimento de abordagens interdisciplinares para discutir as questões ambientais multidimensionais tem se tornado cada vez mais evidente (Hicks et al., 2010). Desde o seu surgimento na década de 1970, as Ciências Ambientais têm estabelecido um papel importante na pesquisa e educação ambiental interdisciplinar no mundo todo (Fortuin et al., 2011). Esse domínio da ciência tem integrado a descrição e a análise do estado do ambiente, a análise de mudanças e o desenvolvimento de soluções para os problemas ambientais (Wissenschaftsrat, 1994). As Ciências Ambientais integram disciplinas relacionadas às ciências naturais, sociais e as ciências aplicadas (Ashley e Boyd, 2006; Roudgarmi, 2011). Segundo a literatura anglo-saxônica, a ênfase nas ciências naturais incluiu a ecologia, toxicologia, geologia, hidrologia e a meteorologia; enquanto os estudos ambientais apresentam um forte apelo social, político e humano (Vincent e Focht 2009).

Os resultados de pesquisas ambientais têm crescido em complexidade, proporção e resolução, e isso tem exigido dos cientistas ambientais a habilidade de sintetizar as informações disponíveis em diferentes fontes para apoiar análises holísticas e gerar novos conhecimentos (Gilbert et al., 2018). Nas Ciências Ambientais, a base de evidências científicas em muitos tópicos de pesquisa é relativamente grande e tem apresentado crescimento constante (Larsen e von Ins, 2010). Todavia, a pesquisa heterogênea e às vezes polarizada, pode dificultar a utilização, interpretação e a divulgação dos resultados de pesquisa em sínteses e revisões da literatura científica (Boyd, 2013). Vale ressatar que as revisões sistemáticas da literatuda em tópicos ambientais têm sido apontadas por alguns cientistas como fatores limitantes do impacto da política e da pesquisa nas Ciências Ambientais (Bilotta et al., 2014; Bilotta et al., 2015).

O conceito de revisão sistemática relaciona-se estreitamente com a realização de análises bibliométricas (Ellegaard, 2018). Cientistas têm considerado fundamental essa etapa inicial do processo científico (Tranfield et al., 2003), por ser um meio útil de sintetizar as informações de estudos anteriores, descobrir as lacunas de pesquisa e destacar os limites do conhecimento (Fang et al., 2017). Especificamente, as revisões sistemáticas têm a particularidade de promover o desenvolvimento da documentação completa da literatura em algum tópico de pesquisa que muitas vezes poder ter uma pequena amplitude. A bibliometria, por outro lado, é uma ferramenta analítica usada em muitos contextos diferentes (Ellegaard, 2018). De acordo com Le Coadic (2004) e Moher et al. (2015) as revisões sistemáticas compreendem a identificação de temas, seleção de relatos relevantes para a pesquisa, elegibilidade de estudos e meta-análise dos resultados. Essas características inerentes às revisões sistemáticas se assemelham aos trabalhos conduzidos no âmbito da Ciência da Informação ao se valerem da bibliometria, da cientometria ou da informetria como formas de avaliação da produção científica. Em Sengupta (1992), Bufrem e Prates (2005) e Hood & Wilson (2001) é possível encontrar informações detalhadas sobre as diferenças epistemológicas desses termos métricos.

Entre as muitas estatísticas sobre a ciência, a bibliometria tem ocupado um lugar privilegiado (*veja a análise sistemática em material suplementar – Fig. S.1 e Fig. S.2.*) (Godin, 2006). A bibliometria é um dos poucos subcampos envolvidos na medição dos resultados de pesquisa (*outputs*) da ciência. De acordo com a maioria das referências históricas, o seu desenvolvimento sistemático inicial é devido a D.J.D. Price e Eugene Garfield, como fundadores (Godin, 2006; Huang et al., 2014). Entre as abordagens mais tradicionais da análise bibliométrica estão a análise de co-ocorrência, co-citação e o acoplamento bibliográfico aplicado aos metadados de um determinado banco de dados, que geralmente se referem ao ano de publicação, número de publicações e autoria, instituições e países, categorias de tópicos, número de citações, principais periódicos e palavras-chave (Durieux e Gevenois, 2010; Suominen e Toivanen, 2016). Essas informações geralmente são analisadas por ferramentas estatísticas e matemáticas que medem as diversas formas de contribuições para a literatura (Rostaing et al., 2007; Şenel e Demir, 2018).

A utilização da bibliometria pela comunidade científica vai muito além da ideia original das listagens da produção científica ou indexação de citações (Ellegaard, 2018). Os estudos bibliométricos podem considerar duas dimensões da produção acadêmica: uma quantitativa e uma qualitativa (Godin, 2006; Davarpanah, 2010; Nejati e Hosseini Jenab, 2010). Análises quantitativas são utilizadas para descobrir interações, tendências e modelos que representam a evolução científica e tecnológica. Nessa perspectiva, as primeiras publicações bibliométricas se preocuparam em focar, especialmente, em análises quantitativas, através da análise matemática e estatística da distribuição de dados, o que deu origem às "leis bibliométricas”: lei Zipf (Zipf, 1949), lei de Lotka (Lotka, 1926), lei de Bradford (Bradford, 1948) – (Sengupta, 1992; Rostaing, 2003). A dimensão qualitativa, por sua vez, faz referência ao número de citações, o número de colaborações e as interações entre diferentes aspectos de cada indicador. Nas Ciências Ambientais a dimensão qualitativa e quantitativa em análises bibliométricas têm sido consideradas fortemente correlacionadas (Dragos e Dragos, 2013).

Nas últimas décadas, a evolução das técnicas bibliométricas levou ao desenvolvimento de diversas ferramentas de visualização (Zhang et al., 2017a), tabelas de análise (Robinson et al., 2013), mapeamentos bibliométricos (Rafols et al., 2010) e *softwares* automatizados (Suominen e Toivanen, 2016; Zhang et al., 2017a). Entre esses recursos, a análise de redes tem recebido crescente atenção e tem se apresentado como uma importante ferramenta de pesquisa (Madani, 2015, Fang et al.,2017). Baseada na teoria matemática dos gráficos, essa abordagem multidisciplinar tem sido empregada em muitas áreas de pesquisa, como a sociologia, a ciência da informação, a ciência da computação e a geografia, e vem provando a sua eficácia para identificar tópicos de pesquisa já estabelecidos e emergentes (Otte e Rousseau 2002), além de revelar grupos de estudos com base na identidade autoral e institucional das publicações (Munoz-Leiva et al. 2015). Atualmente, diversos *softwares* estão disponíveis para este fim, incluindo os *softwares* CiteSpace[1], Pajek[2] e VOSviewer[3]. Nesse estudo, utilizamos o *software* VOSviewer (Van Eck e Waltman 2010) devido à sua alta capacidade de lidar com grandes conjuntos de dados e apresentar variadas opções de visualização e análise dos indicadores bibliométricos.

De acordo com Leydesdorf et al. (2016), o discurso sobre a avaliação da pesquisa e a utilização dos indicadores bibliométricos é moldado principalmente pela tradução da experiência de quatro grupos principais de usuários da bibliometria: i) elaboradores de produtos bibliométricos; ii) gestores iii) bibliometristas, e iv) cientistas. Nesse estudo, acreditamos figurar entre os dois últimos grupos, por essa pesquisa apresentar as características de discutir, propor, refinar e testar indicadores bibliométricos. A contribuição científica desse estudo também está relacionada aos trabalhos produzidos pela comunidade "*non-LIS*" (*Library and Information Science - LIS*), a qual dá ênfase na análise factual e estatística dos indicadores bibliométricos que são estritamente relevantes para os campos de pesquisa que estão sendo investigados (Ellegaard, 2018); nesse caso, as Ciências Ambientais.

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[1] http://cluster.cis.drexel.edu/*cchen/citespace/.
[2] http://vlado.fmf.uni-lj.si/pub/networks/pajek/.
[3] http://www.vosviewer.com.

Justificativas e hipóteses da pesquisa

Existem relativamente poucas publicações bibliométricas que focaram, especificamente, na pesquisa em Ciências Ambientais. É mais frequente o caso em que as Ciências Ambientais estão abordadas em tópicos ou subcampos relacionados (Mamtora et al., 2013). Em parte, isso pode ser explicado pela natureza interdisciplinar desse campo do conhecimento (Fortuin et al., 2011; Khan e Ho, 2012). As publicações indexadas no banco de dados da *Science Citation Index Expanded* (SCI-E) - *Clarivate Analytics* ISI - *Web of Science (WoS)* © têm sido consideradas as principais fontes de citações nas Ciências Ambientais (Mamtora et al., 2013). Por essa razão, essa base de dados foi selecionada como fonte de informações para o desenvolvimento dos indicadores bibliométricos apresentados nesse trabalho. Além disso, consideramos o fato da base *WoS* ser frequentemente utilizada em estudos acadêmicos (Azevedo et al., 2005; Boanares and Azevedo, 2014) e em estudos bibliométricos (Okubo, 1997; Milanez et al., 2013; Van Raan, 2014).

É consenso na literatura que tanto os fatores endógenos como exógenos podem influenciar a dinâmica local e global das estatísticas de pesquisa (Mabe e Amin, 2001; Rhoten, 2004; Kempener et al., 2010; Anadón, 2012). A interdisciplinaridade e a colaboração entre pesquisadores, por exemplo, têm sido citadas como aspectos importantes que podem fortalecer ou fracatear a produtividade científica dos países (Rhoten, 2004; Rhoten e Parker, 2004; Miller et al., 2008; Cummings e Kiesler, 2008; Monroy & Diaz, 2018). Nessa perspectiva, o Brasil representa hoje a nona posição no *ranking* de países que mais acumularam publicações relacionadas à bibliometria e a terceira posição no *ranking* de países que mais acumularam publicações de análises bibliométricas em tópicos das Ciências Ambientais (*veja a análise sistemática em material suplementar – Fig. S.4*). Essas posições nos *rankings* representam cerca de 4,5% e 9,5% do total de publicações acumuladas, respectivamente; o que sinaliza o amplo campo de pesquisa que ainda pode ser desenvolvido no âmbito interdisciplinar das Ciências Ambientais.

Variados tópicos de pesquisas ambientais já foram abordados através da bibliometria (Van Raan, 2005; Liu et al. 2011; Mamtora et al., 2013). No entanto, os estudos bibliométricos classificados na categoria "*Environmental Sciences*" (*veja a análise sistemática em material suplementar – Fig. S.3*) representam somente 5% do total de publicações bibliométricas indexadas na *WoS*. Além disso, existe uma carência de estudos que tratam especificamente da utilização dos indicadores bibliométricos nas Ciências Ambientais, o que poderia favorecer o desenvolvimento de novos estudos e a produção científica nesse campo do conhecimento. De acordo Wouters et al. (2015), a maioria dos estudos bibliométricos não lida concretamente com os efeitos dos indicadores; e isso pôde ser observado nas publicações recuperadas (*WoS categories – Environmental Sciences*) (*veja a análise sistemática em material suplementar – Fig. S.5*).

Sob o viés das informações e estatísticas apresentadas anteriormente, bem como o nosso recorte de estudo em relação à comunidade "LIS", formulamos as seguintes perguntas: i) a utilização da análise bibliométrica em estudos de tópicos das Ciências Ambientais é conducente à criação de novos conhecimentos e pode contribuir com o avanço pesquisa? No tocante às estruturas de carreira da ciência: ii) os indicadores bibliométricos podem tornar mais visíveis (ou invisíveis) a pesquisa e o trabalho de pesquisadores individuais e/ou grupos de pesquisa nas Ciências Ambientais?

MATERIAL SUPLEMENTAR

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REFERÊNCIAS

Adenle, A. A., Haslam, G. E., & Lee, L. (2013). Global assessment of research and development for algae biofuel production and its potential role for sustainable development in developing countries. Energy Policy, 61, 182–195. doi:10.1016/j.enpol.2013.05.088.

Anadón, L. D. (2012). Missions-oriented R&D institutions in energy between 2000 and 2010: A comparative analysis of China, the United Kingdom, and the United States. Research Policy, 41(10), 1742–1756.

Arbeláez-Cortés, E. (2013). Knowledge of Colombian biodiversity: published and indexed. Biodiversity and Conservation, 22(12), 2875–2906. doi:10.1007/s10531-013-0560-y.

Ashley, P. and Boyd, W.E. (2006). Quantitative and qualitative approaches to research in environmental management. Austral. J. Environ. Manage. 13:70-78.

Azevedo, P.G., Mesquita, F.O., Young, R.J., 2005. Fishing for gaps inscience: a bibliographic analysis of Brazilian freshwater ichthyology from 1986 to 2005. J. Fish Biol. 76, 2177–2193.

Bilotta, G., Milner, A. and Boyd, I. (2014) On the use of systematic reviews to inform environmental policies. Environmental Science & Policy, 42, 67-77.

Bilotta, G., Milner, A. and Boyd, I. (2015) How to increase the potential policy impact of environmental science research. Environmental Sciences Europe, 27.

Blettler, M. C. M., Abrial, E., Khan, F. R., Sivri, N., & Espinola, L. A. (2018). Freshwater plastic pollution: Recognizing research biases and identifying knowledge gaps. Water Research, 143, 416–424. doi:10.1016/j.watres.2018.06.015.

Boanares, D., Azevedo, C.S., 2014. The use of nucleation techniques to restore the environment: a bibliometric analysis. Nat. Conserv. 12, 93–98. http://dx.doi.org/10.1016/j.ncon.2014.09.002.

Boyd, I. (2013). Research: a standard for policy-relevant science. Nature. 501:159–60.

Bradford, S.C. (1948). Documentation, Crosby Lockwood & Son, London, 156 p.

Brondizio, E. S., O'Brien, K., Bai, X., Biermann, F., Steffen, W., Berkhout, F., … Chen, C.-T. A. (2016). Re-conceptualizing the Anthropocene: A call for collaboration. Global Environmental Change, 39, 318–327. doi:10.1016/j.gloenvcha.2016.02.006.

Bufrem, L.; Prates, Y. (2005). O saber científico registrado e as práticas de mensuração da informação. Ciência da Informação. 34 (2), 9-25. Disponível em: <http://www.scielo.br/pdf/ci/v34n2/28551.pdf>. Acesso em: 13 fev. 2018.

Cummings, J.N.; Kiesler, S. (2008). Who collaborates successfully?: Prior experience reduces collaboration barriers in distributed interdisciplinary research. In Proceedings of the 2008 ACM conference on computer supported cooperative work (pp. 437–446). ACM.

Davarpanah, M.R. (2010). A scientometric model for the assessment of strength and weakness of scientific disciplines: a domain-based analysis. Library Ver. 59(8) 596–605.

De Jong, M., Joss, S., Schraven, D., Zhan, C., & Weijnen, M. (2015). Sustainable–smart–resilient–low carbon–eco–knowledge cities; making sense of a multitude of concepts promoting sustainable urbanization. Journal of Cleaner Production, 109, 25–38. doi:10.1016/j.jclepro.2015.02.004.

De Laender, F. (2018). Community- and ecosystem-level effects of multiple environmental change drivers: beyond null model testing. Global Change Biology. doi:10.1111/gcb.14382.

Dragos, C. M.; Dragos, S. L. (2013). Bibliometric approach of factors affecting scientific productivity in environmental sciences and ecology. Science of The Total Environment, 449, 184–188. doi:10.1016/j.scitotenv.2013.01.057

Durieux, V.; Gevenois, P.A. (2010). Bibliometric Indicators: Quality Measurements of Scientific Publication. Radiology 255, 342–351.

Ellegaard, O. (2018) The application of bibliometric analysis: disciplinary and user aspects. Scientometrics, 116, 181-202.

Fang, C., Zhang, J., Qiu, W. (2017) Online classified advertising: a review and bibliometric analysis. Scientometrics, 113, 1481-1511.

Ferenhof, H. A., Vignochi, L., Selig, P. M., Lezana, Á. G. R., & Campos, L. M. S. (2014). Environmental management systems in small and medium-sized enterprises: an analysis and systematic review. Journal of Cleaner Production, 74, 44–53. doi:10.1016/j.jclepro.2014.03.027.

Fortuin, K.P.J., van Koppen, C.S.A. (Kris), & Leemans, R. (2011). The Value of Conceptual Models in Coping with Complexity and Interdisciplinarity in Environmental Sciences Education. BioScience, 61(10), 802–814. doi:10.1525/bio.2011.61.10.10.

Fu, H., Ho, Y., Sui, Y., & Li, Z. (2010). A bibliometric analysis of solid waste research during the period 1993–2008. Waste Management, 30(12), 2410–2417. doi:10.1016/j.wasman.2010.06.008.

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? Journal of Cleaner Production, 143, 757–768. doi:10.1016/j.jclepro.2016.12.048.

Gibert, K., Horsburgh, J., Athanasiadis, I., Holmes, G. (2018) Environmental Data Science. Environmental Modelling & Software, 106, 4-12.

Godin, B. (2006). On the origins of bibliometrics. Scientometrics, 68(1), 109–133. doi:10.1007/s11192-006-0086-0.

Grandjean, P., Eriksen, M. L., Ellegaard, O., & Wallin, J. A. (2011). The Matthew effect in environmental science publication: A bibliometric analysis of chemical substances in journal articles. Environmental Health, 10(1). doi:10.1186/1476-069x-10-96.

Hansen, S.B., Padfield, R., Syayuti, K., Evers, S., Zakariah, Z., & Mastura, S. (2015). Trends in global palm oil sustainability research. Journal of Cleaner Production, 100, 140–149. doi:10.1016/j.jclepro.2015.03.051.

Harrison, A.L. (2006). Who's Who in Conservation Biology? An Authorship Analysis. Conservation Biology, 20(3), 652–657. doi:10.1111/j.1523-1739.2006.00448.x.

Hicks, C.C., Fitzsimmons, C., Polunin, N.V.C. (2010). Interdisciplinarity in the environmental sciences: barriers and frontiers. Environmental Conservation, 37(04), 464–477. doi:10.1017/s0376892910000822.

Hood, W. W., Wilson, C. S. (2001). The literature of bibliometrics, scientometrics, and informetrics. Scientometrics, 52(2), 291–314. doi:10.1023/a:1017919924342.

Huang, L.; Zhang, Y.; Guo, Y.; Zhu, D.; Porter, A.L. (2014). Four dimensional science and technology planning: A new approach based on bibliometrics and technology roadmapping. Technol. Forecast. Soc. Chang. 81, 39–48.

Janssen, M. A., Schoon, M. L., Ke, W., Börner, K. (2006). Scholarly networks on resilience, vulnerability and adaptation within the human dimensions of global environmental change. Global Environmental Change, 16(3), 240–252. doi:10.1016/j.gloenvcha.2006.04.001.

Khan, M. A., Ho, Y.-S. (2012). Top-cited articles in environmental sciences: Merits and demerits of citation analysis. Science of the Total Environment, 431, 122–127. doi:10.1016/j.scitotenv.2012.05.035.

Kempener, R., Anadon, L. D., Condor, J. (2010). Governmental energy innovation investments, policies, and institutions in the major emerging economies: Brazil, Russia, India, Mexico: China, and South Africa. In Energy technology innovation policy discussion paper (p. 16).

Larsen, P., von Ins, M. (2010) The rate of growth in scientific publication and the decline in coverage provided by Science Citation Index. Scientometrics, 84, 575-603.

Le Coadic, Y. F. (2004). A ciência da informação. 2. ed. Brasilia, DF: Brinquet de Lemos, 124 p.

Leydesdorff, L., Wouters, P., Bornmann, L. (2016). Professional and citizen bibliometrics: complementarities and ambivalences in the development and use of indicators—a state-of-the-art report. Scientometrics, 109(3), 2129–2150. doi:10.1007/s11192-016-2150-8.

Liu, X., Zhang, L., Hong, S. (2011). Global biodiversity research during 1900–2009: a bibliometric analysis. Biodiversity and Conservation, 20(4), 807–826. doi:10.1007/s10531-010-9981-z.

Lotka A J (1926), "The frequency distribution of scientific productivity", Journal of the Washington academy of sciences, Vol 16, N° 12, p. 317-323.

Lu, W., Yuan, H. (2011). A framework for understanding waste management studies in construction. Waste Management, 31(6), 1252–1260. doi:10.1016/j.wasman.2011.01.018.

Ma, C., Stern, D. I. (2006). Environmental and ecological economics: A citation analysis. Ecological Economics, 58(3), 491–506. doi:10.1016/j.ecolecon.2005.07.023.

Mabe, M., Amin, M. (2001). Growth dynamics of scholarly and scientific journals. Scientometrics, 51(1), 147–162.

Madani, F. (2015). Technology mining bibliometrics analysis: Applying network analysis and cluster analysis. Scientometrics, 105(1), 323–335.

Mamtora, J., Wolstenholme, J. K., Haddow, G. (2013). Environmental sciences research in northern Australia, 2000–2011: a bibliometric analysis within the context of a national research assessment exercise. Scientometrics, 98(1), 265–281. doi:10.1007/s11192-013-1037-1.

Milanez, D.H., Schiavi, M.T., Amaral, R.M., Faria, L.I.L., Gregolin, J.A.R., (2013). Development of carbon-based nanomaterials indicators using the analytical tools and data provided by the web of science database. Mater. Res. 16, 1282–1293. http://dx. doi.org/10.1590/s1516-14392013005000130.

Miller, T., Baird, T., Littlefield, C., Kofinas, G., Chapin, F. S, III, Redman, C. (2008). Epistemological pluralism: Reorganizing interdisciplinary research. Ecology and Society, 13(2), 42.

Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D. G. (2015). The PRISMA Group. Principais itens para relatar revisões sistemáticas e metaanálises: a recomendação PRISMA. Trad. Taís

Freire Galvão e Thais de Souza Andrade Pansani; Retro-trad. David Harrad. Epidemiol. Serv. Saúde, 335, 24(2).
Monroy, S. E., Diaz, H. (2018). Time series-based bibliometric analysis of the dynamics of scientific production. Scientometrics, 115(3), 1139–1159. doi:10.1007/s11192-018-2728-4.
Munoz-Leiva, F., Porcu, L., del Barrio-Garcia, S. (2015). Discovering prominent themes in integrated marketing communication research from 1991 to 2012: A co-word analytic approach. International Journal of Advertising, 34(4), 678–701.
Nejati, A, Hosseini, S.M. (2010). A two-dimensional approach to evaluate the scientific production of countries (case study: the basic sciences). Scientometrics;84(2):357–64.
Okubo, Y., (1997). Bibliometric Indicators and Analysis of Research Systems: Methods and Examples. OECD, Paris.
Otte, E., Rousseau, R. (2002). Social network analysis: A powerful strategy, also for the information sciences. Journal of Information Science, 28(6), 441–453.
Rafols, I.; Porter, A.L.; Leydesdorff, L. (2010). Science overlay maps: A new tool for research policy and library management. J. Am. Soc. Inf. Sci. Technol., 61, 1871–1887.
Robinson, D.K.; Huang, L.; Guo, Y.; Porter, A.L. (2013). Forecasting Innovation Pathways (FIP) for new and emerging science and technologies. Technol. Forecast. Soc. Chang. 80, 267–285.
Romanelli, J. P., Fujimoto, J. T., Ferreira, M. D., Milanez, D. H. (2018). Assessing ecological restoration as a research topic using bibliometric indicators. Ecological Engineering, 120, 311–320. doi:10.1016/j.ecoleng.2018.06.015.
Rhoten, D. (2004). Interdisciplinary research: Trend or transition. Items and Issues, 5(1–2), 6–11.
Rhoten, D., Parker, A. (2004). Risks and rewards of an interdisciplinary research path. Science, 306(5704), 2046–2046.
Rostaing, H. (2003). Basic principles of bibliometrics. Application to Research Development. The competitive intelligence and industrial vision in the 21st century. The competitive intelligence and industrial vision in the 21st century, 2003. <hal-01579923> Available: <https://hal.archives-ouvertes.fr/hal-01579923/document> Acessed on: 01/07/2019.
Rostaing, H., Barts, N., Le´veille´, V. (2007). Bibliometrics: Representation instrument of the multidisciplinar positioning of a scientific area. Implementation for an advisory scientific committee. pp. 341–50 In Proc.8th Int. conf. of the ISKO Spanish Chapter. University of Leon.
Roudgarmi, P. (2011). Qualitative research for environmental sciences: A review. Journal of Food Agriculture & Environment. 9: 871-879.
Schoolman, E. D., Guest, J. S., Bush, K. F., Bell, A. R. (2011). How interdisciplinary is sustainability research? Analyzing the structure of an emerging scientific field. Sustainability Science, 7(1), 67–80. doi:10.1007/s11625-011-0139-z.
Şenel, E., Demir, E. (2018). Bibliometric and Scientometric Analysis of the Articles Published in the Journal of Religion and Health Between 1975 and 2016. Journal of Religion and Health, 57, 1473-1482.
Sengupta, I. N. (1992). Bibliometrics, Informetrics, Scientometrics and Librametrics: An Overview. Libri, 42(2). doi:10.1515/libr.1992.42.2.75.
Smith, D.R. (2008). Citation Analysis and Impact Factor Trends of 5 Core Journals in Occupational Medicine, 1985-2006. Archives of Environmental & Occupational Health, 63(3), 114–122. doi:10.3200/aeoh.63.3.114-122.
Smith, D.R. (2009). Highly Cited Articles in Environmental and Occupational Health, 1919–1960. Archives of Environmental & Occupational Health, 64(sup1), 32–42. doi:10.1080/19338240903286743.

Suominen, A.; Toivanen, H. (2016). Map of science with topic modeling: Comparison of unsupervised learning and human-assigned subject classification. J. Assoc. Inf. Sci. Technol. 67, 2464–2476.

Tao, J., Wang, D., Chen, K., Sui, X. (2016). Productive capacity of fish habitats: a review of research development and future directions. Environmental Earth Sciences, 75(3). doi:10.1007/s12665-015-5056-5.

Tranfield, D., Denyer, D., Smart, P. (2003). Towards a methodology for developing evidence-informed management knowledge by means of systematic review. British Journal of Management, 14(3), 207–222.

Van Eck, N. J.Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics, 84(2), 523–538.

Van Raan, A. F. (2005). Fatal attraction: Conceptual and methodological problems in the ranking of universities by bibliometric methods. Scientometrics, 62(1), 133–143.

Van Raan, A.F.J., (2014). Advances in bibliometric analysis: research performance assessment and science mapping. In: Blockmans, W., Engwall, L., Weaire, D. (Eds.), Bibliometrics: Use and Abuse in the Review of Research Performance. Wenner-Gren International Series. Portland Press Ltd., London, pp. 17–28.

Vincent, S., Focht, W. (2009). US higher education environmental program managers' perspectives on curriculum design and core competencies: Implications for sustainability as a guiding framework. International Journal of Sustainability in Higher Education 10: 164–183.

Wissenshaftsrat (1994). Stelungnahme zur Umweltforschung in Deutschland. (*Statement on environmental research in Germany*). Bonn.

Wouters, P., Thelwall, M., Kousha, K., Waltman, L., de Rijcke, S., Rushforth, A., Franssen, T. (2015). The Metric Tide: Literature Review (Supplementary Report I to the Independent Review of the Role of Metrics in Research Assessment and Management). HEFCE. doi: 10.13140/RG.2.1.5066.3520

Yarime, M., Takeda, Y., Kajikawa, Y. (2009). Towards institutional analysis of sustainability science: a quantitative examination of the patterns of research collaboration. Sustainability Science, 5(1), 115–125. doi:10.1007/s11625-009-0090-4.

Zhang, L., Wang, M.-H., Hu, J., Ho, Y.-S. (2010). A review of published wetland research, 1991–2008: Ecological engineering and ecosystem restoration. Ecological Engineering, 36(8), 973–980. doi:10.1016/j.ecoleng.2010.04.029.

Zhang, Y.; Zhang, Y.; Shi, K.; Yao, X. (2017) a. Research development, current hotspots and future directions of water research based on MODIS images: A critical review with a bibliometric analysis. Environ. Sci. Pollut. Res. Int. 24, 15226–15239.

Zhang, S., Mao, G., Crittenden, J., Liu, X., Du, H. (2017) b. Groundwater remediation from the past to the future: A bibliometric analysis. Water Research, 119, 114–125. doi:10.1016/j.watres.2017.01.029.

Zipf, G.K. (1949). Human behaviour and the principle of least effort, Editions Addison Wesley.

CAPÍTULO 1

Assessing ecological restoration as a research topic using bibliometric indicators[4]

[4] **Artigo publicado em:**

Romanelli, J. P., Fujimoto, J. T., Ferreira, M. D., & Milanez, D. H. (2018). Assessing ecological restoration as a research topic using bibliometric indicators. ***Ecological Engineering***, 120, 311–320. doi:10.1016/j.ecoleng.2018.06.015.

Abstract

A bibliometric analysis was performed to evaluate the global scientific production on ecological restoration from the period of 1997 to 2017. This analysis was based on online database of Science Citation Index Expanded - Web of Science© and a total of 3,297 publications was retrieved. The analysis comprised seven main aspects: (1) publication activity, (2) Web of Science categories, (3) journals, (4) countries, (5) authors, (6) organizations and (7) keywords. The results indicated that the annual publications on ecological restoration study have recently increased. The USA play an important role as they have published highly in this field and have been the most frequent partner in international collaborations. American researchers have accumulated most of the publications. The Chinese Academy of Science is the emblematic organization, with 363 published papers. The Restoration Ecology and Ecological Engineering are the two most used journals to dissiminate results. The major related research areas are ‘‘Environmental Science Ecology", "Forestry" and "Biodiversity Conservation”. Studies about "restoration", " *pinus ponderosa*", "climate change", "biodiversity" and "ecosystem services" have become the main subject of research along the years. Analyses of keywords suggested that there is a relatively lack of information about "soil" and "tropical ecossystems" among the analyzed studies. Overall, this framework proved to be effective to evaluate the recent research trends and to contribute with researchers and goverments on management and decision-making on science.

Keywords: VOSviewer; bibliometric map; restoration ecology; soil; tropical ecosystems; systemic approach

1. Introduction

Environmental restoration techniques have evolved significantly in recent years, especially after the emergence of the science of restoration ecology (Cole et al., 2010), which contributes to substantially enhance the body of related literature (Li and Nan, 2017). Many environmental actions, however, have not yet reached the practice aims of ecological restoration (Araújo et al., 2005; Rodrigues and Gandolfi, 2007) and this fact suggests that the real effects of biodiversity recovery and ecosystem services remain uncertain and not tested (Ren et al., 2016).

Ecological restoration appears to be one of the most promising practices to restore the integrity and functionality of ecosystems in degraded areas (Devoto et al., 2012; Balaguer et al., 2014) and it aims, among other aspects, at ensuring the sustainability of ecosystem services (Robinson et al., 2013; Hu, et al., 2017) in areas affected by the negative effects of recent ecological changes (Covington et al., 2001; SER, 2002). According to initiatives such as the Convention on Biological Diversity (CBD, 2012), the Intergovernmental Science and Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2013) and massive action policies (IUCN, 2014), ecological restoration practices are a global priority (Calmon et al., 2011; Ren et al, 2016; Aronson et al., 2016), and have been recognized as one of the United Nations Sustainability Development Goals (UN, 2015).

Therefore, to better understand part of the breadth from a particular area of science, such as ecological restoration, it is useful to conduct integrated and systematic analyses of global scientific production (Borgman and Furner 2002; Song and Zhao, 2013), investigating the recent status and emerging trends. Some researchers have used this strategy to target their research focus (Neff and Corley 2009; Li and Nan, 2017). In this sense, bibliometric analysis plays an increasingly important role in managing and supporting decisions in the scientific scope, technological policies and research management (Ravichandran, 2012; Song and Zhao, 2013).

Bibliometrics is a statistical technique which includes registered information about scientific publications, citations, patent documents and reports (Okubo, 1997; Van Raan, 2014). Recently, this technique has received special attention from the scientific community (Merigó and Yang, 2017) because it allows the integration of information on the development of specific research fields (Zhang et al., 2016) or whole disciplines (Li et al., 2011; Liao and Huang, 2014). It is a tool that benefits researchers and governments, reducing scientific boundaries between countries or regions (Yu et al., 2017).

In this field, bibliometric mapping is a striking research topic (Borner et al., 2003), since it allows the visualization of indicators presented as networks (Van Eck and Waltman, 2009). Currently, there is a lack of work applying this systematic evaluation model to assess the status and issues surrounding the theme of ecological restoration. In this study, we sought to fill this gap by developing a bibliometric analysis over the last 21 years (1997 - 2017), presenting a global overview and highlighting its hot spots and future trends. Specifically, this study aimed at: (1) examining trends in the "ecological restoration" research activity over the past two decades through the online subscription-based scientific citation indexing service; (2) presenting an overview about “ecological restoration” according to the distribution of papers by: publication activity, Web of Science categories, journals, countries, authors, organizations and keywords; and (3) evaluating the international collaboration networks by bibliometric mapping method.

2. Material and methods

2.1 Data collection

Bibliometric indicators have been developed considering the bibliographic data of publications indexed in the online database of Science Citation Index Expanded (SCI-E) - Clarivate Analytics’ ISI - Web of Science© (https://webofknowledge.com/), which has an extensive and multidisciplinary coverage of bibliographic data of cutting edge scientific publications. The database is usually used as a source for academic studies (Azevedo et al., 2005; Boanares and Azevedo, 2014) and for bibliometric studies (Okubo, 1997; Milanez, et al., 2013; Van Raan, 2014). The term “ecological restoration” was designated to describe the scientific knowledge about restoration associated to ecological theories.

The search expression consisted in applying “ecological restoration” to the “Topic” field, which seeks for publications though their title, abstract, author's keywords, and WoS-assigned keywords called Keywords Plus (Boudry et al., 2018). These records necessarily brought the words "ecological restoration" in an associated way and in that exact order, due the use of quotation marks (Ştirbu et al., 2015). Only articles and reviews have been considered in this analysis, because they represent the majority of documents with complete research results and outcomes (Fu et. al., 2013; Boudry et al., 2018). The research comprised the timespan from 1997 to 2017 and dataset were downloaded on January 22, 2018. After searching, a total of 3,297 bibliographic data of scientific publications were retrieved and collected (94,26% articles and 5,74% reviews). The assessment involved the following information obtained from the collected sample: (1) publication activity, (2) Web of Science categories, (3) journals, (4) countries, (5) authors, (6) organizations and (7) keywords. The synthesis of the methodology employed is presented in Figure 1.

2.2 Data analyses

All analyses were performed using the “Analyzing Results” tool provided by the database with support of the MS Excel (v. 2016) to perform calculations and develop charts (indicator visualization). Maps of collaboration based on co-authorship and co-occurrence analysis were developed using VOSviewer software (version 1.6.6; www.vosviewer.com) to understand how countries, research institutions, and authors have been organizing themselves in this theme. VOSviewer is a robust tool that uses clustering algorithms and functionalities based on the strengths of the connections among items to help the analyses of the network. The evaluation of the authors' affiliation was performed based on the "Author Information", contained in the publications and it may not to represent all of their academic links.

To investigate the most popular research topics, their overall trends and knowledge gaps, an assessment comparing the Keywords Plus and Author's keywords has been carried out. Keywords Plus supplies additional search terms extracted from titles on cited papers and footnotes (Garfield, 1990), and include important terms for research (Boudry et al., 2018). Web of Science uses these keywords in order to improve information retrieving routines (Milanez et al., 2013). In this sense, non-repeated words or terms obtained by comparison between Keywords Plus and Author's Keywords with few occurences were considered non-focused themes on studies about ecological restoration. The meaningless words (also called stopwords) were not taken into account, and the final listed words were separated into two groups: generic words (representing general terms) and directive words (representing specific terms). The set of directive words was used to validate the keywords analysis through a second search on Web of Science.

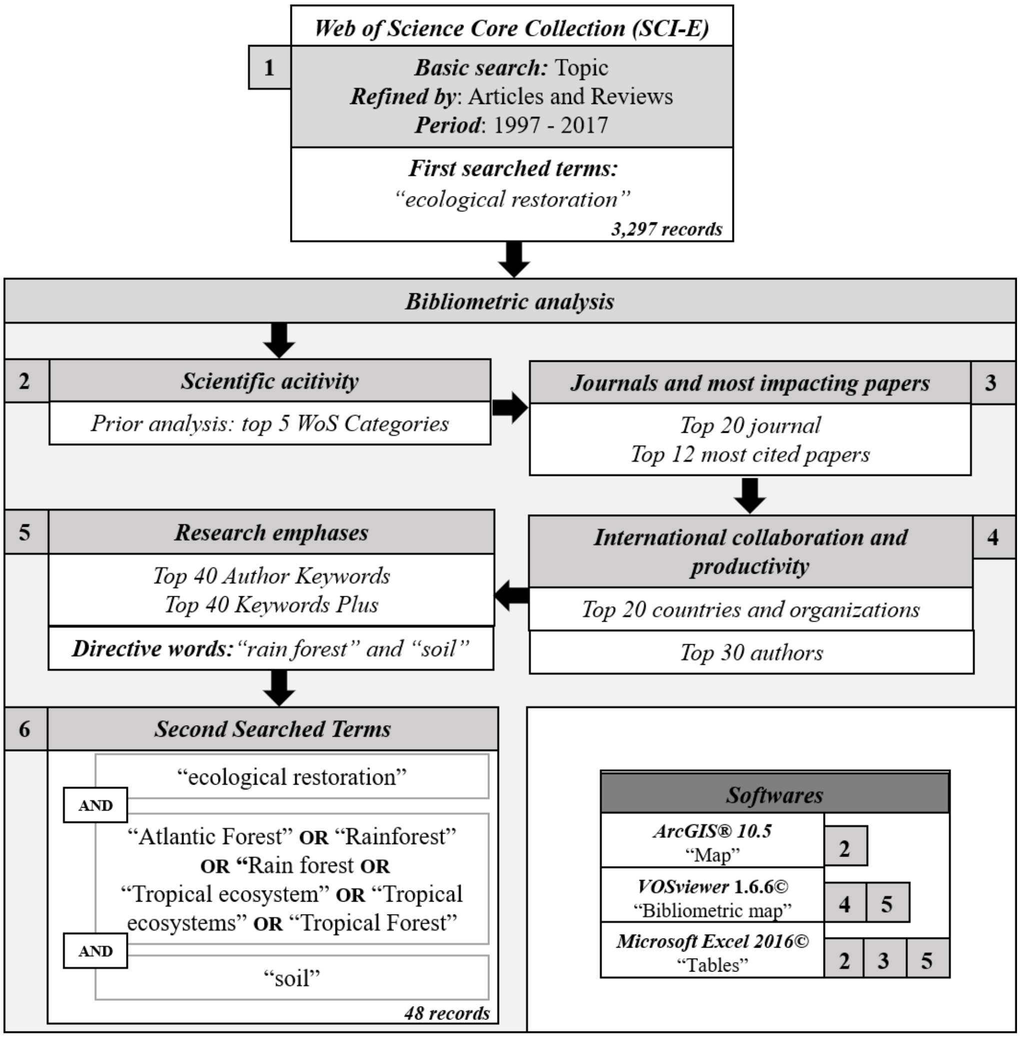


Fig. 1. Synthesis of the employed methodology.

3. Results and Discussion

3.1 Evolution of scientific activity: prior analysis

Restoration of ecosystems is an ancient practice. However, the scientific field of restoration ecology is relatively recent (Anderson, 2005). The 1980s are considered a historical landmark that characterizes the two phases of the restoration domain (Rodrigues et al., 2009; Oliveira and Engel, 2011), which is defined: by scientific knowledge associated to techniques; and by the association of these techniques with ecological theories (Young et al., 2005; Durigan and Mello, 2011).

The domain of ecological restoration has developed a broad and diversified body of literature in recent decades, which addresses several aspects of ecological interaction (Weiner, 1995; McPherson and DeStefano, 2003). This fact is relevant both to the science of restoration ecology and to the practice of ecological restoration (Young et al., 2005). The evolution of publications between the years 1997 to 2017 associated with the five main WoS Categories can be found in Figure 2.

It is clear that ecological restoration can be considered an emerging theme of research as consequence of the general trends shown by the chart column (Fig. 2). Moreover, concerns about the environmental preservation in favor of sustainable development have been promoting the increase of the global scientific production on ecological restoration (Bloomfield et al., 2017).

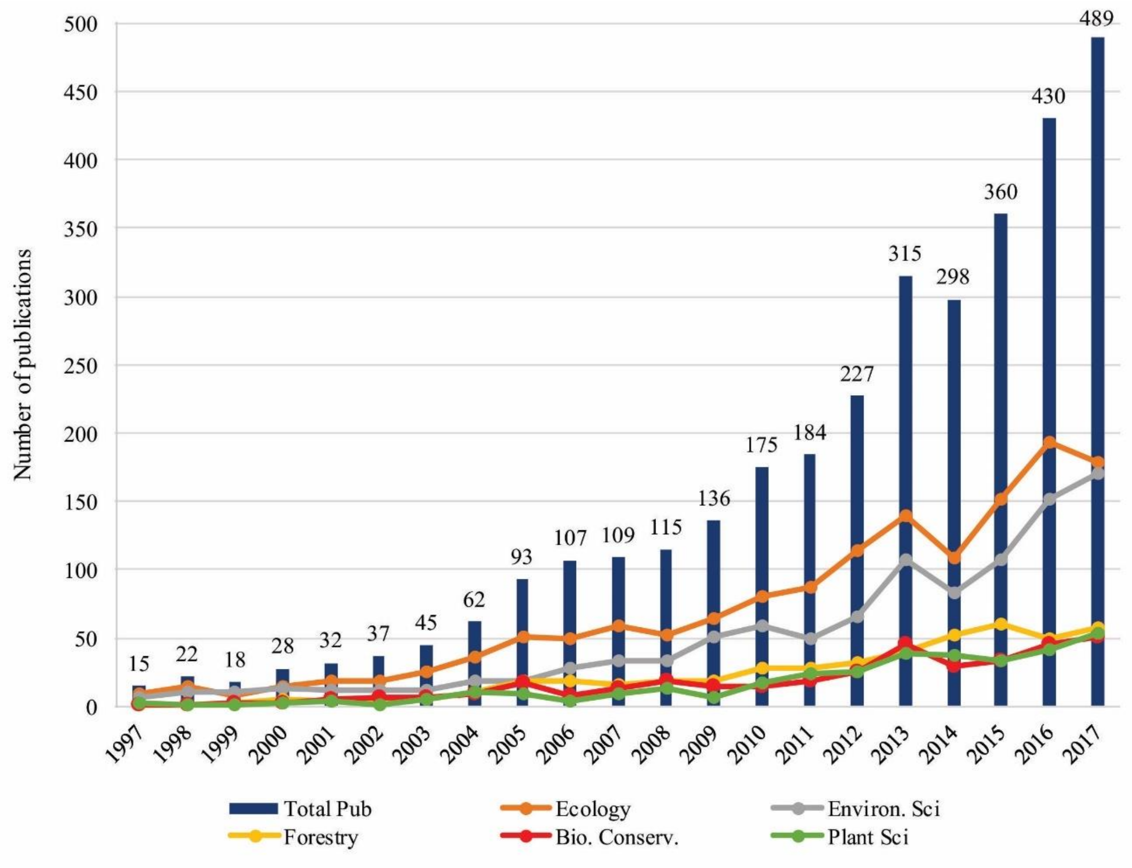


Fig. 2. Total publications from WoS Core Collection (SCI-E) involving ecological restoration from 1997 to 2017 and association to the growth trends of the top 5 main WoS categories.

In general, this topic has shown to be relevant all over the world, covering 107 different countries. Among them, the USA and China have accumulated the largest number of publications. Of course, the analysis should take into account the fact that most ISI-listed journals are published in English, which favors countries that speak this language (Okubo, 1997; Tao et al., 2015).

3.2 Main journals and most impacting papers

Overall, all retrieved papers were published in a wide range of 596 different journals. However, most journals (about 96%) have published fewer than 20 papers in the last two decades. Consequently, it is understood that these journals are peripheral in relation to scientific studies concerning ecological restoration. The top 20 most active journals, which represent about 40% of all publications, are listed in Table 1. The journal that publishes on behalf of the Society for Ecological Restoration (SER) – Restoration Ecology – is responsible for 9.7% from the total number of publications retrieved, heads the journals ranking and shows the importance of the Society.

The second most influent journal in the ranking, the Ecological Engineering, published over half of the first ranked journal (5.3%), followed by Forest Ecology and Management (4.1%), Journal of Applied Ecology (2.6%), and Ecological Applications (1.9%). This skewed distribution is expected in bibliometrics (Bradford law), since just some few journals are devoted to specific themes, although, many others may publish scientific papers about the subject (Okubo, 1997).

Table 1. Top 20 journals ranked by total publications

Rank	Journal	NP	Rank	Journal	NP
1	Restoration Ecology	320	11	Journal of Environ. Management	36
2	Ecological Engineering	175	12	Science of The Total Environment	34
3	Forest Ecol. and Manag.	136	13	Sustainability	34
4	Journal of A. Ecology	87	14	Conservation Biology	29
5	Ecological Applications	65	15	Environmental Earth Sciences	28
6	Biological Conservation	62	16	Biodiversity and Conservation	25
7	Environ. Management	57	17	Environmental M. and Assessment	24
8	PLOS ONE	54	18	Journal of Arid Environments	24
9	Applied Veg. Science	48	19	Ecological Indicators	23
10	Ecology and Society	39	20	Environ. Science and Polluiton R.	22

Abbreviations: NP=Number of publications; 3 - Forest Ecology and Management; 4 - Journal of Applied Ecology; 7 - Environmental Management; 9 - Applied Vegetation Science; 11 - Journal of Enviromental Management; 17 - Environmental Monitoring and Assessment; 20 - Environmental Science and Pollution Research

The analysis of the 12 most cited articles in the last 21 years (Table 2) revealed that there is no close relationship between the number of citations from a specific publication and the most active journals in the area. The most cited article on ecological restoration was published by the Journal of the North American Benthological Society, which was not listed in the top 20 journals. This study, specifically, focused on the ecological restoration of draining urban land (Walsh et al., 2005), and may have been cited not only in areas related to ecological restoration but also external to it. The most cited paper in the time span of this analysis was not vehiculated by one of the top 20 journals from Table 1. Nonetheless, some of them could be found: Forest Ecology and Management, Ecological Applications and Restoration Ecology.

Table 2. Top 12 most cited papers.

R	Year	Title	Journal	Authors	NC
1	2005	The urban stream syndrome: current knowledge and the search for a cure	*Journal of The North American Benthological Society*	Walsh, CJ et al.	920
2	2011	The value of estuarine and coastal ecosystem services	*Ecological Monographs*	Barbier, EB et al.	781
3	2005	Basic principles of forest fuel reduction treatments	*Forest Ecology and Management*	Agee, JK; Skinner, CN	545
4	2009	Novel ecosystems: implications for conservation and restoration	*Trends in Ecology & Evolution*	Hobbs, RJ et al.	533
5	2002	Ecological restoration of Southwestern ponderosa pine ecosystems: A broad perspective	*Ecological Applications*	Allen, CD et al.	468
6	2003	Ecological restoration of mine degraded soils, with emphasis on metal contaminated soils	*Chemosphere*	Wong, MH	456
7	2003	Plant ecotypes: genetic differentiation in the age of ecological restoration	*Trends in Ecology & Evolution*	Hufford, KM; Mazer, SJ	422
8	2009	Enhancement of Biodiversity and Ecosystem Services by Ecological Restoration: A Meta-Analysis	*Science*	Benayas, JMR et al.	417
9	2004	The interaction of fire, fuels, and climate across rocky mountain forest	*Bioscience*	Schoennagel, T et al.	397
10	1997	Determining reference conditions for ecosystem management of southwestern ponderosa pine forest	*Ecological Applications*	Fulé, PZ et al.	387
11	2002	Exotic plant species as problems and solutions in ecological restoration: A synthesis	*Restoration Ecology*	D'Antonio, C; Meyerson, LA	348
12	2005	Restoration success: How is it being measured?	*Restoration Ecology*	Ruiz-Jaen, MC; Aide, TM	336

Abbreviation: R=Rank; NC=Number of citation

An analysis of the content of the studies presented in Table 2 was performed. Two studies evaluated the managment of estuarine and coastal ecosystems (ECE) (Benayas et al., 2009; Barbier et al., 2011), and establishing actions of restoration programs focused on increasing biodiversity (Benayas et al., 2009). The use of fire and the disturbance regime of forest fires on ecosystems were also frequently cited (Schoennagel et al, 2004; Fulé et al., 1997), with a focus on the Rocky Mountain ecosystems (Schoennagelet al., 2004) and pinus ponderosa forests (Fulé et al., 1997; Agee and Skinner, 2005), from the perspective of restoring natural processes (Allen et al., 2002).

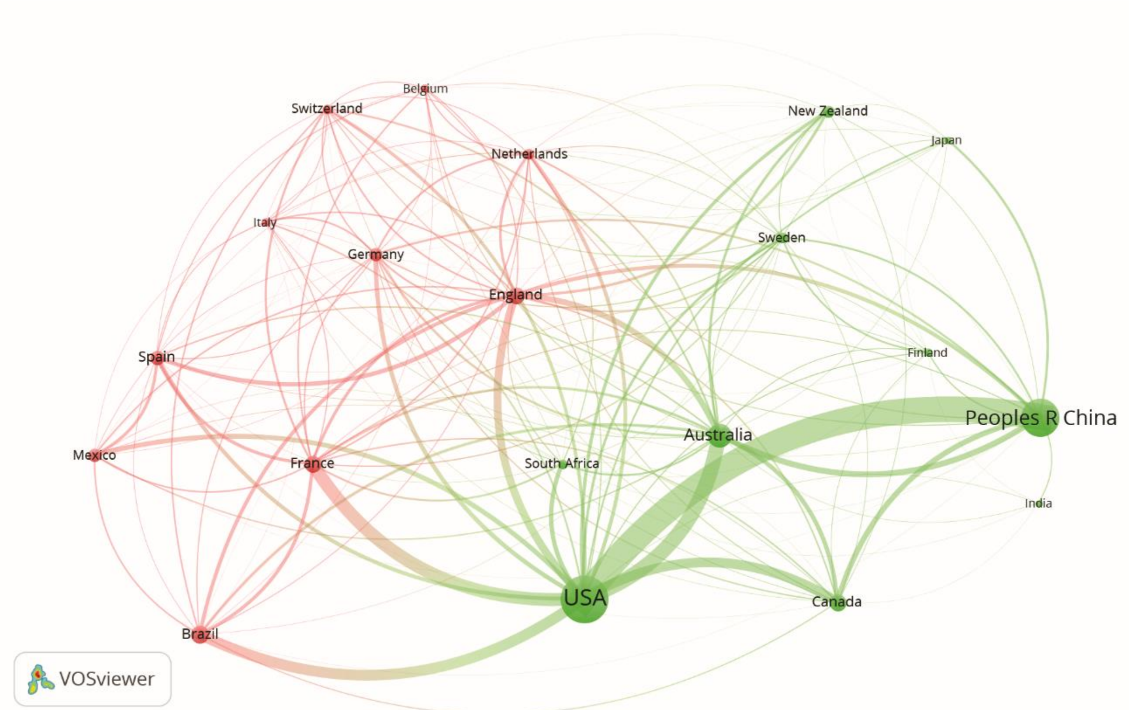
In general, the biotic and abiotic environmental changes involved with ecological restoration were discussed under the restoration and conservation aspects (Hobbs et al., 2009), and restoration ecology and population genetics (Hufford and Mazer, 2003) . The effects of exotic species on the restoration process were also widely cited (D'Antonio and Meyerson, 2002). Specifically, considering the physical environment, the ecological aspects of soil restoration in mining regions were investigated (Wong, 2003). Finally, the success criteria of restoration were analyzed through guidelines of the Society for Ecological Restoration (SER) (Ruiz-Jaen and Aide, 2005) and have been received high attention from the academic community.

It must be emphasized that the longer scientific articles are indexed the higher the probability is to be cited. On the other hand, items that have been recently published and have a high number of citations may indicate new perspectives on the area (Okubo, 1997). Thus, to verify this information, an analysis of highly cited papers published in the last 5 years was also carried out, as follows.

The assisted gene flow of adaptation to local climatic changes has been frequently cited in the recent context of ecological restoration (Aitken and Whitlock, 2013), as well as restoration of forest resilience and its spatial reference patterns (Churchill et al., 2013), and the integration of ecological restoration in global environmental policy deliberations (Aronson and Alexander, 2013). In addition, the effects of biodiversity loss, species restoration (Seddon et al., 2014), and the use of models based on functional traits have been also widely used as references. Among all subjects, the evaluation of the success criteria of restoration continues the trend of highly cited issues (Wortley et al., 2013).

3.3 International collaboration and productivity

To understand how countries, organizations and authours have organized themselves as players that conduct researches on ecological restoration, an assessment of international collaboration based on co-authorship was carried out, considering the accumulated number of publication. Figures 3, 4 and 5 show three networks where the size of the node is proportional to the number of accumulated publications as well as the thickness of the edges. The colors indicate which cluster the item belongs to. Respectively, these figures were limited to present only the top 20 countries and organizations, and the top 30 authors.



Cluster 1

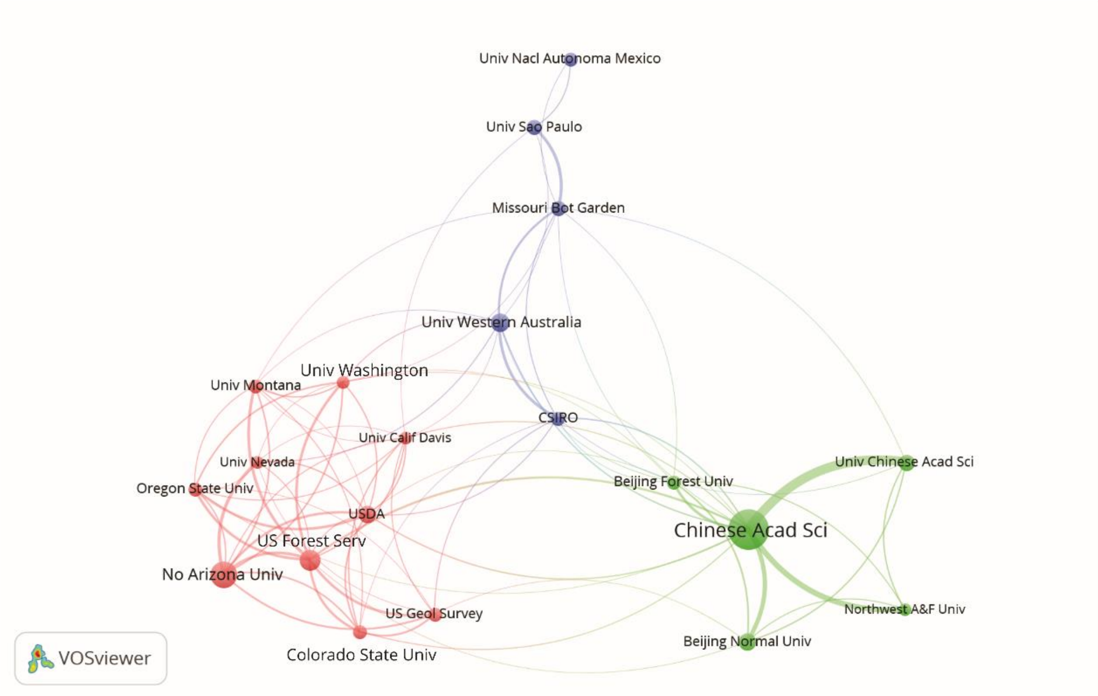
Rank	Country	NP	Rank	Country	NP
4	Brazil	193	10	Mexico	106
6	France	165	12	Netherlands	71
7	England	160	14	Switzerland	62
8	Spain	131	16	Italy	47
9	Germany	111	17	Belgium	46

Cluster 2

Rank	Country	NP	Rank	Country	NP
1	USA	1248	13	Sweden	66
2	Peoples R China	819	15	South Africa	54
3	Australia	339	18	Finland	46
5	Canada	167	19	India	37
11	New Zealand	91	20	Japan	36

Abbreviation: NP=Number of publications=Record count

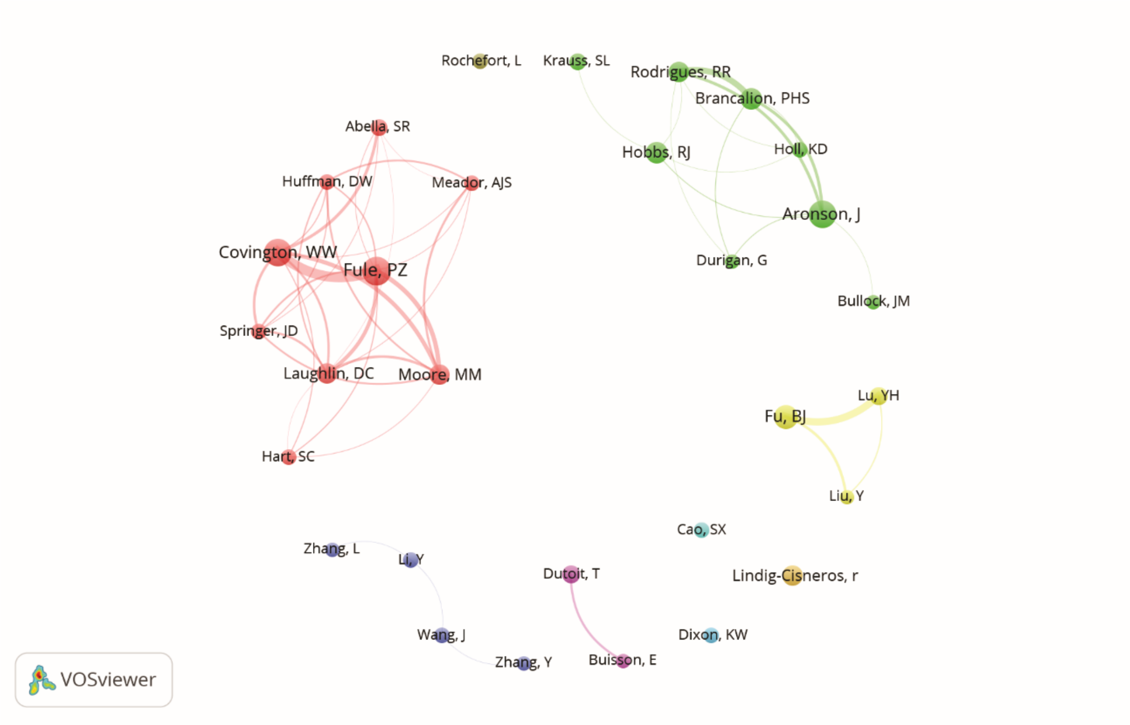
Fig. 3. Network visualization map for country collaboration.



Rank	Cluster 1	NP	C	Rank	Cluster 2	NP	C
				1	Chinese Acad Sci	363	CHI
2	No Arizona Univ	159	USA	5	Beijing Normal Univ	75	CHI
3	US Forest Serv	104	USA	7	Univ Chinese Acad Sci	58	CHI
6	US Dept Agr (USDA)	67	USA	10	Beijing Forestry Univ	49	CHI
11	US Geol Survey	53	USA	17	Northwest A F Univ	45	CHI
13	Oregon State Univ	48	USA	**Rank**	**Cluster 3**	**NP**	**C**
15	Univ Montana	45	USA	4	Univ Western Australia	82	AUS
16	Colorado State Univ	45	USA	8	Missouri Bot Garden	56	USA
18	Univ Calif Davis	40	USA	9	Univ Sao Paulo	53	BRA
19	Univ Washington	38	USA	12	Comm Sci Ind Resr Org (CSIRO)	48	AUS
20	Univ Nevada	37	USA	14	Univ N. Autonoma Mexico	46	MEX

Abbreviation: NP=Number of publicartions; C=Country; CHI=China; USA= United States of America; BRA=Brazil; MEX=Mexico; AUS=Autralia.

Fig. 4. Network visualization map for organization collaboration.



Rank	Cluster 1	NP	Organization	C	Rank	Cluster 3	NP	Organization	C
1	Fule PZ	51	No Arizona Univ	USA	18	Li Y	16	Nort China E P Univ	CHI
3	Covington WW	44	No Arizona Univ	USA	24	Wang J	14	Shenyang Agr Univ	CHI
7	Moore MM	25	No Arizona Univ	USA	28	Zhang Y	13	Zhengzhou Univ	CHI
9	Laughlin DC	25	Univ Waikato	NEW Z	30	Zhang L	13	Chinese Acad Sci	CHI
13	Abella SR	18	Univ Nevada	USA	**Rank**	**Cluster 4**	**NP**	**Organization**	**C**
16	Hart SC	16	Univ Calif Merced	USA	4	Fu BJ	36	Chinese Acad Sci	CHI
19	Huffman DW	16	No Arizona Univ	USA	12	Lu YH	19	Chinese Acad Sci	CHI
21	Meador AJS	14	No Arizona Univ	USA	29	Liu Y	13	Chinese Acad Sci	CHI
23	Springer JD	14	No Arizona Univ	USA	**Rank**	**Cluster 5**	**NP**	**Organization**	**C**
					11	Dutoit T	20	Aix Marseille Univ	FRA
Rank	**Cluster 2**	**NP**	**Organization**	**C**	25	Buisson E	13	Aix Marseille Univ	FRA
2	Aronson J	46	Missouri Bot Gar	USA	**Rank**	**Cluster 6**	**NP**	**Organization**	**C**
5	Hobbs RJ	28	Univ W Australia	AUS	20	Cao SX	14	Minzu Univ China	CHI
6	Brancalion PHS	27	Univ Sao Paulo	BRA	**Rank**	**Cluster 7**	**NP**	**Organization**	**C**
8	Rodrigues RR	25	Univ Sao Paulo	BRA	15	Dixon KW	16	Curtin Univ	AUS
14	Krauss SL	17	Univ W Australia	AUS	**Rank**	**Cluster 8**	**NP**	**Organization**	**C**
17	Holl KD	16	Univ Calif S. Cruz	USA	10	Lindig-Cisneros R	24	Univ N A Mexico	MEX
26	Bullock JM	13	NERC CTR E&H	ENG	**Rank**	**Cluster 9**	**NP**	**Organization**	**C**
27	Durigan G	13	State Forest Assis	BRA	22	Rochefort L	14	Univ Laval	CAN

Abbreviation: NP=Number of publications; C=Country; USA=United States of America; CHI=China; AUS=Australia; CAN=Canada; BRA=Brazil; MEX=Mexico; FRA=France; ENG=England; NEW Z=New Zealand

Fig. 5. Network visualization map for top 30 author collaboration.

Clearly, the USA and China have contributed significantly to the development of ecological restoration research and have published a considerable number of collaborative scientific studies (9,54% and 14,53%, respectively). The USA and Australia can be considered the core countries of this network due to the fact that they developed research in collaboration with all other top 20 countries (Figure 3).

The bibliometric mapping of Figure 3 also reveals the existence of two clusters among these 20 most productive countries. Specifically, cluster 1colored in red presents the characteristic of being composed mostly by European countries, extending the collaboration network to Mexico and Brazil. On the other hand, cluster 2 (in green) consists of members from several continents and presents the largest number of accumulated publications, although it presents three members with fewer than 50 publications (Finland, India and Japan). The USA, England, France and Australia are countries which most connected members from the two clusters.

The largest number of papers with co-authorship was evidenced by the USA and China, with 119 registered documents, followed by USA and Australia (69 documents), USA and France (60 documents), USA and Brazil (50 documents) and USA and Canada (45 documents). Although some countries, such as Brazil and France, present a large number of studies in partnership with the USA, bibliometric mapping has not characterized them in the same cluster. This is explained by the strong influence of China in this scenario, which shapes the formation of clusters in function of its network of collaborations with the USA, and more specifically, with the other countries from its cluster.

Figure 4 shows the existence of three clusters of collaboration among the most productive organizations. Cluster 1 (red) is characterized, exclusively, by North American organizations, whereas cluster 2 (green) has only members from China, highlighting the network of collaboration between the Chinese Academy of Science (CAS) and the University Chinese Academy of Science (UCAS) (under the direct leadership of the CAS). Cluster 3 (blue), unlike the others, is characterized by the diversity of origin of organizations. The results show that the collaboration network between organizations from the same country (cluster 1 and cluster 2) is closer than the organizations of different countries. The organizations Chinese Academy of Science, USDA and Univ California Davis presented the largest international collaboration network: 13, 11 and 11 links, respectively. However, the organizations Chinese Academy of Science, CSIRO and Beijing Forest Univ are central organizations of this collaboration network, since they presented the largest number of collaborators among the different clusters (9, 6 and 5, respectively).

The bibliometric mapping of the 30 main authors (Figure 5) revealed the existence of 9 clusters of research productions. In general, it was possible to observe that cluster 1, 2 and 4 presented the most characteristic collaboration networks. The other clusters were configured as restricted collaboration networks, with few authors from the same country (clusters 3 and 5), or as single members of a cluster (cluster 6, 7, 8 and 9).

Specifically, cluster 1 has as main characteristic the predominance of American authors (9 authors), most of which are linked to Northern Arizona University (6 authors). Members Fulé PZ, Covington WW and Laughlin DC are the researchers with the largest number of partnerships within this cluster and also among the others from the top 30. The largest number of co-authored papers was observed among researchers Fulé PZ and Covington WW (27 documents), both linked to Northern Arizona University. In terms of origin of the authors, cluster 2 stands out for its diversity of nationalities, with members from four countries (USA, Australia, Brazil and England). In this cluster, authors Rodrigues RR and Brancalion PHS presented the highest number of papers with co-authorship (16 papers).

Although cluster 3 is composed only by members from China, the collaboration network presented a linear aspect, which indicates that there are restricted partnerships among its members. On the other hand, cluster 4, which is also composed by Chinese, presented the characteristic network aspect, suggesting that there is collaboration among all authors. This fact can be explained by the same organizational link of Chinese researchers (Chinese Acad Sic). In the same way, the members of cluster 5 also belong to the same organization (Aix Marseille University). The other clusters (6, 7, 8 and 9) are composed by only one member, which indicates the lack of research developed in collaboration with the other top 30 authors.

Clustering techniques have been developed mainly in fields such as statistics, computer science, and network science, and play an important role in bibliometric research. These techniques are used to identify groups of related publications, authors, or journals (Van Eck and Waltman, 2017). In an international context, it was evident that there is a great diversity of research focus in the field of ecological restoration (Weiner, 1995; McPherson and DeStefano, 2003; Young et al., 2005), and this may be associated to the different research groups and the scientific demands of each region or country. In this sense, the paper contents from each author's cluster were analyzed in order to reveal the profile of subjects and study areas associated with each group. The top 50 most cited author keywords were investigated through the co-occurrence analysis (see supplemental data for detailed information, Fig. S1 to Fig. S9).

3.4 Research emphases: keywords analysis

Keywords are an important source of information about the subjects addressed in a publication (Liu et al 2011; Wang et al., 2013). The terms considered as keywords can be used to analyze the trends of a research area and to show the existing gaps (Guo et al., 2016). In this study, the 40 main author's keywords and keywords plus (Table 3) were considered to investigate any possible tendency.

From 1997 to 2017, it was estimated that 9,117 author expressions have been used in studies involving ecological restoration, which suggests the existence of a great diversity of research focus (Chuang et al., 2007). The term "ecological restoration" appears highly associated to "restoration", "*pinus ponderosa* or *ponderosa pine*" and "climate change". This first analysis suggests that among all retrieved documents involving ecological restoration, a considerable amount of studies have addressed temperate forest ecosystems, which can be evidenced by the main plant species that was cited as author-keyword.

Table 3. Top 40 of the most frequently used keywords

R	***Keywords Plus***	***RC***	***R***	***Author's keywords***	***RC***
1	Ecological restoration	886	1	Ecological restoration	891
2	Management	370	2	Restoration	282
3	Conservation	358	3	Ponderosa Pine	116
4	Biodiversity	318	4	Climate change	98
5	Vegetation	306	5	Biodiversity	97
6	Diversity	293	6	Ecosystem Services	93
7	Ecosystem or ecosystems	279	7	Forest Restoration	64
8	Restoration	262	8	Restoration ecology	63
9	Forest or Forests	221	9	Conservation	61
10	Climate change	209	10	Invasive species	53
11	Ecosystem services	174	11	Succession	52
12	Communities	154	12	Revegetation	47
13	Growth	149	13	Prescribe Fire	45
14	Impacts	148	14	Genetic Diversity	43
15	Plant or plants	143	15	Adaptative Management	40
16	Soil	140	16	Disturbance	37
17	Dynamics	131	17	Species richness	37
18	Patterns	124	18	Forest Management	35
19	Land-use	119	19	Grassland	34
21	Ecology	105	20	Fire	33
20	Succession	105	21	Monitoring	32
22	Species richness	96	22	Reforestation	32
23	Landscape	95	23	Resilience	32
24	Establishment	94	24	Vegetation	32
25	Regeneration	92	25	Thinning	31
26	Nitrogen	82	26	Diversity	30
27	Plant communities	81	27	Eutrophication	29
29	Disturbance	79	28	Ecosystem function	28
28	Grassland	79	29	Rehabilitation	28

30	Water	79	30	Remote sensing	28
31	Fire	78	31	Carbon sequestration	27
32	Rain forest	76	32	Loess Plateau	26
33	Habitat	72	33	Nitrogen	26
34	Responses	72	34	Ecosystem Management	25
36	Land	65	35	Local adaptation	25
35	Perspective	65	36	Community Assembly	24
37	Ponderosa Pine Forests	63	37	Sustainability	24
38	Populations	62	38	Wetland	24
39	Systems	59	39	Competition	23
40	Model	57	40	Functional traits	23

Gray color=repeated words or synonymous. Abbreviations: R=Rank; RC=Record count

Many scientists are committed to the study of ecological restoration. However, many questions remain unclear (Ren et al., 2016). To detect the gaps surrounding the theme, the strategy of comparison between keywords plus and author’s keywords were used (Table 3), in order to verify what is being discussed in the papers, although, it was not a specific research subject (author’s keywords). Comparing these two groups of words, it was noticed that in some cases words are repeated and others are not. Moreover, some terms, although they are not written in the same way, can be considered as synonyms (eg. community assembly and communities, or genetic diversity and biodiversity).

Furthermore, after separating words with the same meaning, non-repeated words and stopwords, the following list from keywords plus it was obtained: dynamics, establishment, growth, habitat, impacts, land, landscape, land-use, model, patterns, perspective, populations, rain forest, regeneration, responses, soil and water. Among this group of words, were considered as generic words: dynamics, establishment, growth, habitat, impacts, land, landscape, model, patterns, perspective, populations, land-use, regeneration and responses; and as directive words: rain forest, water and soil.

In addition, it is possible to consider that there are some knowledge gaps in the context of ecological restoration involving the directive words. They were highly cited as keywords plus (words extracted by WoS from cited papers - titles and abstracts), consequently, they are important terms in this domain. However, they were rarely used or not frequently included as author’s keywords, what suggests they were not the main focus of study. Thus studies involving the set of directive words may be an incipient research area.

Taking everything into account, to validate these results, a second search on Web of Science was conducted (Fig. 1) combining the main term “ecological restoration” along with the two directive words considered as the most important ones: “rain forest” (and its main synonyms) and “soil”. After the search, 48 documents were retrieved from the initial amount (3,297 documents) from the first search, which represents about 1,5% of all publications. Therefore, it was possible to confirm that there is a lack of knowledge involving this specific set of subjects into the domain of ecological restoration. It is important to highlight that this second search involves not only keywords, but also the title and abstract.

4. Conclusions

In conclusion, this work evaluated the researches on ecological restoration from 1997 to 2017 through bibliometric analysis to understand quantitatively the tendencies of the body of literature related to the theme. The bibliometric mapping proved to be effective in evaluating the networks of connections between the selected items, making it easier the interpretation of the obtained results. The main evaluated aspects revealed the rapid development of the domain of ecological restoration, mainly after 2006, where more than 100 studies were registered per year.

The networks of collaborations tend to present new configurations according to the scope of the research (number of analyzed items) and the employed terms at the initial search. In general, rankings tend to be influenced by: i) the coverage of papers and citations in the database; ii) how the indicators are calculated; and iii) the assessed disciplines. Indicator rankings display the visibility of the scholar results in some specific database, not their impact on the whole academic community (Wildgaard, 2015).

Application of boolean operators and quotation marks was the key factor to retrieve the selected data of this research. The analysis of cooperation among countries, organizations and authors have shown that the international collaboration network is less expressive than the collaboration between the organizations or authors from the same country, which tends to direct the studies to some specific research areas, as it was evident in the analysis of the author’s cluster.

Based on the analysis of the keywords and author’s cluster, it is suggested that future studies should contemplate the following aspects: (1) the systemic approach to ecological restoration, seeking to circumvent the gap of information about soil; (2) ecological restoration of tropical ecosystems and other critical ecosystems; (3) ecological restoration addressing anthropogenic and environmental issues in an integrated manner. In addition, other critical points of study are likely to emerge with the advance of ecological restoration studies. Finally, this work revealed the current status of research and knowledge gaps on ecological restoration, which may favor the development of new studies and the global scientific production.

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Supplemental material

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ecoleng.2018.06.015.

References

Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management. 211, 83-96. http://dx.doi.org/10.1016/j.foreco.2005.01.034.

Aitken, S.N., Whitlock, M.C., 2013. Assisted Gene Flow to Facilitate Local Adaptation to Climate Change. Annual Review of Ecology, Evolution, And Systematics. 44, 367-388. http://dx.doi.org/10.1146/annurev-ecolsys-110512-135747.

Allen, C.D., Savage, M., Falk, D.A., Suckling, K.F., Swetnam, T.W., Schulke, T., Stacey, P.B., Morgan, P., Hoffman, M., Klingel, J.T., 2002. Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. Ecological Applications. 12, 1418–1433.

Anderson, M.K., 2005. Tending the Wild: Native American knowledge and the management of California's natural resources. Journal of California and Great Basin Anthropology. 25, 255 – 259.

Araújo, F.S., Martins, S.V., Meira Neto, J.A.A., Lani, J.L., Pires, I.E., 2005. Structure of the shrub and tree vegetation colonizing an area degraded by Kaolin Mining, in Brás Pires, MG, Brazil. Revista Árvore. 29, 107–116.

Aronson, J., Alexander, S., 2013. Ecosystem Restoration is Now a Global Priority: Time to Roll up our Sleeves. Restoration Ecology. 21, 293-296. http://dx.doi.org/10.1111/rec.12011.

Aronson, J.C., Blatt, C.M., Aronson, T.B, 2016. Restoring ecosystem health to improve human health and well-being: physicians and restoration ecologists unite in a common cause. Ecology and Society. 4, 39. https://doi.org/10.5751/ES-08974-210439

Azevedo, P.G., Mesquita, F.O., Young, R.J., 2005. Fishing for gaps inscience: a bibliographic analysis of Brazilian freshwaterichthyology from 1986 to 2005. J. Fish Biol. 76, 2177–2193.

Balaguer, L., Escudero, A., Martín-Duque, J. F., Mola, I, Aronson, J. 2014. The historical reference in restoration ecology: Re-defining a cornerstone concept. Biological Conservation.176, 12-20. http://dx.doi.org/10.1016/j.biocon.2014.05.007.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecological Monographs. 81, 169-193. http://dx.doi.org/10.1890/10-1510.1.

Benayas, J.M.R., Newton, A.C., Diaz, A., Bullock, J.M., 2009. Enhancement of Biodiversity and Ecosystem Services by Ecological Restoration: A Meta-Analysis. Science. 325, 1121-1124. http://dx.doi.org/10.1126/science.1172460.

Bloomfield, G., Bucht, K., Martínez-Hernández, J.C., Ramírez-Soto, A.F., Shesenã-Hernández, I., Lucio-Palacio, C.R., Inzunza, E.R, 2017. Capacity building to advance the United Nations sustainable development goals: An overview of tools and approaches related to sustainable land management. Journal Of Sustainable Forestry. 37, 157-177. http://dx.doi.org/10.1080/10549811.2017.1359097.

Boanares, D., Azevedo, C.S., 2014. The use of nucleation techniques to restore the environment: a bibliometric analysis. Natureza & Conservação. 12, 93-98. http://dx.doi.org/10.1016/j.ncon.2014.09.002.

Borgman C.L., Furner, J., 2002. Scholarly communication and bibliometrics. Annual Review of Information Science and Technology. 36, 3-72.

Borner, K., Chen, C., Boyack, K. W., 2003. Visualizing knowledge domains. Annual Review of Information Science and Technology. 37, 179–255.

Boudry, C., Baudouin, C., Mouriaux, F. 2018. International publication trends in dry eye disease research: A bibliometric analysis. The Ocular Surface. 16, 173-179. http://dx.doi.org/10.1016/j.jtos.2017.10.002.

Calmon, M., Brancalion, P.H.S., Paese, A., Aronson, J., Castro, P., Silva, S.C., Rodrigues, R.R., 2011. Emerging threats and opportunities for large Scaleecological restoration in the Atlantic forest of Brazil. Restor. Ecol. 19, 154–158.

Chuang, K.Y., Huang, Y.L., Ho, Y.S., 2007. A bibliometric and citation analysis of stroke-related research in Taiwan. Scientometrics. 72, 201–212. https://doi:10.1007/s11192-007-1721-0

Cole, R.J., Holl, K.D., Zahawi, R.A., 2010. Seed rain under treeislands planted to restore degraded lands in a tropicalagricultural landscape. Ecol. Appl. 20, 1255–1269.

Convention on Biological Diversity, 2012. UNEP/CBD/COP Decision XI/16 Ecosystem Restoration. https://www.cbd.int/doc/decisions/cop-11/cop-11-dec-16-en.pdf (accessed 12.24.17).

Covington, W.W., Fulé, P. Z., Hart, S.C., Weaver, R.P., 2001. Modeling Ecological Restoration Effects on Ponderosa Pine Forest Structure. Restoration Ecology. 9, 421-431. http://dx.doi.org/10.1046/j.1526-100x.2001.94011.x

D'Antonio, C., Meyerson, L.A., 2002. Exotic Plant Species as Problems and Solutions in Ecological Restoration: A Synthesis. Restoration Ecology. 10, 703–713. doi:10.1046/j.1526-100X.2002.01051.x

Churchill, D.J., Larson, A.J., Dahlgreen, M.C., Franklin, J.F., Hessburg, P.F., Lutz, J.A., 2013. Restoring forest resilience: From reference spatial patterns to silvicultural prescriptions and monitoring. Forest Ecology and Management. 291, 442-457. https://doi.org/10.1016/j.foreco.2012.11.007.

Devoto, M., Bailey, S., Craze, P., Memmot, J. 2012. Understanding and planning ecological restoration of plant–pollinator networks. Ecol. Lett. 15, 319 - 328.

Dobson, A. P.; Bradshaw, A. D., Baker, A. J. M., 1997. Hopes for the future: Restoration ecology and Conservation Biology. Science. 277, 515–522.

Durigan, G., Melo, A.C.G., 2011. An overview of public policies and research on ecological restoration in the state of São Paulo, Brazil. In: Figueiro, A. E. B. Biodiversity conservation in the Americas: lessons and policy recommendations. Santiago: Editorial FEN - Universidad de Chile. 320-355.

Fu, H.Z., Wang, M. H., Ho, Y. S. 2013. Mapping of drinking water research: a bibliometric analysis of research output during 1992 - 2011. Sci Total Environ. 443, 757-765. https://doi.org/10.1016/j.scitotenv.2012.11.061

Fulé, P.Z., Covington, W.W., Moore, M.M., 1997. Determining reference conditions for ecosystem management of southwestern ponderosa pine forests. Ecological Applications. 7, 895–908.

Garfield, E., 1990. KeyWords PlusTM - ISIS breakthrough retrieval method. 1. Expanding your searching power on current-contents on diskette. Curr Comments. 32, 5-9.

Guo, L., Xu, F., Feng, Z., Zhang, G., 2016. A bibliometric analysis of oyster research from 1991 to 2014. Aquaculture International. 24, 327-344. http://dx.doi.org/10.1007/s10499-015-9928-1

Hobbs, R.J., Higgs, E., Harris, J.A., 2009. Novel ecosystems: implications for conservation and restoration. Trends in Ecology & Evolution, 24, 599-605. http://dx.doi.org/10.1016/j.tree.2009.05.012.

Hu, J., Lu, Y., Fu, B, Comber, A. J., Harris, P. 2017. Quantifying the effect of ecological restoration on runoff and sediment yields. Progress In Physical Geography. 41,753-774. http://dx.doi.org/10.1177/0309133317738710.

Hufford, K.M., Mazer, S.J., 2003. Plant ecotypes: genetic differentiation in the age of ecological restoration. Trends In Ecology & Evolution. 18, 147-155. http://dx.doi.org/10.1016/s0169-5347(03)00002-8.

Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), 2013. Deliverable 3(b) (i): Thematic assessment on land degradation and restoration. https://www.ipbes.net/sites/default/files/downloads/pdf/IPBES_MEP_5_12.pdf (accessed 12.24.17).

International Union for Conservation of Nature (IUCN), 2014. Forest and Landscape Restoration. http://cmsdata.iucn.org/downloads/roar_web_version.pdf. (accessed 12.24.17).

Li, J., Wang, M.H., Ho, Y.S., 2011. Trends in research on global climate change: a science citation index expanded-based analysis. Glob Planet Chang. 77, 13–20.

Li, X., Nan, R., 2017. A bibliometric analysis of eutrophication literatures: an expanding and shifting focus. Environmental Science And Pollution Research. 24, 17103-17115. http://dx.doi.org/10.1007/s11356-017-9294-9

Liao, J., Huang, Y., 2014. Global trend in aquatic ecosystem research from 1992 to 2011. Scientometrics 98, 1203–1219. http://dx.doi:10.1007/s11192-013-1071-z

Liu, X., Zhang, L., Hong, S., 2011. Global biodiversity research during 1900–2009: a bibliometric analysis. Biodivers Conserv. 20, 807–826.

McPherson, G.R., DeStefano, S., 2003. Applied ecology and natural resource management. Cambridge, UK: Cambridge University Press.

Merigó, J.M., Yang, J., 2017. A bibliometric analysis of operations research and management science. Omega. 73, 37-48. http://dx.doi.org/10.1016/j.omega.2016.12.004

Milanez, D.H., Schiavi, M.T., Amaral, R.M., Faria, L.I. L, Gregolin, J.A.R., 2013. Development of carbon-based nanomaterials indicators using the analytical tools and data provided by the web of science database. Materials Research.16, 1282-1293. http://dx.doi.org/10.1590/s1516-14392013005000130.

Neff, M.W., Corley, E. A., 2009. 35 years and 160,000 articles: a bibliometric exploration of the evolution of ecology. Scientometrics. 80, 657–682.

Okubo, Y., 1997. Bibliometric indicators and analysis of research systems: methods and examples. Paris: OECD.

Oliveira, R. E.; Engel, V. L., 2011. A Restauração ecológica em destaque: Um retrato dos últimos vinte e oito anos de publicações na área. Oecologia Australis. 15, 303-315. (in Portuguese).

Ravichandran, P., 2012. Bibliometric analysis on publication trends in the biodiversity research: a study. Journal of Advances in Library and Information Science. 1, 94-99.

Ren, Y., Lü, Y., Fu, B., 2016. Quantifying the impacts of grassland restoration on biodiversity and ecosystem services in China: A meta-analysis**.** Ecological Engineering. 95, 542-550. http://dx.doi.org/10.1016/j.ecoleng.2016.06.082

Robinson, D.A., Hockley, N., Cooper, D.M.; Emmett, B.A., Keith, A.M., Lebron, I., Reynolds, B., Tipping, E., Tye, A. M., 2013. Natural capital and ecosystem services, developing an appropriate soils framework as a basis for valuation. Soil Biology & Biochemistry. 57, 1023–1033.

Rodrigues, R.R., Gandolfi, S., 2007. Restoration actions. In: Rodrigues, R.R., Martins, S.V., Gandolfi, S. (Eds.), High DiversityForest Restoration in Degraded Areas. Nova SciencePublishers, New York, pp. 77–101.

Rodrigues, R.R., Lima, R.A.F., Gandolfi, S., Nave, A.G., 2009. On the restoration of high diversity forests: 30 years of experience in the Brazilian Atlantic Forest. Biological Conservation. 142, 1242-1251.

Ruiz-Jaen, M.C., Aide, T.M., 2005. Restoration Success: How Is It Being Measured? Restoration Ecology. 13, 569–577. doi:10.1111/j.1526-100X.2005.00072.x.

Schoennagel, T., Veblen, T.T., Romme, W.H., 2004. The Interaction of Fire, Fuels, and Climate across Rocky Mountain Forests. Bioscience. 54, 661-676. http://dx.doi.org/10.1641/0006-3568(2004)054[0661:tioffa]2.0.co;2.

Seddon, P.J., Griffiths, C.J., Soorae, P.S., Armstrong, D.P., 2014.Reversing defaunation: Restoring species in a changing world. Science. 345, 406-412. http://dx.doi.org/10.1126/science.1251818.

Society for Ecological Restoration Science & Policy Working Group, 2002. The SER Primer on Ecological Restoration. https://nau.edu/uploadedFiles/Centers-Institutes/ERI/_Forms/Resources/ser-primer.pdf (acessed: 12.24.17).

Society for Ecological Restoration International Science & Policy Working Group, 2004. The SER International Primer on Ecological Restoration. http://www.ser.org/page/SERDocuments (acessed: 03.28.18).

Song, Y., Zhao, T., 2013. A bibliometric analysis of global forest ecology research during 2002–2011. **Springerplus.** 2, 204. http://dx.doi.org/10.1186/2193-1801-2-204.

Ştirbu, S., Thirion, P., Schmitz, S., Haesbroeck, G., Greco, N., 2015. The Utility of Google Scholar When Searching Geographical Literature: Comparison with Three Commercial Bibliographic Databases. The Journal of Academic Librarianship. 41, 322-329. Elsevier BV. http://dx.doi.org/10.1016/j.acalib.2015.02.013.

Tao, J., Che, R., He, D., Yan, Y., Sui, X., Chen, Y., 2015. Trends and potential cautions in food web research from a bibliometric analysis. Scientometrics. 105, 435-447. http://dx.doi.org/10.1007/s11192-015-1679-2

United Nations (U.N.), 2015. Goal 15: sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss. http://www.un.org/sustainabledevelopment/wp-content/uploads/2016/08/15_Why-it-Matters_Goal15__Life-on-Land_3p.pdf (acessed 12.24.17).

Van Eck, N.J., Waltman, L., 2009. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics. 84, 523-538. http://dx.doi.org/10.1007/s11192-009-0146-3

Van Eck, N.J., Waltman, L., 2017. Citation-based clustering of publications using CitNetExplorer and VOSviewer. Scientometrics.111, 1053-1070. http://dx.doi.org/10.1007/s11192-017-2300-7.

Van Raan, A.F.J., 2014. Advances in bibliometric analysis: research performance assessment and science mapping In: W. Blockmans, L. Engwall, D. Weaire (Eds.). Bibliometrics: Use and Abuse in the Review of Research Performance. Wenner-Gren International Series. London: Portland Press Ltd. pp. 17-28.

Zhang, Y., Yao, X., Qin, B., 2016. A critical review of the development, current hotspots, and future directions of lake taihu research from the bibliometrics perspective. Environ Sci Pollut Res. 23, 12811– 12821.

Wang H.J., Liu, M.Y., Hong, S., Zhuang, Y.H., 2013. A historical review and bibliometric analysis of GPS research from 1991–2010. Scientometrics. 95, 35–44.

Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M., Morgan, R.P., 2005. The urban stream syndrome: current knowledge and the search for a cure. Journal of The North American Benthological Society, 24, 706-723. http://dx.doi.org/10.1899/04-028.1.

Weiner, J., 1995. On the practice of ecology. Journal of Ecology. 83, 153-158.

Wildgaard, L., 2015. A comparison of 17 author-level bibliometric indicators for researchers in Astronomy, Environmental Science, Philosophy and Public Health in Web of Science and Google Scholar. Scientometrics. 104, 873-906. Springer Nature. http://dx.doi.org/10.1007/s11192-015-1608-4.

Wong, M.H., 2003. Ecological restoration of mine degraded soils, with emphasis on metal contaminated soils. Chemosphere, 50,775-780. http://dx.doi.org/10.1016/s0045-6535(02)00232-1.

Wortley, L., Hero, J., Howes, M., 2013. Evaluating Ecological Restoration Success: A Review of the Literature. Restoration Ecology. 21, 537-543. http://dx.doi.org/10.1111/rec.12028.

Young, T.P., Petersen, D.A., Clary, J.J., 2005. The ecology of restoration: Historical links, emerging issues and unexplored realms. Ecology Letters. 8, 662-673.

Yu, H., Zhi, Z., Zhang, C., Yang, H., 2017. Research on Literature Involving Zirconia-Based on Pubmed Database: A Bibliometric Analysis. Current Science. 112, 1134. http://dx.doi.org/10.18520/cs/v112/i06/1134-1137.

CAPÍTULO 2

Bibliometric anlysis on the enzyme immobilization research[5]

[5] **Artigo publicado em:**

Pereira Gonçalves, M. C., Kieckbusch, T. G., Firmani Perna, R., Tomiê Fujimoto, J., Andres Villalba Morales, S., & Romanelli, J. P. (2018). Research on the enzyme immobilization based on bibliometric analysis. ***Process Biochemistry***. doi:10.1016/j.procbio.2018.09.016.

Abstract

In this survey, a bibliometric analysis of the global scientific production on enzyme immobilization researches was developed using Web of Science© database. The time-span comprised the period from 1991 to 2017. A total of 9,636 documents related to the subject were retrieved and analyzed according to seven main aspects: publication years, journals, countries, authors, organizations, keywords, and Web of Science categories. The results indicated that the countries with the highest number of publications were China and the United States. The most expressive international collaborative networks were evidenced between Brazil and Spain and between the USA and China. Additionally, the Spanish researchers were the ones that contributed most to this domain, while the Consejo Superior de Investigaciones Científicas and the Chinese Academy of Sciences were the most emblematic organizations. Finally, the analysis of *keywords* revealed that *biosensor*, *lipase* and *glucose oxidase* were the most cited terms among all publications, and also indicated the existence of a possible knowledge gap involving the terms *Escherichia coli, Candida rugosa lipase* and *cytochrome-c* in the context of enzyme immobilization. This study was efficient to evaluate the trends of the body of literature on enzyme immobilization research, subsidizing future decision-making in this field of science.

Keywords: Bibliometric Map; Enzymatic Immobilization; VOSviewer.

1. Introduction

During the last decade, the biotechnological industries have been seeking the improvements in enzymatic productivities and in the development of new approaches in order to satisfy current market demands to increase the lifespan of biocatalysts. These requirements are essential to assist the large-scale production and to promote economic developments (Datta et al., 2013; Hanefeld et al., 2009) and are consistent with normative legal adjustments and with principles of sustainability and green chemistry (Marconi, 1989).

Enzymes are high specificity catalysts (Barbosa et al., 2015) that, unlike the conventional chemical catalysts (Wang et al., 2009), function under mild reaction conditions (Barbosa et al., 2015; Hernandez and Fernandez-Lafuente, 2011), with high catalytic activities, regiospecificity and stereospecificity (Wang et al., 2017; Krajewska, 2004). According to the Business Communications Company, in 2016, the sales value of enzymes for industrial usage was estimated at 6 billion dollars, with a global demand annual growth of 9.1% (Singh et al., 2016).

The upgrade of enzymatic processes is an attractive alternative that can be applied to several production lines (Manecke, 1972; Perna et al., 2018), such as antibiotics (Schirmbock et al., 1994; Suzuki and Karube, 1979), biodiesel (Adlercreutz, 2013; Liese and Hilterhaus, 2013), food ingredients (DiCosimo et al., 2013; Liese and Hilterhaus, 2013; Fernandez-Fernandez and Sanroman, 2013), bioremediation (Liese and Hilterhaus, 2013), biosensors (Adlercreutz, 2013; Fernandez-Fernandez and Sanroman, 2013), synthesis of esters (Adlercreutz, 2013), hydrolysis of pectin (DiCosimo et al., 2013; Liese and Hilterhaus, 2013), enrichment of fatty acids (Adlercreutz, 2013; Liese and Hilterhaus, 2013), among others, substantiating the expansion of enzymes global consumer market (Straathof et al., 2002). Enzymatic technologies are prominent implements in obtaining products of high added value (Brady and Jordaan, 2009).

The use of enzymes in the free or solubilized form presents issues related to low operational stability, high prices, and failure in enzyme reuse and/or product recovery, among other factors. These disadvantages hamper the commercialization of enzymatic products but can be minimized when different enzyme immobilization arrangements are used (Wang et al., 2017). The immobilization consists in the entrapment of the biocatalyst in an insoluble solid support (Krajewska, 2004; Khosla et al., 2017; Bayramoğlu and Arıca, 2008) and presents advantages compared to the use of free enzymes. The benefits obtained by enzyme immobilization include gain in operational stability (Dos Santos et al., 2014), ready separation of products and biocatalysts (Khosla et al., 2017; Polakovic et al., 2017; Mateo et al., 2007), easy implementation of continuous enzymatic processes (Aguiar-Oliveira and Maugeri, 2012; Fernandez-Arrojo et al., 2013), the possibility of recovery and reuse of the enzymes (Fernandez-Arrojo et al., 2013; Ferrarotti et al., 2006), the reduction of operational costs (Fernandez-Arrojo et al., 2013; Ganaie et al., 2014) and the absence of the biocatalyst in the product stream (Platková et al., 2006).

Efficient immobilization procedures result from the holistic combination mechanisms related to the process, the biocatalyst used, the support for the immobilization and the chosen immobilization method (Cantone et al., 2013). In the past five years, some specific biocatalysts and support materials have been widely used in enzymes immobilization processes, such as laccase (Fernandez-Fernandez and Sanroman, 2013), lipase (Adlercreutz, 2013; Rodrigues et al., 2013; Moreno-Perez et al., 2017), trypsin (Rocha-Martin et al., 2017), silica (Sheldon and van Pelt, 2013), hydrogels, polymers and mesoporous materials (Sheldon and van Pelt, 2013; Zhou and Hartmann, 2013).

The most used immobilization mechanisms are physical adsorption, encapsulation, covalent bonds (Hou et al., 2014; Razmi and Mohammad-Rezaei, 2013) and cross-linking (Razmi and Mohammad-Rezaei, 2013; Chen et al., 2013). In physical adsorption, the enzymes are immobilized on the support surface by means of hydrophobic interactions, Van der Waals forces, hydrogen bonds and ionic bonds (Fernandez-Fernandez et al., 2013; Garcia-Galan et al., 2011; Zhou et al., 2012). In the encapsulation method, the inclusion of proteins occurs inside polymeric structures with pore sizes that allow the permeation of substrates and products but block the passage of the protein (Souza et al., 2016). In covalent attachment, a high stiffness is provided for the structure of the enzyme (Mateo et al., 2007; Macario et al., 2009; Miletić et al., 2009). The crosslinking, in turn, occurs between a crosslinking agent and the enzyme, which can be present in solubilized (Manecke, 1972), crystallized (Hou et al., 2014; Abraham et al., 2004), atomized (Amotz, 1987) or aggregated form (Cruz et l., 2012; Gupta et al., 2009).

Currently, enzymatic immobilization is considered the most promising technique for applications of enzymes in industrial scale, with a large potential of development and exploration (Ganaie et al., 2014). Nevertheless, although many methods have been described in patents and publications, few processes that employ immobilized enzymes have been successfully commercialized (Platková et al., 2006) due to the high operating costs associated with most bioprocesses. In this sense, it becomes useful to explore the indexed bases and apply bibliometric analysis as a tool to situate the status of research in this field, the trends and possible gaps in knowledge that involve this subject, implementing a significant role in the management and decision-making about science and technology (Flaatten, 2015; Romanelli et al., 2018).

Bibliometric analysis enables, mainly, the development of analytical methods and bibliometric indicators from statistical criteria (Rodrigues et al., 2013; Romanelli et al., 2018), besides promoting the integration of information about the development of specific research fields and whole disciplines (Song and Zhao, 2013; Merigó and Yang, 2017). It is a tool that handles records of information about publications, citations, patent documents, reports, among others (Romanelli et al., 2018; Okubu, 1997, Van Raan, 2014). In this field, the bibliometric mapping is a striking research topic (Borner et al., 2003), since it allows the visualization of indicators presented as networks (Romanelli et al., 2018; Van Eck and Waltman, 2009; Liao and Huang, 2014).

In this sense, this study has the purpose to develop a bibliometric analysis of the global scientific production that involves enzyme immobilization research in the last 27 years (1991-2017), using as database online the Web of Science©. Specifically, our study aims: (1) detecting the trends and gaps on enzyme immobilization research; (2) analyzing publication data according to publication years, journals, countries or regions, organizations, authors, Web of Science categories and keywords; and (3) demonstrating the potential of bibliometric mapping to evaluate the international collaborative network.

2. Bibliometric Methods

2.1. Data retrieval

The bibliometric analysis developed in this research was based on the online database of the Science Citation Index Expanded (SCI-E), Web of Science (WoS) (https://webofknowledge.com/). This database is usually used as a source for academic (Boanares and Azevedo, 2014) and bibliometric studies (Romanelli et al., 2018). The search expressions consisted in applying the terms "immobilized enzyme", "immobilized enzymes", "enzymatic immobilization", "enzymatic immobilisation", "enzyme immobilization", "enzymes immobilization", "enzyme immobilisation", and "enzymes immobilisation" to the "Topic" field, which seeks for words on titles, abstracts, author's keywords and WoS keywords – also called *Keywords Plus*. The search for terms between quotation marks on WoS allow to scan for publications that contain these words in an associated way and in that exact order. This strategy as well as the use of boolean operators were key factors to select the final dataset (Ştirbu et al., 2015). All retrieved publications comprised the time-span 1991 and 2017 (most studies on enzyme immobilization were published in this period - please see supplementary material for complete information - Figure 1.S). Data were downloaded on July 8, 2018.

A total of 9,636 publications were retrieved and after refinement, qualified as articles (94.55%) and reviews (5.45%). These types of documents were selected because they contain complete research results (Boudry et al., 2018). The assessment involved the following information obtained from the collected sample: (1) publication activity by years (2) Web of Science categories (3) top 40 most influent journals, (4) top 20 countries or regions, (5) top 30 most influent authors, (6) top 20 organizations and universities, and top 50 most occurring keywords. Some aspects were discussed under the time-span 27 years, 10 years and 5 years, in order to understand the trajectory of the enzyme immobilization research. Publications from England, Scotland, North Ireland, and Wales were analyzed separately (not as United Kingdom - UK). Articles from Hong Kong were included under the heading of China (Fu et al., 2013; Zhang et al., 2008).

To investigate the most popular research topics, their trends and gaps, the main author's keywords and Keywords Plus were compared. Non-repeated terms were listed and considered as emerging topics (Milanez et al., 2013). Keywords Plus provides additional search terms that are not listed among the author's keywords and consists of extracting keywords from the titles of references cited by papers (Boudry et al., 2018). Hence, we obtained a list of words, which have been separated between two groups named "generic words" (representing general terms) and "directive words" (representing specific terms). Meaningless words (also called stop words) were not taken into account. The "directive words" were used to validate this analysis through a second search on the Web of Science database. The synthesis of the methodology used in this research is presented in Figure 1.

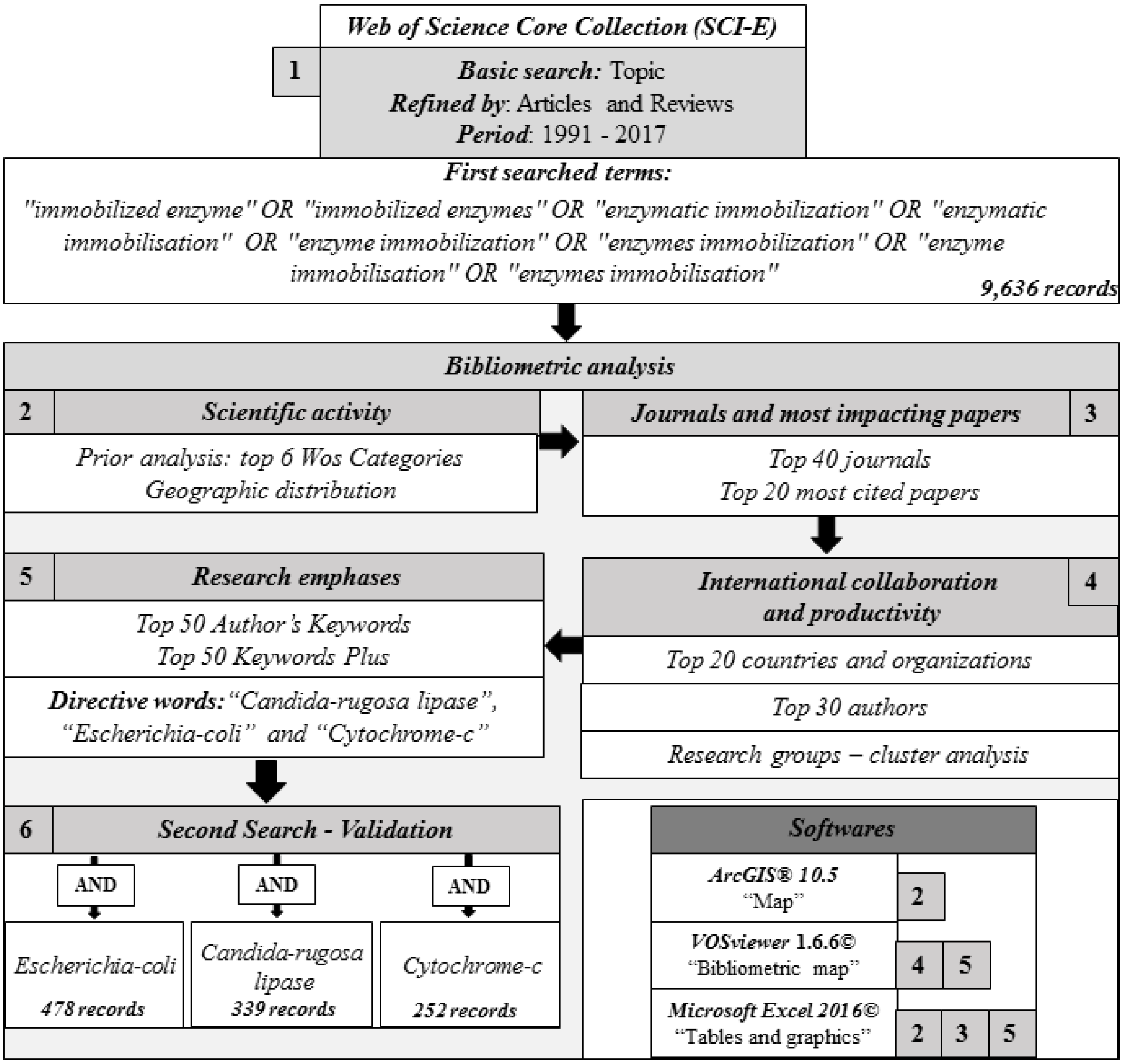


Fig 1. Synthesis of the employed methodology.

2.2. Data analysis

All analyses were performed using the "Analyzing Results" tool provided by WoS with MS Excel support (v. 2016) to perform calculations and to develop graphs (visualization of bibliometric indicators) using the following information: i) number of publications, ii) number of citations iii) impact factor (for journals) and iv) h-index (for journals and authors). The impact factor of journals (IFs) was analyzed according to the Journal Citation Report (JCR, 2017) (Hirsch, 2004).

The bibliometric analysis of the international collaborative network was generated by VOSviewer© software version 1.6.8 (www.vosviewer.com), to scrutinise how countries, research institutions, universities, and authors have been performing in this area. This software presents clustering functionalities of network considering the strength of the connection between items (Merigó and Yang, 2017). The graphical representation was based on the co-authorship criteria. Items scored with the same number of publications records had the number of citations as ranking classification criteria.

The cartographic analysis of the spatial distribution of the most productive countries on enzyme immobilization research was categorized according to the most expressive intervals in the number of publications and was developed through ArcGIS® 10.5 software. Finally, the authors' affiliation analysis was based on the "authors' information" contained in the most recent publications and may not represent all of their academic links.

3. Results and Discussion

3.1. Publication outputs: general results

Since 1991 the studies in the field of enzyme immobilization have reached a mark of more than 200 annual publications, which shows the wide scope and outstanding importance of this area in the international scientific community. Currently, the body of literature related to this subject involves a vast description of different methodologies (Brady and Jordaan, 2009).

In general, most of the publications on this topic were related to six main categories according to the Web of Science Categories: *Biotechnology Applied Microbiology, Chemistry Physical, Chemistry Analytical, Engineering Chemical, Biochemistry Molecular Biology* and *Chemistry Multidisciplinary*. Figure 2 shows the evolution of the number of publications on enzyme immobilization researches considering the period 1991 to 2017. Until 1991 the number of publications was inferior to 50 articles per year; nonetheless, this number increased gradually and today reached around 650 annual outputs (2017). These numbers might indicate a growing interest in researches as a consequence of innovation in enzyme immobilization techniques, as well as of the rise in the number of patent requests (Brady and Jordaan, 2009). The six main categories of WoS showed in Figure 2 have been playing a relevant role in the development of this subject and evidence that this topic is in continuous ascension over the last years.

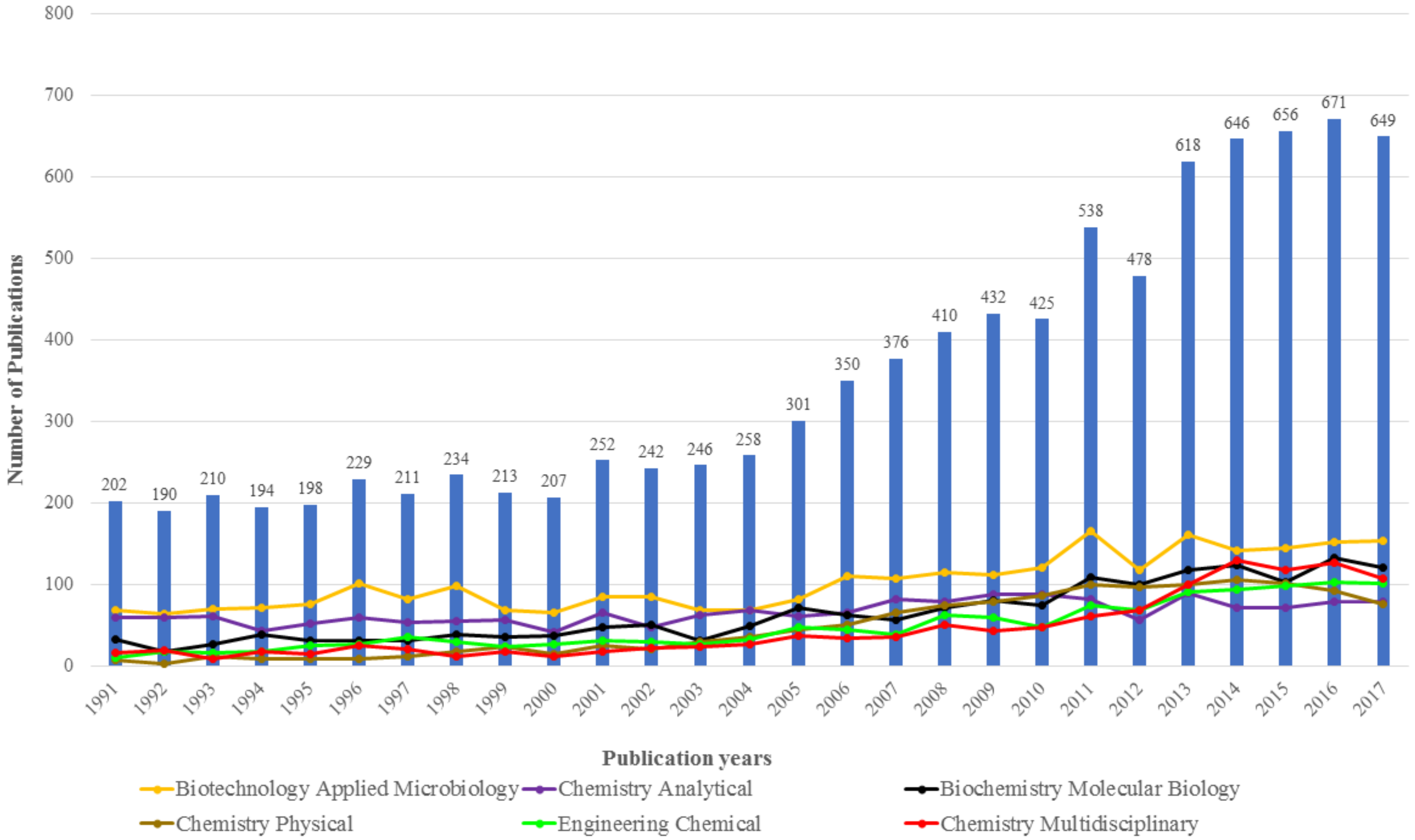
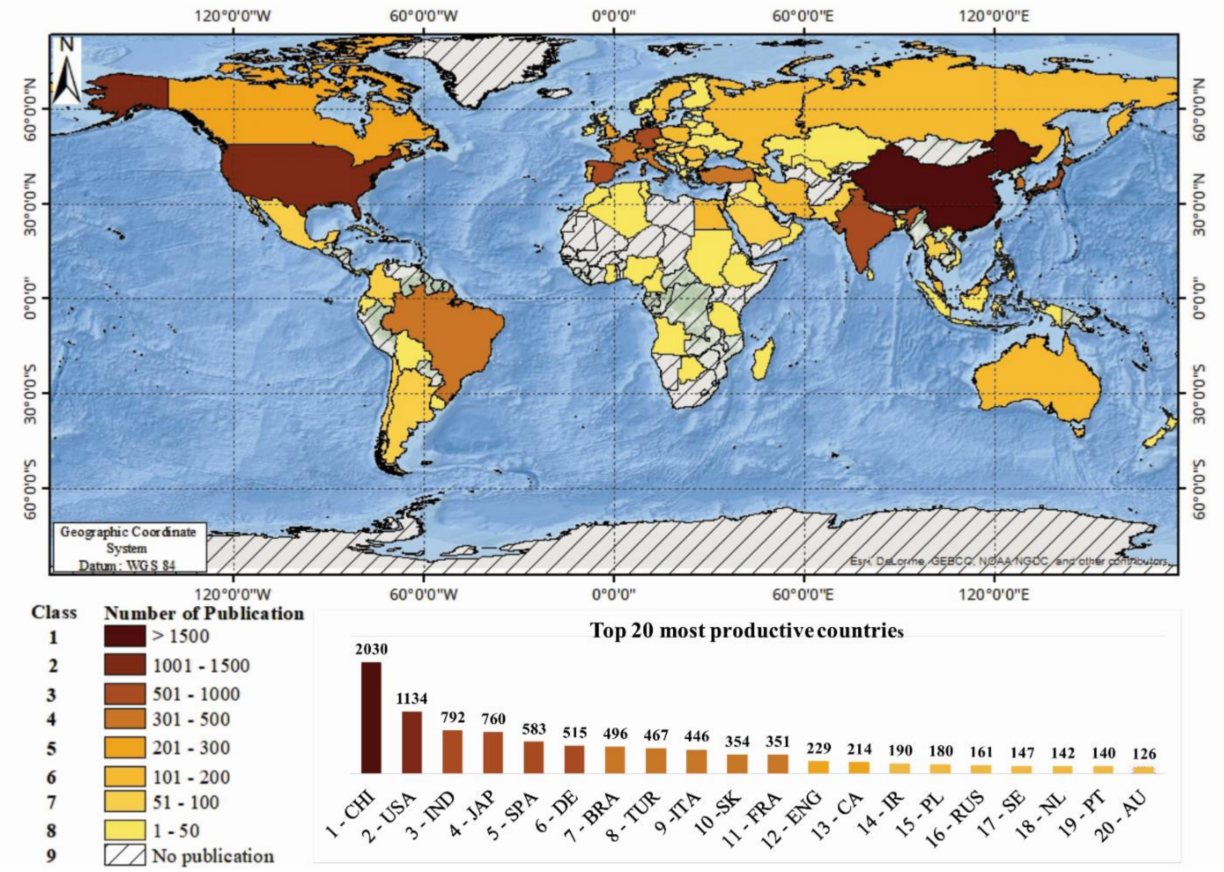


Fig 2. Total publications from WoS Core Collection (SCI-E) enzyme immobilization from 1991 to 2017 and association to the growth trends of the top six main WoS categories.

Research on enzyme immobilization has shown to be relevant all over the world, covering 92 different countries in the last 27 years. The list of the top 20 countries ranked by the number of publications and categorized in classes is shown in Figure 3. In general, researches in this domain show a relative heterogeneity in terms of the number of publications among the countries. Class 1, for example, is composed only by China (>1500 articles published in the last 27 years), representing approximately 21% of the total publications in this field. Class 2 (1001-1500 publications) contains only the United States and represents 12% of all records in the category. China and the USA have been playing a relevant role in the research on enzyme immobilization. This tendency can be attributed, among other aspects, to the strong economic influence of these countries and the massive investment in the fields of research, development, and innovation (Lee, 2013; Nooruddin and Pauton, 2010).

Class 3 (501–1000 documents) contains members from two different continents, among them, India, Japan, Spain and Germany, and class 4 (301–500 documents) has as members Brazil, Turkey, Italy, South Korea and France. Class 5 (201-300 documents) is composed by England and Canada, while Class 6 (101-200 documents) holds Iran, Poland, Russia, Sweden, Netherlands, Portugal, Australia, Egypt, Austria, Romania, and Malaysia. Class 7 (51 - 100 publications) is composed by fifteen countries: Mexico, Czech Republic, Switzerland, Hungary, Singapore, Belgium, Bulgaria, Pakistan, Denmark, Saudi Arabia, Chile, Argentina, Colombia, Israel, and Thailand. Finally, the last class, Class 8 (1-50 publications), contains the largest number of members, totalizing 53 countries, i.e., 58% of all countries listed. The ranking of the twenty most productive countries is also listed in Figure 4.



CHI= China, USA= United States of America, IND= India, JAP= Japan, SPA= Spain, DE= Germany, BRA= Brazil, TUR= Turkey, ITA= Italy, SK= South Korea, FRA= France, ENG= England, CA= Canada, IR= Iran, PL= Poland, RUS= Russia, SE= Sweden, NL= Netherlands, PT= Portugal, AU= Australia.

Fig. 3. Global geographic distribution according to the total number of publications.

3.2. Distribution of articles in different journals

The survey identified 874 different journals that have published results on enzyme immobilization researches in the last 27 years. Nevertheless, approximately 92% of these journals did publish less than 20 articles. Table 1 shows the 40 main journals in the category. These journals hold around 48% of all publications, ranking them based on relevance in researches in this domain.

The periodical *Journal of Molecular Catalysis B Enzymatic* was the most proliferant, publishing around 4.30% of all publications with 5.10% of the total citations, followed by *Enzyme and Microbial Technology* (3.10% of the publications and 4.98% of the citations) and *Biosensors Bioelectronics* (2.56% of the publications and 4.97% of the citations).

However, *Biosensors Bioelectronics* has the highest impact factor (7.291) as well as h-index (57) among the 3 most influent periodicals in this area. The h-index indicate (in this case) that 57 papers in this journal had effectively 57 citations or more. It is worth mentioning that the number of citations shows the total number of references cited between 1991 and 2017 of all items found in the WoS citation report.

Please, Insert Table 1 here

An analysis of the list in Table 1 reveals that 40% of the most productive journals are from Netherlands, 30% from United States, 15% from England, 12.5% from Germany and 2.5% from Switzerland. Therefore, around 70% of the publications are associated with European journals, and the others (30%) are related to American journals.

However, in the past 5 years, the order of the most influential journals has changed (please, see supplementary material - Table 1.S). Currently, according to the number of publications, the first position in the rank is occupied by the journal *RSC Advances*, followed by the *Journal of Molecular Catalysis B Enzymatic* and *Process Biochemistry*, which occupied the tenth, first and fourth places in the former classification in Table 1, respectively. Regarding the number of citations, the most cited journal remains the *Journal of Molecular Catalysis B Enzymatic* (2nd highest h-index), followed by *RSC Advances* and *Biosensors Bioelectronics*. The journal *Biosensors Bioelectronics* still occupy it position as the highest h-index among the 40 most influential journals (HI = 21) and has now he third largest impact factor (IF = 7.291).

Still considering the publications trend in the last 5 years, the journal with the highest impact factor (*ACS Catalysis*) occupies the 34th position in terms of number of publications concerning enzyme immobilization, along with *ACS Applied Materials & Interfaces* (7th position). On the other hand, *Enzyme and Microbial Technology* (2nd place in the ranking of publications and citations in the last 27 years) is now on the 10th position.

3.3. Most cited papers

The analysis of the 20 most cited publications in the last 27 years (Table 2) indicated that there is no close relationship between the most productive journals and the publications that have accumulated more citations in this field. Citation analysis in bibliometrics studies has been established as an indicator of the paper's quality and as the main contribution from an individual work (Garfield, 1979). It is worth mentioning that the earliest scientific researches tend to be more cited, which is related to their indexing time. On the other hand, items that have been recently published and have already many citations may indicate new perspectives in the field (Okubo, 1997).

The most cited papers regarding enzyme immobilization have addressed the main immobilization approaches and the types of supports used. The most employed methodologies for enzyme immobilization were: physical adsorption (Rodrigues et al., 2013; Garcia-Galan et al., 2011; Cosnier, 1999), attachment to a prefabricated support (Sheldon, 2007), encapsulation in polymeric matrices (Sheldon, 2007; Cosnier, 1999; Sheldon and van Pelt, 2013), reticulation (Sheldon and van Pelt, 2013; Cosnier, 1999), covalent bonding (Garcia-Galan et al., 2011; Cosnier, 1999) and electrospinning (Bhardwaj and Kundu, 2010; Agarwal et al., 2008). Regarding the supports used, enzymes have been immobilized, mainly, in mesoporous structures (Sheldon and van Pelt, 2013; Lai et al., 2003; Hartmann, 2005), materials based on chitin (Krajewska, 2004), chitosan (Sheldon and van Pelt, 2013; Kang et al., 2009) and graphene (Kang et al., 2009), in porous carbon materials (Lee et al., 2006), polymeric surfaces (Cosnier, 1999; Goddard and Hotchkiss, 2007), micro and nanotubes (Martin and Kohli, 2003), silicas and hydrogels (Sheldon and van Pelt, 2013). Studies involving the use of porous alumina and polymeric membranes filter as models to synthesize nanostructures (Lakshmi et al., 2007) were also presented, as well as the application of a polydopamine surface coating that provides chemical activation at the surfaces of materials (Lee et al., 2009). Most of these researches have contributed with literature reviews, presenting strategies to optimize the enzymatic attributes during the application of immobilization protocols.

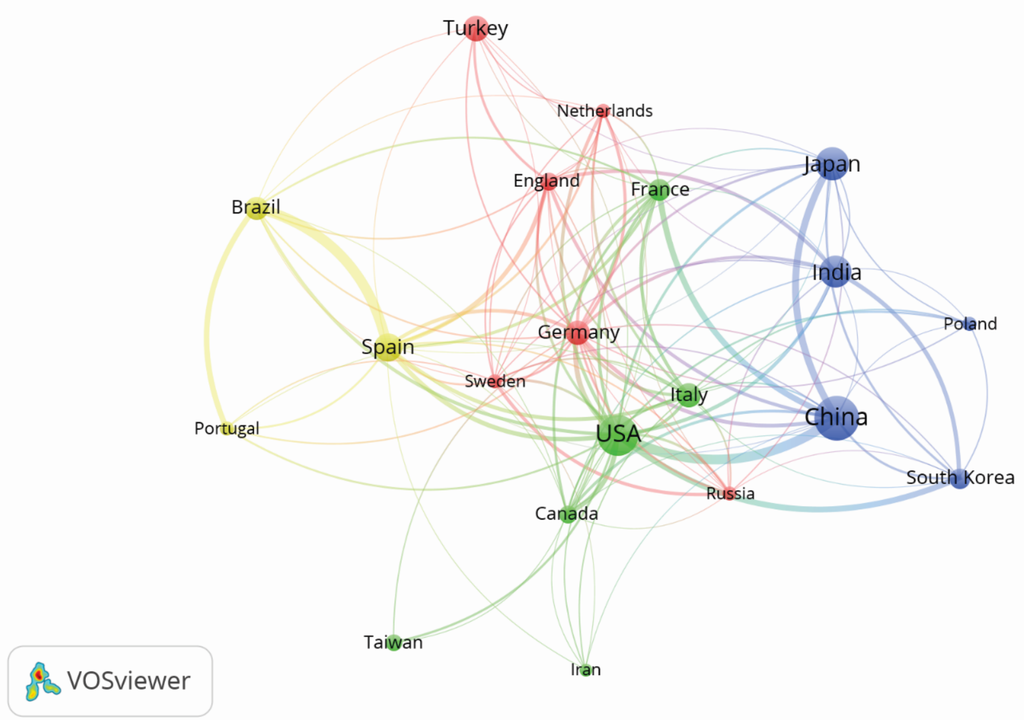
Please, Insert Table 2 here

The most cited article (Mateo et al., 2007) indicated in Table 2 received 1,600 citations and was published in *Enzyme and Microbial Technology* (IF 2.932), which holds the second position among the 40 more productive journals of our research. This article is a review of the literature that approaches different strategies to enhance the functional properties of the enzymes during the enzyme immobilization. This paper was written by the Spanish authors C Mateo, JM Palomo, G Fernández-Lorente, JM Guisan and R Fernandez-Lafuente. In addition, two other articles produced by the same Spanish research group are also present in Table 2. The scientific contribution of these publications is related to advances in enzymatic immobilization techniques to improve their catalytic performance (Rodrigues et al., 2013; Garcia-Galan et al., 2011). These last two articles were published in *Chemical Society* (IF 40.182) and *Advanced Synthesis & Catalysis* (IF 5.123).

3.4. International collaboration

The international collaborative network that involves the subject enzyme immobilization was evaluated from the co-authorship analysis for countries, organizations, and authors presented in Figures 4, 5 and 6, respectively. Data on authors are also presented in Table 3. The results were analyzed cooperatively to acknowledge any consistent trend in the literature. The bibliometric mapping concerning the collaborative network was limited to the output of the twenty main countries and organizations, and the thirty main authors. In the networks shown in Figures 4, 5 and 6 the sizes of the nodes are proportional to the number of publications and the thickness of the edges and the colors indicate which cluster the item belongs to.

The twenty most productive countries accounted for 96.83% of all publications and 99.35% of the citations. The top twenty of the most productive institutions made up 18.58% of the total registrations and 18.31% of the citations among the 2,973 organizations that have published researches on this subject. The most productive authors during the last twenty-seven years of research in this field (Table 3 and Tables 5.S and 6.S – please, see supplementary material) represented around 13.60% of the publications and 21.37% of the citations, among 15,194 authors with publications in this area.

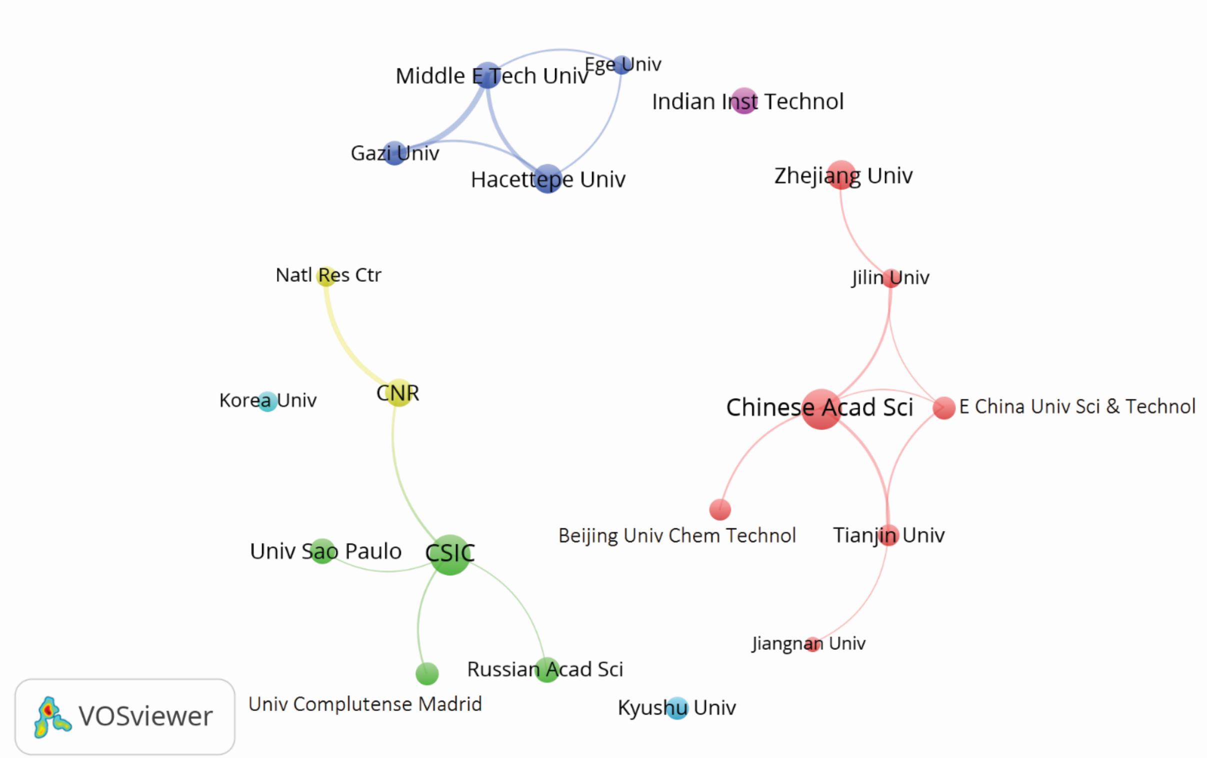


Rank	Cluster 1 (Red)	NP(1)	NC(2)
6	Germany	515	14,707
8	Turkey	467	10,135
12	England	229	6,510
17	Russia	161	2,316
18	Sweden	147	4,924
19	Netherlands	142	6,730
Rank	**Cluster 2 (Green)**	**NP(1)**	**NC(2)**
2	USA	1,134	45,476
9	Italy	446	11,344
11	France	351	10,025
13	Taiwan	224	5,167
14	Canada	214	5,703
15	Iran	190	2,899

Rank	Cluster 3 (Blue)	NP(1)	NC(2)
1	China	1,806	36,638
3	India	792	17,765
4	Japan	760	15,949
10	South Korea	354	8,876
16	Poland	180	4,057
Rank	**Cluster 4 (Yellow)**	**NP(1)**	**NC(2)**
7	Brazil	496	10,448
20	Portugal	140	3,586
5	Spain	583	18,917

NP=Number of publications. NC= Number of citations.

Fig. 4. Network visualization map for the collaboration among the twenty most productive countries in enzyme immobilization, according to the number of publications and citations, considering the time-span 1991 - 2017. The thickness of the link between any two countries is indicative of the extent of co-authorship (e.g., collaboration), and the colors indicate groups of countries with a high degree of collaboration (cluster).



Rank	Cluster 1 (Red)	C	$NP^{(1)}$	$NC^{(2)}$
1	Chinese Acad. Sci.	CHI	236	6,349
4	Zhejiang Univ.	CHI	102	2,884
9	Beijing. Univ. C. T.	CHI	74	1,445
11	Tianjin Univ.	CHI	68	1,221
12	E. China Univ. Sci. T.	CHI	66	1,512
16	Jilin Univ.	CHI	63	1,176
19	Jiangnan Univ.	CHI	59	779
Rank	**Cluster 2 (Green)**	**C**	**$NP^{(1)}$**	**$NC^{(2)}$**
2	CSIC	SPA	221	10,247
3	Univ. Sao Paulo	BRA	118	1,925
8	Russian Acad. Sci.	RUS	76	862
18	Univ. Compl. Madrid	SPA	60	1,223

Rank	Cluster 3 (Royal Blue)	C	$NP^{(1)}$	$NC^{(2)}$
6	Hacettepe Univ.	TUR	85	2,304
10	Middle E. T. Univ.	TUR	72	1,619
15	Gazi Univ.	TUR	64	1,682
20	Ege Univ.	TUR	57	613
Rank	**Cluster 4 (Yellow)**	**C**	**$NP^{(1)}$**	**$NC^{(2)}$**
5	CNR	ITA	93	1,811
13	Natl. Res. Ctr.	EGY	66	1,107
Rank	**Cluster 5 (Purple)**	**C**	**$NP^{(1)}$**	**$NC^{(2)}$**
7	Indian Inst. Technol.	IND	84	3,718
Rank	**Cluster 6 (Turquoise Blue)**	**C**	**$NP^{(1)}$**	**$NC^{(2)}$**
14	Korea Univ.	SK	65	1,104
Rank	**Cluster 7 (Blue)**	**C**	**$NP^{(1)}$**	**$NC^{(2)}$**
17	Kyushu Univ.	JAP	61	1,054

C= Countries, NP=Number of publications. NC=Number of citations.

Fig. 5 Network visualization map for the collaboration among the twenty most productive organizations on enzyme immobilization research according to the number of publications and citations, considering the time-span 1991 - 2017. The thickness of the link between any two countries is indicative of the extent of co-authorship, and the colors indicate groups of countries with a high degree of collaboration (cluster).

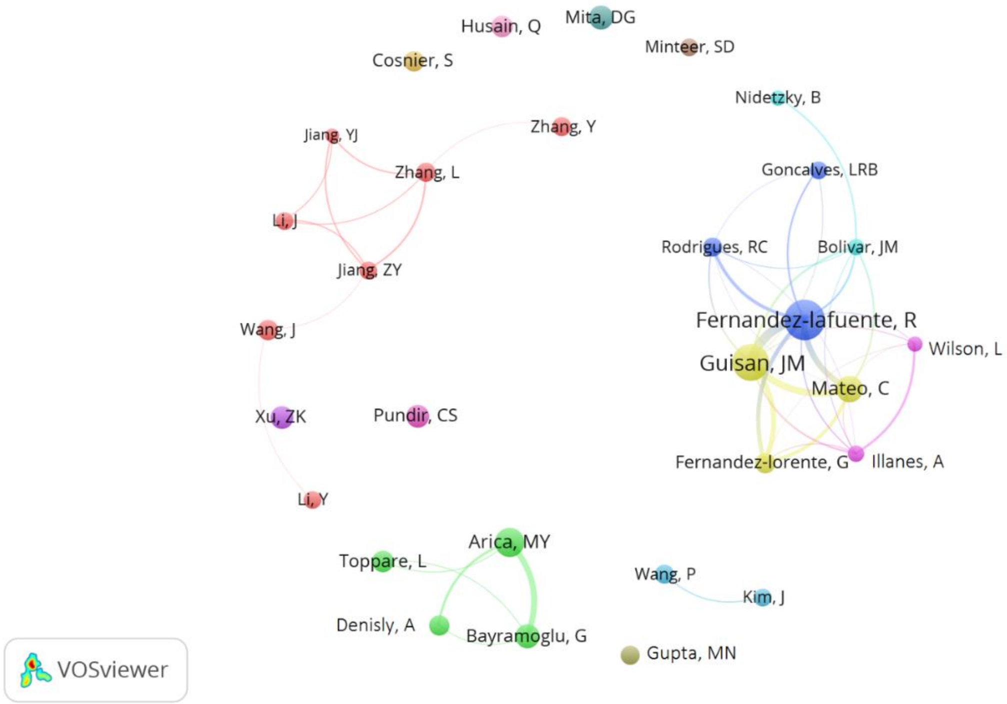


Fig. 6 Network visualization map for the collaboration among the thirty most productive authors on enzyme immobilization research according to the number of publications and citations, considering the time-span 1991 - 2017. The thickness of the link between any two countries is indicative of the extent of co-authorship, and the colors indicate groups of countries with a high degree of collaboration (cluster).

Please, insert Table 3 here

The arrangement of Figure 4 reveals the existence of 4 clusters of collaboration among the 20 most productive countries in enzyme immobilization studies. Cluster 1 is composed of European and Euro-Asian countries, suggesting a collaborative network between these continents. In Cluster 2, the USA produced research work with all the other members of the top twenty countries listed in Figure 4.

Cluster 3 represents a close collaborative network between China and Japan, the largest co-authoring countries (27 papers) in this cluster. Although China and the USA are placed in different clusters, the two countries that have accumulated more publications according to Figure 4, have established a collaborative network with 46 co-authorships between them.

Cluster 4 evidences a steady partnership among South America (Brazil) and Europe (Spain and Portugal), especially between Brazil and Spain, which have 49 papers published as co-authorship.

The bibliometric mapping of the twenty most productive organizations (Figure 5) reveals the existence of 7 clusters of collaboration. Cluster 1 is composed, exclusively, by Chinese organizations, evidencing a restrict internal collaborative network aside the other top twenty members. A more expressive collaborative network was observed between Cluster 2, which are composed of Brazilian, Spanish and Russian institutions, and Cluster 4, composed of Italian and Egyptian organizations. Cluster 3 contains only Turkish institutions and also without collaborative network with any other clusters of the top twenty. The remaining clusters (5, 6 and 7), in turn, are not inserted in collaborative networks with the other institutions presented in Figure 5.

The most fruitful collaborative network among organizations in the top twenty was established between Gazi University and Middle East Technical University (12 records), both in Turkey (Cluster 3), and between the Consiglio Nazionale delle Ricerche - CNR (Italy) and the National Research Centre (Egypt), with 10 records (Cluster 4).

The number of publications collected in Figure 5 point out that the Chinese Academy of Sciences (CAS - China) is the most productive organization in this field, followed by the Consejo Superior de Investigaciones Científicas (CSIC - Spain). However, considering the number of citations, CSIC ranked first, followed by CAS, Indian Institute of Technology (India), Zhejiang University (China) and Hacettepe University (Turkey).

China holds the largest number of the cited organizations (seven organizations) among the twenty most productive ones, followed by Turkey, with four institutions. Notwithstanding the fact that USA is rated as second in the ranking of countries with the largest number of publications, no North-American institution made the list in Figure 5.

The map of international collaborative networks presented in Figure 5 is limited to the most productive organizations regarding enzyme immobilization research. It is worth mentioning, however, that there are other kind of partnerships between organizations that also contributed in developing and disseminating knowledge on this topic. The Spanish organization CSIC, for example, is engaged in collaborative network with countries in America, mainly Latin American. A growing number of co-publications could be identified between CSIC and the following Brazilian universities: UFRGS – Universidade Federal do Rio Grande do Sul, UFC – Universidade Federal do Ceará, UFRJ – Universidade Federal do Rio de Janeiro, UFscar – Universidade Federal de São Carlos, UNIFAL – Universidade Federal de Alfenas, UERGS – Universidade Estadual do Rio Grande do Sul, UNILAB - Universidade da Integração Internacional da Lusofonia Afro-Brasileira and UNESP – Universidade Estadual de São Paulo, besides USP – Universidade de São Paulo, as already indicated in Cluster 2 (Figure 5).

The two Colombian organizations Universidad Industrial de Santander and Universidad de Tolima also have publications in partnership with CSIC. In addition, coauthored publications can be identified between the Spanish organization and Mexican universities, such as Universidad de Guadalajara, Consejo Nacional de Ciencia y Tecnologia - CONACYT, Instituto Tecnológico de Veracruz and Universidad Autónoma Metropolitana, in Mexico City.

Spain and Chile also established important collaborative networks, such as CSIC and Pontificia Universidad Católica de Valparaíso, Universidad de Chile and Universidad de Antofagasta. Finally, coauthored publications were identified between CSIC and Uruguayan universities, such as the Universidad de La República and Universidad ORT. As a consequence, the international collaborative network boosted CSIC to the first and second position in terms of the number of citations and publications, respectively, as indicated in Figure 5.

The bibliometric mapping of the international collaborative network of the thirty most productive authors (Figure 6 and Table 3) reveals that the Spanish author R Fernandez-Lafuente is the most influent researcher, followed by JM Guisán (Spain). These authors are responsible for the highest number of publications, citations and h-indexes in enzyme immobilizations researches. Considering only the ranking of publications, MV Arica (Turkey) and C Mateo (Spain) occupy the third and fourth positions, respectively. With regard to the number of citations, C Mateo and G Fernandez-Lorente (Spain) appear in the third and fourth places, who occupy the 4^{th} and 10^{th} positions in the rank according to the number of publications, respectively. With the exception of MV Arica, all these authors are Spanish and linked to the same research group at Consejo Superior de Investigaciones Científicas (CSIC).

A set of 14 collaborative clusters was assembled among the main authors. Figure 6 indicated that Clusters 1 and 2 are solely composed by Chinese and Turkish authors, respectively, and they did not create a collaborative network with any other clusters formed by the top thirty authors, which might limit the coverage of the research focus. On the other hand, between Clusters 3, 4, 5 and 6, the most expressive international collaborative network was held, involving researchers from Brazil, Spain, Chile and Austria, mainly between the Spanish authors R Fernandez-Lafuente and JM Guisán (65 records), C Mateo and JM Guisán (44 records), who detain the highest number of partnerships among the top thirty authors, both of them working at CSIC.

The partnerships between the Spanish author R Fernandez-Lafuente and the Brazilian authors RC Rodrigues (17 records) (UFRGS – Universidade Federal do Rio Grande do Sul) and LRB Gonçalves (8 records) (UFC – Universidade Federal do Ceará), in Cluster 3, is also noteworthy. Clusters 7 to 14 operated as a very restricted collaborative network. These clusters contain one or two members and have no co-authored papers with any others of the top thirty authors.

Inspecting the main organizations (Figure 5) and the research institutions of the most productive authors in the area of enzyme immobilization, 17 researchers affiliated to organizations in the top institutions were identified, confirming a close relationship between publication records and number of citations attributed to each country and also the collaborative network established between the organizations and the most productive authors. Among the thirty authors listed, 10 are Chinese, 4 Spanish, 3 Turkish, 3 Indians, 2 Brazilians, 2 Chilean, 2 Austrians, 1 South-Korean, 1 French, 1 Italian and 1 American. These numbers can explain why China is the country that holds the higher number of publications on enzyme immobilization research. Nonetheless, some of the most productive organizations and authors indicated by the bibliometric mapping (Figures 5 and 6, respectively) are Spanish, which might be justified by the fact that the most expressive international collaboration clusters were established between researchers and institutions of this country. Furthermore, it must be highlighted that the results of the collaborative networks are more evident for the most productive countries due to the broader dissemination of publications with co-authorship published between authors and the organizations associated to them.

3.5. Bibliometric indicators trajectory: 27 years, 10 years and 5 years

In order to evaluate the bibliometric indicators trajectory on enzyme immobilization research, a comparative analysis was performed based on the thirty most productive authors in this field taking the last 27, 10 and 5 years into account (for complete information, please see Table 3 and supplementary material - Tables 5.S and 6.S). The purpose of this analysis is only exploratory, not exhaustive, seeking to detect some trends concerning these indicators along the years. The bibliometric research did not detect significant changes in these indicators when comparing the three time-spans considered in this research and showed that the most productive author in regard to number of publications, citations, and h-index is the Spanish R Fernandez-Lafuente, linked to CSIC. In all the three periods covered in this study, the main collaborative networks were identified between this researcher and Brazilian authors, such as RC Rodrigues, JCS dos Santos and LRB Gonçalves, Spanish authors such as JM Guisán, C Mateo and G Fernández-Lorente, who are also members of CSIC, and C Ortiz and R Torres, who are members of Universidad Industrial de Santander, Colombia.

In the last 27 years, JM Guisán has occupied the second position in the ranking of number of publications accumulated and also in number of citations of these scientific papers.

Considering these same bibliometric indicators in the scenario of the last 10 and 5 years, this author still occupied the second place according to the number of publications, however, based on the number of citations, this position gots to the Brazilian author RC Rodrigues, who has publications in co-authorship with the Spanish R Fernández-Lafuente and is affiliated to the Universidade Federal do Rio Grande do Sul (UFRGS), oddly enough, an institution not listed among the top twenty organizations (Figure 5).

The three most cited authors over the last 27 years (R Fernandez-Lafuente, JM Guisán and C Mateo) are affiliated to the same institution (CSIC) and constitute among themselves an expressive collaborative network, with many papers co-authored between R Fernandez-Lafuente and JM Guisán (65 records), JM Guisán and C Mateo (44 records) and R Fernandez-Lafuente and C Mateo (36 records).

A comparison of the accumulated results (27 years) and the production in the last 10 and 5 years (Table 3 and Tables 5.S and 6.S), indicates that only the authors R Fernandez-Lafuente and JM Guisán continued among the top five positions in the number of publications ranking. In the last 10 years scenario, newcomers with a large number of publications in the field of enzyme immobilization have emerged, such as: J Li, Chongqing University, China (0.76% of publications); RC Rodrigues, Universidade Federal do Rio Grande do Sul, Brazil (0.69% of publications) and YJ Jiang, Hebei University, China (0.67% of publications). For the past 5 years, the only author included in the first five positions who was not present in the previous analysis (10 years) is the Brazilian JCS dos Santos, Universidade Federal do Ceará (0.83% of publications).

The number of citations followed the same trend observed with the number of publications. New authors who have not been listed in the top five positions in the last 27 years span have now emerged in the last 10 years' analysis, such as J Liu, Chinese Academy of Sciences, China (1.48% of citations); G Bayramoglu, Gazi University, Turkey (1.08% of citations) and MV Arica, Gazi University, Turkey (1.08% of citations). In the past 5 years scenario, authors such as C Ortiz, Universidad Industrial de Santander, Colombia (3.55% of citations); R Torres, Universidad Industrial de Santander, Colombia (3.39% of citations) and O Barbosa, Universidad del Tolima, Colombia (2.28% of citations) were also ranked among the top positions in the ranking.

It is worth mentioning that there is a considerable difference between the number of citations of the main author (R Fernandez-Lafuente) and the remaining ones in the list. When analyzing the shorter time-spans (10 and 5 years) this difference becomes even larger. This fact may be attributed to the inclusion of new authors in the first positions of the ranking, who in some cases belong to the same research groups, while some researchers very prominent during the last 27 years left the best positions. Among these emerging authors some new research groups influential in the area were identified, as is the case of the groups of J Li and YJ Jiang; G Bayramoglu and MV Arica; and C Ortiz, R Torres, O Barbosa, JCS Dos Santos and RC Rodrigues, which have significantly contributed to compose the current scenario of enzymatic immobilization.

The rankings analyzed and presented in this research are influenced by the coverage of articles and citations from a single database (WoS). Therefore, the calculation of bibliometric indicators shows the visibility of these academic results in a specific area, not representing all the impact on the academic community (Wildgard, 2015). Consequently, the analysis of other indexed databases and the use of other search terms could introduce changes in the trends found as well as in the configuration of the collaborative networks that can be induced, among other aspects, by new research scopes over the years.

The 40 most cited papers published in the last 27, 10 and 5 years (please, see supplementary material - Tables 2.S, 3.S, and 4.S) were related to the main authors who pointed out innovations on the subject of enzymatic immobilization. The article that occupies the first place in the ranking of Table 2 (27 years) is a literature review co-authored by C Mateo, G Fernandez-Lorente, JM Guisan and R Fernandez-Lafuente (4^{th}, 10^{th}, 2^{nd}, and 1^{st} place in the ranking of Table 2, respectively). The research titled "Improvement of enzyme activity, stability and selectivity via immobilization techniques" was written by the Spanish researchers linked to CSIC.

In the past ten years, a paper by RC Rodrigues (Brazil) and R Fernandez-Lafuente (Spain) (4^{th} and 1^{st} places in Table 5.S) advanced from the twelfth position (Table 2) to the fifth place (Table 3.S), and, in the last five years, it reached the first position in the rank (Table 4.S). The paper is also a review and deals with modifications of enzymatic activity and selectivity by immobilization techniques.

3.6. Enzyme immobilization by keywords analysis

In order to investigate the trajectory of researches on enzyme immobilizations, an analysis of the main keywords used by the authors in their publications was performed, in order to provide information of the central topics of the researches (González-Sala et al., 2017; Liu et al., 2011; Wang et al., 2013). The top 50 main *author's keywords* and *keywords plus* (Table 4) were compared to detect trends and possible gaps of knowledge related to the subject. In the past 27 years, around 10,100 *author's keywords* were used to characterize the enzyme immobilization research, which suggests the existence of a great diversity of research focuses.

Please, Insert Table 4 here

Ignoring the obvious three words associated to the "searched terms" (immobilization, enzyme immobilization and immobilized enzyme), the terms *biosensor*, *lipase* and *glucose oxidase* were the most cited author keywords, representing around 9.50% of all occurrences. These results suggest that a great deal of the retrieved publications involved aspects of immobilization of the enzymes lipase and glucose oxidase, associated to the development of biosensors (Wang et al., 2017; Razmi and Mohammad-Rezaei, 2013; Chen et al., 2013; Devasenathipathy et al., 2015; Parente et al., 1992; Herrera-López, 2012; Kartal et al., 2007). In this sense, it is worth mentioning that, currently, immobilization methods have been widely used to develop optical, electrochemical or gravimetric enzyme biosensors (Wang et al., 2017; Razmi and Mohammad-Rezaei; Phadke, 1992; Sassolas et al., 2012).

A comparative analysis of the main *author's keywords* and *keywords plus* (Table 4) was also performed. Comparing these two groups, the output in Table 4 indicate that many *keywords* are repeated between these two groups and that some of them, despite different spelling, are synonyms. In this way, the replicated expressions were separated, and the keywords that did not repeat were selected for a more precise analysis. After this procedure, the following words could be considered generic: *protein, purification, electrode, system, sensor, support, membrane, stabilization, oxidase, nanoparticles, organic-solvents, acid, beads, films, surface, microspheres, oxidation, silica, reactor, binding, particles, encapsulation, optimization, biosensor,* and *matrix*. The terms considered as directive are *Candida rugosa lipase, Escherichia coli, and cytochrome-c*.

The concept "directive terms" might suggest gaps of knowledge, since they appear profusely as *keywords plus* (words extracted by WoS from cited papers - titles and abstracts), and, therefore are meaningful terms in this domain, but were not included as *author's keywords*, which indicates they are not the main subject of the study. Hence, the terms *Candida rugosa lipase, Escherichia coli,* and *cytochrome-c* might represent incipient investigations in the global context of enzyme immobilization currently reported in the literature with applications in different types of enzyme preparations (Domínguez de María et al., 2006; Chen et al., 2011; Dyal et al., 2003; Chiou and Wu, 2004; Chang et al., 1994; Soares et al., 1999; Dalmau et al., 2000; Knezevic et al., 2006; Huang et al., 2011; Muralidhar et al., 2001; Arica et al., 2010;

Perna et al., 2017; Bennett et al., 2009; Lehman et al., 1957; Duerre and Ribi, 1963; Beacham et al., 1976; Jardine et al., 2002; Mauve et al., 2016; Fergunson et al., 2016; Zhu et al., 2016; Shah and Duncan, 2015; Planta et al., 2017; Yoo et al., 2017; Alleyne et al., 2017; Li et al., 2016; Khokhlova and Zubareva, 2015; Zsengeller et al., 2014; Barathi and Kumar, 2013).

In addition, a second search was performed in Web of Science database combining the eight terms described previously in bibliometric methods, with the directive words *cytochrome-c*, *Candida rugosa lipase* and *Escherichia coli* in order to validate what was pointed out with the use of these terms. In fact, among all the 9,636 publications, only 252 documents were retrieved with *cytochrome-c*, which represents only 2.61% of all publications; 339 documents in the second case (3.52%) and 478 documents for *Escherichia coli* (4.96%). These results confirm the relatively low occurrences of these "directive words" on the domain of enzyme immobilization.

To investigate whether the trend among the main author-keywords pointed out by bibliometric analysis is altered when considering different time-spans, Tables 4, 7.S and 8.S (please see in the supplementary material) were composed, which list the top fifty author-keywords during the past 27, 10 and 5 years of researches on enzyme immobilization.

The author-keywords with the highest number of occurrences for the past 27, 10 and 5 years were *lipase* and *glucose oxidase* (Yücel et al., 2011; Mislovičová et al., 2007; Pereira et al., 2003; Gricajeva et al., 2018; Lee et al., 2007; Sun et al., 2015; Zhang et al., 2011; Foulds and Lowe, 1988; Bulmus et al., 1997; Valentová et al., 1981) associated with the use of *chitosan*, a material widely used as immobilization matrix for several enzymes, such as fructosyltransferase (Ganaie et al., 2014), lipase (Melo et al., 2017; Elias et al., 2017; Baghban et al., 2017; Cubides-Roman et al., 2017; Bayramoğlu, 2017), glucoamylase (Amirbandeh et al., 2017), laccase (Alver and Metin, 2017), oxidase (Wang and Koo, 2017), trypsin (Mondal et al., 2017), among others.

Biosensors have also been pointed out in the bibliometric research as one of the recurrent author-keywords on enzyme immobilization. Currently, one of the main applications of immobilized enzymes are biosensors, which are devices assembled by the co-immobilization of enzymes in a miniaturized electrode using electropolymerization (Scouten et al., 1995). The development of biosensors based on lipase and glucose oxidase is receiving increasing attention (Wang et al., 2017; Razmi and Mohammad-Rezaei, 2013; Devasenathipathy et al., 2015; Herrera-López, 2012) and may be associated with the use of chitosan as a support for immobilization (Fu et al., 2011; Rezvani et al., 2017; Solanki et al., 2016; Narang et al., 2013; Narang and Pundir, 2011). This emerging technology has a growing demand in the fields of veterinary science, livestock breeding, food industry and environmental monitoring (Phadke, 1992), and reached the consumer market (Scouten et al., 1995; Rocchitta et al., 2016).

The terms withdrawn from the list of the top fifty author-keywords were again separated into generic words and directives. Generic terms removed from the list are *flow injection analysis, enzyme electrode, flow injection, amperometry, enzyme reactor, chemiluminescence, hydrolysis*, and *bioreactor*. The directive terms include *invertase, glucoamylase, peroxidase, penicillin g acylase, tyrosinase, catalase, acetylcholinesterase, polyaniline, mesoporous materials, lactose hydrolysis* and *hydrogen peroxide*. This output may indicate a reduction in the number of studies related to the immobilization of the mentioned enzymes, the use of polyaniline and mesoporous materials substrates, as well as the application of immobilized enzymes that promote the hydrolysis of lactose and the decomposition of hydrogen peroxide.

On the other hand, new terms have also been added to the top fifty author-keywords list. The main generic terms are: *nanoparticles, kinetic parameters, reusability, direct electron transfer* and *self-assembly*; and the directive terms are: *magnetic nanoparticles, gold nanoparticles, mesoporous silica, silica, cellulase, beta-glucosidase, lipase, xylanase, response surface methodology, glucose biosensor, entrapment, cross-linked enzyme aggregates (CLEAs), graphene* and *graphene oxide*.

These directive terms indicate a possible turn of interest to investigations involving immobilization of the enzymes cellulase, beta-glucosidase, lipase and xylanase, and the use of magnetic and gold nanoparticles in the immobilization procedures, mainly concerning the composition of the biosensors (Jena and Raj, 2006; Luo et al., 2004; Liu and Lu, 2003; Hutter and Maysinger, 2013). The entrapment method and the building of glucose biosensors also appear as new trends in this area. In addition, the use of silica, mainly mesoporous, as a support for immobilization has emerged as a growing methodology in recent years (Carlsson et al., 2014; Takahashi et al., 2001; Takahashi et al., 2000; Wang and Caruso, 2005), along with the application of response surface methodologies to optimize operating conditions of immobilized systems (Pal and Khanum, 2011; Zhou et al., 2013; Osho et al., 2016; Bussamara et al., 2012). The list of new terms added also contains graphene and graphene oxide as immobilization supports, confirming the increasing use of this material, mainly in the form of oxide (Tian et al., 2017; Zhang et al., 2010; Bolibok et al, 2017), and the term cross-linked enzyme aggregates (CLEAs), a feature that involves the precipitation of enzymes from aqueous buffer followed by chemical cross-linking of the resulting physical aggregates of enzyme molecules (Sheldon, 2007).

4. Conclusions

Research on enzyme immobilization has grown sharply globally since 1991 when more than 200 articles per year began to be registered. Currently, this number has reached the mark of 650 annual publications. China has published most of these studies; however, Spain has presented the largest network of international partnerships and also stands out in terms of number of publications and number of citations. Considering the last 27, 10 and 5 years, the bibliometric analysis did not indicate significant changes in bibliometric indicators trajectory and in the trends of the body of literature. The analysis of networks of international collaborations, limited to the top thirty authors, top twenty organizations and top twenty countries, revealed expressive partnerships between organizations and authors from the same country, as well as a wide collaborative network between different countries, mainly between Spain and the countries of Latin America.

The most cited articles in the past 27, 10 and 5 years have, mainly, the authorship of Spanish and Brazilian researchers. Some common objectives among these more cited studies refer to the procedures for improvements and modifications of the enzymatic activity, stability, and selectivity through the immobilization techniques. The reason for the high number of citations of these publications may be associated, among other aspects, with the fact that they are literature reviews on the subject. The analysis of the trends found and gaps of the research topics, which was intermediated by the comparison of keywords, indicated that future studies should consolidate the knowledge about the immobilization of *Candida rugosa lipases*, the use of *Escherichia coli* as a source of acquisition of several enzymes and the immobilization of cytochrome-c. It is worth mentioning that other critical points may emerge with the advancement of research in the sector.

Finally, bibliometric mapping proved to be effective in evaluating the main collaborative networks and facilitated the interpretation of the results, which can acquire new configurations according to the number of items analyzed. The use of boolean operators and of quotation marks in the initial search of the terms was a key factor in retrieving the sample from WoS database. The bibliometric indicators presented in this research show the visibility of the academic results of a specific database (WoS) and do not fully demonstrate the impact of the research on enzyme immobilization for the entire academic community.

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Supplementary Material

Appendix A. Supplementary data

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References

Abraham, T.E., Joseph, J.R., Bindhu, L.B.V., Jayakumar, K.K., Crosslinked enzyme crystals of glucoamylase as a potent catalyst for biotransformations, Carbohydr Res. 339 (2004) 1099-104.

Adlercreutz, P., Immobilisation and application of lipases in organic media, Chem. Soc. Rev. 42 (2013) 6406-6436.

Agarwal, S., Wendorff, J.H., Greiner, A., Use of electrospinning technique for biomedical applications, Polym. J. 49 (2008) 5603-5621.

Aguiar-Oliveira E., Maugeri, F., Effects of the addition of substrate and salts in both the fructosyltransferase immobilization and its catalytic properties. J. Food Biochem. 37 (2012) 520-527.

Alleyne, T., Ignacio, D.N., Sampson, V.B., Ashe, D., Wilson, M., Simulating the slow to fast switch in cytochrome c oxidase catalysis by introducing a loop flip near the enzyme's cytochrome c (substrate) binding site, Biotechnol. Appl. Biochem. 64 (2017) 677-685.

Alver, E., Metin, M.U., Chitosan based metal-chelated copolymer nanoparticles: laccase immobilization and phenol degradation studies, Int. Biodeterior. Biodegradation. 125 (2017) 235-242.

Amirbandeh, M., Taheri-Kafrani, A., Soozanipour, A., Gaillard, C., Triazine-functionalized chitosan-encapsulated superparamagnetic nanoparticles as reusable and robust nanocarrier for glucoamylase immobilization, Biochem. Eng. J. 127 (2017) 119-127.

Amotz, S., Method for production of an immobilized enzyme preparation by means of a crosslinking agent. Novo Industri A/S. US4665028; 1987.

Baghban, A., Heidarizadeh, M., Doustkhah, E., Rostamnia, S., Rezaei, P.F., Covalently bonded pancreatic lipase onto the dithiocarbamate/chitosan-based magnetite: stepwise fabrication of Fe_3O_4@CS/NHCS-Lip as a novel and promising nanobiocatalyst, Int. J. Biol. Macromol. 103 (2017) 1194-1200.

Barathi, P., Kumar, A.S., Electrochemical conversion of unreactive pyrene to highly redox-active 1,2-quinone derivatives on a carbon nanotube-modified gold electrode surface and its selective hydrogen peroxide sensing, Langmuir 29 (2013) 10617-10623.

Barbosa, O., Ortiz, C., Berenguer-Murcia, Á., Torres, R., Rodrigues, R.C., Fernandez-Lafuente, R., Strategies for the one-step immobilization-purification of enzymes as industrial biocatalysts, Biotechnol. Adv. 33 (2015) 435-456.

Barbosa, O., Ortiz, C., Berenguer-Murcia, Á., Torres, R., Rodrigues, R.C., Fernandez-Lafuente, R. Glutaraldehyde in bio-catalysts design: a useful crosslinker and a versatile tool in enzyme immobilization, RSC Adv. 4 (2014) 1583–1600.

Barbosa, O., Torres, R., Ortiz, C., Berenguer-Murcia, Á., Rodrigues, R.C., Fernandez-Lafuente, R. Heterofunctional supports in enzyme immobilization: from traditional immobilization protocols to opportunities in tuning enzyme properties, Biomacromolecules. 14 (2013) 2433–2462.

Bayramoğlu, G., Arıca, M.Y., Enzymatic removal of phenol and p-chlorophenol in enzyme reactor: Horseradish peroxidase immobilized on magnetic beads, J. Hazard. Mater. 156 (2008) 148–155.

Bayramoğlu, G., Methacrylated chitosan based uv curable support for enzyme immobilization, Mater. Res. 20 (2017) 452–459.
Beacham, I.R., Taylor, N.S., Youell, M., Enzyme secretion in *Escherichia coli*: synthesis of alkaline phosphatase and acid hexose phosphatase in the absence of phospholipid synthesis, J. Bacteriol. 128 (1976) 522–527.
Bennett, B. D., Kimball, E. H., Gao, M., Osterhout, R., Van Dien, S. J., Rabinowitz, J. D, Absolute metabolite concentrations and implied enzyme active site occupancy in *Escherichia coli*, Nat. Chem. Biol. 5 (2009) 593–599.
Bhardwaj, N., Kundu, S.C., Electrospinning: a fascinating fiber fabrication technique, Biotechnol. Adv. 28 (2010) 325-47.
Boanares, D., Azevedo, C.S., The use of nucleation techniques to restore the environment: a bibliometric analysis. Natureza & Conservação**.** 12 (2014) 93-98.
Bolibok, P., Wiśniewski, M., Roszek, K., Terzyk, A.P., Controlling enzymatic activity by immobilization on graphene oxide, Sci. Nat. 104 (2017).
Borner, K., Chen, C., Boyack, K.W., Visualizing knowledge domains. Annual Review of Information Science and Technology 37 (2003) 179–255.
Boudry, C., Baudouin, C., Mouriaux, F., International publication trends in dry eye disease research: a bibliometric analysis, The Ocular Surf. 16 (2018) 173-179.
Brady, D., Jordaan, J., Advances in enzyme immobilization, Biotechnol. Lett. 31 (2009) 1639-1650.
Bulmuş, V., Ayhan, H., Pişkin, E., Modified PMMA monosize microbeads for glucose oxidase immobilization, Chem. Eng. J. and Biochem. Eng. J. 65 (1997) 71-76.
Bussamara, R., Dall'Agnol, L., Schrank, A., Fernandes, K.F., M.H. Vainstein, Optimal conditions for continuous immobilization of *Pseudozyma hubeiensis* (strain HB85A) lipase by adsorption in a packed-bed reactor by response surface methodology, Enzyme Res. 2012 (2012).
Cantone, S., Ferrario, V., Corici, L., Ebert, C., Fattor, D., Spizzo, P., Gardossi, L., Efficient immobilization of industrial biocatalysts: criteria and constraints for the selection of organic polymeric carriers and immobilization methods, Chem. Soc. Rev. 42 (2013) 6262-6276.
Carlsson, N., Gustafsson, H., Thörn, C., Olsson, L., Holmberg, K., Åkerman, B., Enzymes immobilized in mesoporous silica: a physical–chemical perspective, Adv. Colloid Interface Sci. 205 (2014) 339-360.
Chang, R.C., Chou, S.J., Shaw, J.F., Multiple forms and functions of *Candida rugosa* lipase, Biotechnol. Appl. Biochem. 19 (1994), 93-98.
Chen, L., Wei, B., Zhang, X.T., Li, C., Bifunctional graphene/gamma-Fe_2O_3 hybrid aerogels with double nanocrystalline networks for enzyme immobilization, J. Intern. Adsorp. Soc. 9 (2013) 2331-2340.
Chen, S.Y., Chen, Y.T., Lee, J.J., Cheng, S., Tuning pore diameter of platelet SBA-15 materials with short mesochannels for enzyme adsorption, J. Mater. Chem. 21 (2011) 5693-5703.
Chiou, S.H., Wu, W.T., Immobilization of *Candida rugosa* lipase on chitosan with activation of the hydroxyl groups, Biomaterials 25 (2004) 197-204.
Cosnier, S., Biomolecule immobilization on electrode surfaces by entrapment or attachment to electrochemically polymerized films. Biosens. Bioelectron. 14 (1999) 443-456.
Cruz, J., Barbosa, O., Rodrigues, R.C., Fernandez-Lafuente, R., Torres, R., Ortiz, C., Optimized preparation of CALB-CLEAs by response surface methodology: the necessity to employ a feeder to have an effective crosslinking, J. Mol. Catal. B: Enzym. 80 (2012) 7-14.
Cubides-Roman, D.C., Perez, V.H., de Castro, H.F., Orrego, C.E., Giraldo, O.H., Silveira, E.G., David, G.F., Ethyl esters (biodiesel) production by *Pseudomonas fluorescens* lipase

immobilized on chitosan with magnetic properties in a bioreactor assisted by electromagnetic field, Fuel 196 (2017) 481-487.

Dalmau, E., Montesinos, J.L., Otti, M.L., Casas, C., Effect of different carbon sources on lipase production by *Candida rugosa*, Enzyme Microb. Technol. 26 (2000) 657-663.

Datta, S., Christena, L.R., Rajaram, Y.R.S. Enzyme immobilization: an overview on techniques and support materials, 3 Biotech. 3 (2013) 1-9.

Devasenathipathy, R., Mani, V., Chen, S.M., Huang, S.T., Huang, T.T., Lin, C.M., Hwa, K.Y., Chen, T.Y., Chen, B.J., Glucose biosensor based on glucose oxidase immobilized at gold nanoparticles decorated graphene-carbon nanotubes, Enzyme Microb. Technol. 78 (2015) 40-45.

DiCosimo, R., McAuliffe, J., Poulose, A.J., Bohlmann, G., Industrial use of immobilized enzymes, Chem. Soc. Rev. 42 (2013), 6437-6474.

Domínguez de María, P., Sánchez-Montero, J.M., Sinisterra, J.V., Alcántara, A.R., Understanding *Candida rugosa* lipases: an overview, Biotechnol. Adv. 24 (2006) 180-196.

Dos Santos, J.C.S., Garcia-Galan, C., Rodrigues, R.C., de Sant' Ana H.B., Gonçalves, L.R.B., Fernandez-Lafuente, R., Improving the catalytic properties of immobilized Lecitase via physical coating with ionic polymers, Enzyme Microb. Technol. 60 (2014) 1–8.

Duerre, J.A., Ribi, E., Enzymes released from *Escherichia coli* with the aid of a servall cell fractionator, Appl. Microbiol. 11(1963) 467–471.

Dyal, A., Loos, K., M. Noto, S.W. Chang, C. Spagnoli, K.V. P. M. Shafi, A. Ulman, M. Cowman, R.A. Gross, Activity of *Candida rugosa* lipase immobilized on γ-Fe_2O_3 magnetic nanoparticles, J. Am. Chem. Soc. 125 (2003) 1684–1685.

Elias, N., Chandren, S., Attan, N., Mahat, N.A., Razak, F.I.A., Jamalis, J., Wahab, R.A., Structure and properties of oil palm-based nanocellulose reinforced chitosan nanocomposite for efficient synthesis of butyl butyrate, Carbohydr. Polym. 176 (2017) 281-292.

Ferguson, S.A., Cook, G.M., Montgomery, M.G., Leslie, A.G.W., Walker, J.E., Regulation of the thermoalkaliphilic F-1-ATPase from *Caldalkalibacillus thermarum*, Proc. Natl. Acad. Sci. USA 113 (2016) 10860-10865.

Fernandez-Arrojo, L., Rodriguez-Colinas, B., Gutierrez-Alonso, P., Fernandez-Lobato, M., Alcalde, M., Ballesteros, A.O., Plou, F.J., Dried alginate-entrapped enzymes (DALGEEs) and their application to the production of fructooligosaccharides, Process Biochem. 48 (2013) 677-682.

Fernandez-Fernandez, M., M.A. Sanroman, D. Moldes, Recent developments and applications of immobilized laccase, Biotechnol. Adv. 31 (2013) 1808-1825.

Ferrarotti, S.A., Bolivar, J.M., Mateo, C., Wilson, L., Guisan, J.M., Fernandez-Lafuente, R., Immobilization and stabilization of a cyclodextrin glycosyltransferase by covalent attachment on highly activated glyoxyl-agarose supports, Biotechnol. Prog. 22 (2006) 1140–1145.

Flaatten, H., Publication footprints and pitfalls of bibliometry, The Acta Anaesthesiologica Scandinavian Foundation 60 (2015) 3–5.

Foulds, N.C., Lowe, C.R., Immobilization of glucose oxidase in ferrocene-modified pyrrole polymers, Anal. Chem. 60 (1988) 2473–2478.

Fu, G.L., Yue, X.L., Dai, Z.F., Glucose biosensor based on covalent immobilization of enzyme in sol-gel composite film combined with prussian blue/carbon nanotubes hybrid, Biosens. Bioelectron. (26) 2011 3973-3876.

Fu, H.Z., Wang, M.H., Ho, Y.S., Mapping of drinking water research: a bibliometric analysis of research output during 1992 – 2011, Sci Total Environ. 443 (2013) 757-765.

Ganaie, M.A., Rawatb, H.K., Wania, O.A., Guptaa, U.S., Kango, N., N, Immobilization of fructosyltransferase by chitosan and alginate for efficient production of fructooligosaccharides, Process Biochem. 49 (2014) 840-844.

Garcia-Galan, C., Berenguer-Murcia, A., Fernandez-Lafuente, R., Rodrigues, R.C., Potential of different enzyme immobilization strategies to improve enzyme performance, Adv. Synth. Catal. 16 (2011) 2885-904.

Garfield, E., Is citation analysis a legitimate evaluation tool? Scientometrics 1 (1979) 359–375.

Goddard, J.M., Hotchkiss, J.H., Polymer surface modification for the attachment of bioactive compounds, Prog. Polym. Sci. 32 (2007) 698-725.

González-Sala, F., Osca-Lluch, J., Gil, F.T., Ortega, M.P., Characterization of legal psychology through psychology journals included in criminology & penology and law categories of Web of Science, Anales de Psicología 33 (2017) 411-416.

Gricajeva, A., S. Kazlauskas, L. Kalėdienė, V. Bendikienė, Analysis of *Aspergillus* sp. lipase immobilization for the application in organic synthesis, Int. J. Biol. Macromol. 108 (2018) 1165-1175.

Gupta, P., Dutt, K., Misra, S., Raghuwanshi, S., Saxena, R.K., Characterization of cross-linked immobilized lipase from thermophilic mould *Thermomyces lanuginosa* using glutaraldehyde, Bioresour. Technol. 100 (2009) 4074-4076.

Hanefeld, U., Gardossi L., Magner E., Understanding enzyme immobilization, Chem. Soc. Rev. 38 (2009) 453-68.

Hartmann, M., Ordered mesoporous materials for bioadsorption and biocatalysis. Chem. Mater. 17 (2005) 4577–4593.

Hernandez, K., Fernandez-Lafuente, R., Control of protein immobilization: coupling immobilization and site-directed mutagenesis to improve biocatalyst or biosensor performance, Enzyme Microb. Technol. 48 (2011) 107–122.

Herrera-López, E.J., Lipase and phospholipase biosensors: a review, Methods. Mol. Biol. 861 (2012) 525-543.

Hirsch, J.E., An index to quantify an individual's scientific research output, Proc. Natl. Acad. Sci. 102 (2005) 16569–16572.

Hou, J.W., Dong, G.X., Ye, Y., Chen, V., Laccase immobilization on titanium nanoparticles and titanium-functionalized membranes, J. Membr. Sci. 452 (2014) 229-240.

Huang, X.J., Chen, P.C., Huang, F., Ou, Y., Chen, M.R., Xu, Z.K., Immobilization of *Candida rugosa* lipase on electrospun cellulose nanofiber membrane, J. Mol. Catal. B Enzym. 70 (2011) 95-100.

Hutter, E., Maysinger, D., Gold-nanoparticle-based biosensors for detection of enzyme activity, Trends Pharmacol. Sci. 34 (2013) 497-507.

Jardine, O., Gough, J., Chothia, C., Teichmann, S.A., Comparison of the small molecule metabolic enzymes of *Escherichia coli* and *Saccharomyces cerevisiae*, Genome Res. 12 (2002) 916–929.

Jena, B.K., Raj Dr, C.R., Enzyme-free amperometric sensing of glucose by using gold nanoparticles, Chem. Eur. J. 12 (2006) 2702-2708.

Jesionowski, T., J. Zdarta, B. Krajewska, Enzyme immobilization by adsorption: a review, J. Intern. Adsorp. Soc. 20 (2014) 801-821.

Kang, X.H., Wang, J., Wu, H., Aksay, I.A., Liu, J., Lin, Y.H., Glucose oxidase-graphene-chitosan modified electrode for direct electrochemistry and glucose sensing, Biosens. Bioelectron. 25 (2009) 901-905.

Kartal, F., Kilinc, A., Timur, S., Lipase biosensor for tributyrin and pesticide detection, Int. J. Environ. Anal. Chem. 87 (2007) 715–722.

Khokhlova, T.D., Zubareva, N.A., gamma-Fe_2O_3 modified with C-18 carboxylic acids: A magnetic carrier for immobilized organic compounds, Prot. Met. Phys. Chem. Surf. 51 (2015) 221-225.

Khosla, K., Rathour, R., Maurya, R., Maheshwari, N., Gnansounou, E., Larroche, C., Thakur, I.S., Biodiesel production from lipid of carbon dioxide sequestrating bacterium and lipase of psychrotolerant *Pseudomonas* sp. ISTPL3 immobilized on biochar, Bioresour. Technol. 245 (2017) 743-750.

Knezevic, Z., N. Milosavic, D. Bezbradica, Z. Jakovljevic, R. Prodanovic, Immobilization of lipase from *Candida rugosa* on Eupergit® C supports by covalent attachment, Biochem. Eng. J. 30 (2006) 269-278.

Krajewska, B., Application of chitin- and chitosan-based materials for enzyme immobilizations: a review, Enzyme Microb. Technol. 35 (2004) 126-39.

Lai, C.Y., Trewyn, B.G., Jeftinija, D.M., Jeftinija, K., Xu, S., Jeftinija, S., Lin ,V.S.Y., A mesoporous silica nanosphere-based carrier system with chemically removable CDS nanoparticle caps for stimuli-responsive controlled release of neurotransmitters and drug molecules, J. Am. Chem. Soc. 125 (2003) 4451–4459.

Lakshmi, B.B., Patrissi, C.J., Martin, C.R., Sol−gel template synthesis of semiconductor oxide micro- and nanostructures, Chem. Mater. 9 (2007) 2544–2550.

Lee, D.H., Kim, J.M., Shin, H.Y., Kim, S.W., Optimization of lipase pretreatment prior to lipase immobilization to prevent loss of activity, J. Microbiol. Biotechnol. 17 (2007) 650-654.

Lee, H., Rho, J., Messersmith, P.B., Facile conjugation of biomolecules onto surfaces via mussel adhesive protein inspired coatings, Adv. Mater. 21 (2009) 431–434.

Lee, J., Kim, J., Hyeon, T., Recent progress in the synthesis of porous carbon materials, Adv. Mater. 18 (2006) 2073–2094.

Lee, J.W., Will the renminbi emerge as an international reserve currency, World Econ. 37 (2013).

Lehman, I. R., Bessman, M.J., Simms, E. S., Kornberg, A., Enzymatic synthesis of deoxyribonucleic acid, J. Biol. Chem. 233 (1957) 163-170.

Li, J., Wang, M.H., Ho, Y.S., Trends in research on global climate change: a science citation index expanded-based analysis, Glob. Planet. Chang. 77 (2011) 13–20.

Li, L.K., Rola, A.S., Kaid, F.A., Ali, A.M., Alabsi, A.M., Goniothalamin induces cell cycle arrest and apoptosis in H400 human oral squamous cell carcinoma: a caspase-dependent mitochondrial-mediated pathway with downregulation of NF-kappa beta, Arch. Oral. Biol. 64 (2016) 28-38.

Liao, J., Huang, Y., Global trend in aquatic ecosystem research from 1992 to 2011, Scientometr. 98 (2014) 1203–1219.

Liese A., Hilterhaus, L., Evaluation of immobilized enzymes for industrial applications, Chem. Soc. Rev. 42 (2013), 6236-6249.

Liu, J., Lu, Y., A colorimetric lead biosensor using DNAzyme-directed assembly of gold nanoparticles, J. Am. Chem. Soc. 125 (2003) 6642-6643.

Liu, X., Zhang, L., Hong, S., Global biodiversity research during 1900–2009: a bibliometric analysis, Biodivers. Conserv. 20 (2011) 807–826.

Luo, X.L., Xu, J.J., Du, Y., Chen, H.Y., A glucose biosensor based on chitosan–glucose oxidase–gold nanoparticles biocomposite formed by one-step electrodeposition, Anal. Biochem. 334 (2004) 284-289.

Macario, A., Moliner, M., Corma, A., Giordano, G., Increasing stability and productivity of lipase enzyme by encapsulation in a porous organic–inorganic system. Microporous Mesoporous Mat. 118 (2009) 334-340.

Manecke, G., Immobilization of enzymes by various synthetic polymers, Biotechnol. Bioeng. Symp. 3 (1972) 185-187.

Marconi, W., Immobilized enzymes: their catalytic behavior and their industrial and analytical applications, Reac. Polym. 11(1989) 1-19.

Maria Chong, A.S., Zhao, X.S., Functionalization of SBA-15 with APTES and characterization of functionalized materials, J. Phys. Chem. B 107 (2003) 12650–12657.

Martin, C.R., Kohli, P., The emerging field of nanotube biotechnology, Nat. Rev. Drug. Discov. 2(2003) 29-37.

Mateo C., Palomo, J.M., Fernandez-Lorente, G., Guisan, J.M., Fernandez-Lafuente, R., Improvement of enzyme activity, stability and selectivity via immobilization techniques, Enzyme Microb. Technol. 40 (2007) 1451-1463.

Mauve, C., Giraud, N., Boex-Fontvieille, E.R.A., Antheaume, I., Tea, I., Tcherkez, Kinetic, G., commitment in the catalysis of glutamine synthesis by GS1 from Arabidopsis using N-14/N-15 and solvent isotope effects, Plant. Physiol. Biochem. 108 (2016) 203-211.

Melo, A.D.Q., Silva, F.F.M., dos Santos, J.C.S., Fernandez-Lafuente, R., Lemos, T.L.G., Dias, F.A., Synthesis of benzyl acetate catalyzed by lipase immobilized in nontoxic chitosan-polyphosphate beads, Molecules 22 (2017).

Merigó, J.M., Yang, J., A bibliometric analysis of operations research and management science, Omega 73 (2017) 37-48.

Milanez, D.H., Schiavi, M.T., Amaral, R.M., Faria, L.I.L., Gregolin, J.A.R., Development of carbon-based nanomaterials indicators using the analytical tools and data provided by scientific publication database, J. Mater. Res. 16 (2013) 1282–1293.

Miletić, N., Vuković, Z., Nastasović, A., Loos, K., Macroporous poly(glycidyl methacrylate-co-ethylene glycol dimethacrylate) resins – Versatile immobilization supports for biocatalysts, J. Mol. Catal. B: Enzym. 56 (2009) 196-201.

Mislovičová, D., Michálková, E., Vikartovská, A., Immobilized glucose oxidase on different supports for biotransformation removal of glucose from oligosaccharide mixtures, Process Biochem. 42 (2007) 704-709.

Mondal M.K., Mukherjee, S., Saha, S.K., Chowdhury, P., Babu, S.P.S., Design and synthesis of reduced graphene oxide based supramolecular scaffold: a benign microbial resistant network for enzyme immobilization and cell growth, Mater. Sci. Eng. C Mater. Biol. Appl. 75 (2017) 1168-1177.

Moreno-Perez, S., Luna, P., Señorans, J., Rocha-Martin, J., Guisan, J.M., Fernandez-Lorente, G., Enzymatic transesterification in a solvent-free system: synthesis of sn-2 docosahexaenoyl monoacylglycerol, Biocatal. Biotransformation 36 (2017) 265–270.

Muralidhar, R.V., Chirumamila, R.R., Marchant, R., Nigam, P., A response surface approach for the comparison of lipase production by *Candida cylindracea* using two different carbon sources, Biochem. Eng. J. 9 (2001) 17-23.

Narang, J., Chauhan, N., Pundir, C.S., Construction of triglyceride biosensor based on nickel oxide-chitosan/zinc oxide/zinc hexacyanoferrate film, Int. J. Biol. Macromol. 60 (2013) 45-51.

Narang, J., Pundir, C.S., Construction of a triglyceride amperometric biosensor based on chitosan-ZnO nanocomposite film, Int. J. Biol. Macromol. 49 (2011) 707-715.

Nooruddin, I., Payton, A.L., Dynamics of influence in international politics: the ICC, BIAs, and economic sanctions, J. Peace Res. 47 (2010) 711-721.

Okubo, Y., Bibliometric indicators and analysis of research systems: methods and examples, OECD Sci. (1997) 6-70.

Osho, M., Popoola, T., Adeleye, T., Adetunji, C., Response surface methodology for optimal immobilization of *Aspergillus niger* ATCC 1015 lipase by adsorption method, Int. J. Biol. Res. 4 (2016).

Pal, A., Khanum, F., Covalent immobilization of xylanase on glutaraldehyde activated alginate beads using response surface methodology: characterization of immobilized enzyme, Process Biochem. 46 (2011) 1315-1322.

Parente, A.H., Marques, E.T., Azevedo, W.M., Diniz, F.B., Melo, E.H., Lima Filho, J.L., Glucose biosensor using glucose oxidase immobilized in polyaniline, Appl. Biochem. Biotechnol. 37 (1992) 267-73.

Pereira, E.B., Zanim, G.M., Castro, H.F., Immobilization and catalytic properties of lipase on chitosan for hydrolysis and esterification reactions, Braz. J. Chem. Eng. 20 (2003).

Perna, R.F., Cunha, J.S., Goncalves, M.C.P., Basso, R.C., Silva, E.S., Maiorano, A.E., Microbial fructosyltransferase: production by submerged fermentation and evaluation of pH and temperature effects on transfructosylation and hydrolytic enzymatic activities, Int. J. Eng. Sci. 4(2018) 43-50.

Perna, R.F., P.C. Tiosso, L.M. Sgobi, A.M.S. Vieira, M.F. Vieira, P.W. Tardioli, C.M.F. Soares, G.M. Zanin, Effects of triton X-100 and PEG on the catalytic properties and thermal stability of lipase from free and immobilized on glyoxyl-agarose, The Open Biochem. J. 11 (2017) 66-76.

Phadke, R.S., Biosensors and enzyme immobilized electrodes, Biosyst. 27 (1992), 203-206.

Planta, J., Xiang, X.L., Leustek, Messing, T., J., Engineering sulfur storage in maize seed proteins without apparent yield loss, Proc. Natl. Acad. Sci. USA 114 (2017) 11386-11391.

Platková, Z., Polakovic, M., Stefuca, V., Vandáková, M., Antosová, M., Selection of carrier for immobilization of fructosyltransferase from *Aerobasidium pullulans*, Chem. Pap. 60 (2006) 469–472.

Polakovic, M., Vitel, J.S., Bucko, M., Filip, J., Nedela, V., Ansorge-Schumacher, M.B., Gemeiner, P., Progress in biocatalysis with immobilized viable whole cells: systems development, reaction engineering and applications, Biotechnol. Lett. 39 (2017) 667-683.

Razmi, H., Mohammad-Rezaei, R., Graphene quantum dots as a new substrate for immobilization and direct electrochemistry of glucose oxidase: application to sensitive glucose determination, Biosens. Bioelectron. 41 (2013) 498-504.

Remonatto, D., de Oliveira, J.V., Guisan, J.M., de Oliveira D., Ninow J., Fernandez-Lorente, G. Production of FAME and FAEE via alcoholysis of sunflower oil by eversa lipases immobilized on hydrophobic supports, Appl. Biochem. Biotechnol. 185 (2018) 705–716.

Rezvani, M., Najafpour, G.D., Mohammadi, M., Zare, H. Amperometric biosensor for detection of triglyceride tributyrin based on zero point charge of activated carbon, Turk. J. Biol. 41 (2017) 268-277.

Rocchitta, G., Spanu, A., Babudieri, S., Latte, G., Madeddu, G., Galleri, G., Nuvoli, S., Bagella, P., Demartis, M.I., Fiore, V., Manetti, R., Serra, P.A., Enzyme biosensors for biomedical applications: strategies for safeguarding analytical performances in biological fluids, Sensors. 16 (2016) 780.

Rocha-Martin, J., Fernández-Lorente, G., Guisan, J.M., Sequential hydrolysis of commercial casein hydrolysate by immobilized trypsin and thermolysin to produce bioactive phosphopeptides, Biocatal. Biotransformation 36 (2017) 159–171.

Rodrigues, R.C., Ortiz, C., Berenguer-Murcia, A., Torres, R., Fernandez-Lafuente, R., Modifying enzyme activity and selectivity by immobilization, Chem. Soc. Rev. 42(2013) 6290-6307.

Romanelli, J.P., Fujimoto, J.T., Ferreira, M.D., Milanez, D.H., Assessing ecological restoration as a research topic using bibliometric indicators, Ecol. Eng. 120 (2018) 311-320.

Roy, J.J., Abraham, T.E., Preparation and characterization of cross-linked enzyme crystals of laccase, J. Mol. Catal. B: Enzym. 38 (2006) 31-36.

Sassolas, A., Blum, L.J., Leca-Bouvier, B.D., Immobilization strategies to develop enzymatic biosensors, Biotechnol. Adv. 30 (2012) 489-511.

Schirmbock, M., Matlteo, L., Yong-Li, W., Hayes, K. C., Arisan-Atac, I., Scala, F., Harman, G.E., C. P. Kubicek, Parallel formation and synergism of hydrolytic enzymes and peptaibol antibiotics, molecular mechanisms involved in the antagonistic action of *Trichoderma harzianum* against phytopathogenic fungi, Appl. Environ. Microbiol. 60 (1994) 4364-4370.

Scouten, W.H., Luong, J.H.T., Brown, R.S., Enzyme or protein immobilization techniques for applications in biosensor design, Trends Biotechnol. 13 (1995) 178-185.

Shah, N.B., Duncan, T.M., Aerobic growth of *Escherichia coli* is reduced, and ATP synthesis is selectively inhibited when five C-terminal residues are deleted from the epsilon subunit of ATP synthase, J. Biol. Chem. 290 (2015) 21032-21041.

Sheldon, R.A., Cross-linked enzyme aggregates (CLEAs): stable and recyclable biocatalysts, Biochem. Soc. Trans. 35 (2007) 1583-1587.

Sheldon, R.A., Enzyme Immobilization: The quest for optimum performance, Adv. Synth. Catal. 349 (2007) 1289–1307.

Sheldon, R.A., van Pelt S., Enzyme immobilisation in biocatalysis: why, what and how, Chem. Soc. Rev. 42 (2013) 6223-6235.

Singh, R., Kumar, M., Mittal, A., Mehta, P.K. Microbial enzymes: industrial progress in 21st century, 3 Biotech. 6 (2016) 174.

Soares, C.M.F., De Castro, H.F., De Moraes, F.F., Zanin, G.M., Characterization and utilization of *Candida rugosa* lipase immobilized on controlled pore silica, Appl. Biochem. Biotechnol. 79 (1999) 745-757.

Solanki, S., Pandey, C.M., Soni, A., Sumana, G., A.M. Biradar, An amperometric bienzymatic biosensor for the triglyceride tributyrin using an indium tin oxide electrode coated with electrophoretically deposited chitosan-wrapped nanozirconia, Microchim. Acta. 183 (2016) 167-176.

Song, Y., Zhao, T., A bibliometric analysis of global forest ecology research during 2002–2011, Springerplus. 2(2013) 204.

Souza, L.T.A., Veríssimo, L.A.A., João, B.C.P., Santoro, M.M., Resende, R.R.; Mendes, A.A., Imobilização Enzimática: princípios fundamentais e tipos de suporte, Biotecnologia Aplicada à Agro&Indústria: fundamentos e aplicações, 4, Edit. Edgard Blucher Ltda., 529-568, 2016.

Ştirbu, S., Thirion, P., Schmitz, S., Haesbroeck, G., Greco, N., The utility of google scholar when searching geographical literature: comparison with three commercial bibliographic databases, The Journal of Academic Librarianship. 41 (2015) 322-329.

Straathof, A.J.J., Panke, S., Schmid, A., The production of fine chemicals by biotransformations, Curr. Opin. Biotechnol. 13 (2002) 548-56.

Sun, J., Chen, Y., Sheng, J., Sun, M., Immobilization of *Yarrowia lipolytica* lipase on macroporous resin using different methods: characterization of the biocatalysts in hydrolysis reaction, Biomed. Res. Int. 2015 (2015).

Suzuki, S., Karube, I., Production of antibiotics and enzymes by immobilized whole cells. Immobilized Microbial Cells 106 (1979) 59-72.

Takahashi, H., Sasaki, B.L.T., Miyazaki, C., Kajino, T., Inagaki, S., Immobilized enzymes in ordered mesoporous silica materials and improvement of their stability and catalytic activity in an organic solvent, Microporous Mesoporous Mater. 44–45 (2001) 755-762.

Takahashi, H., Sasaki, B.L.T., Miyazaki, C., Kajino, T., Inagaki, S., Catalytic activity in organic solvents and stability of immobilized enzymes depend on the pore size and surface characteristics of mesoporous silica, Chem. Mater. 12 (2000) 3301-3305.

Tian, K.L., Nie, F., Luo, K., Zheng, X.H., Zheng, J.B., Sensitive electrochemiluminescence glucose biosensor based on graphene quantum dot prepared from graphene oxide sheets and hydrogen peroxide, J. Electroanal. Chem. 801 (2017) 162-170.

Valentová, O., Marek, M., Švec F., Štamberg, J., Vodrážka, Z., Comparison of different methods of glucose oxidase immobilization, Biotechnol. Bioeng. 23 (1981) 2093-2104.

Van Eck, N.J., Waltman, L., Software survey: VOSviewer, a computer program for bibliometric mapping, Scientometr. 84 (2009) 523-538.

Van Raan A.F.J., Advances in bibliometric analysis: research performance assessment and science mapping. In: Bibliometrics: use and abuse in the review of research performance, Portland Press. (2014) 17–28.

Veymar, G., Tacias-Pascacio, J., Virgen-Ortíz, M. Jiménez-Pérez, M. Yates, B. Torrestiana-Sanchez, A. Rosales-Quintero, R. Fernandez-Lafuente. Evaluation of different lipase biocatalysts in the production of biodiesel from used cooking oil: critical role of the immobilization support, Fuel 200 (2017) 1-10.

Wang, B., Koo, B., H.G. Monbouquette, enzyme deposition by polydimethylsiloxane stamping for biosensor fabrication, Electroanalysis 29 (2017) 2300-2306.

Wang, H.J., Liu, M.Y., Hong, S., Zhuang, Y.H., A historical review and bibliometric analysis of GPS research from 1991–2010, Scientometr. 95 (2013) 35–44.

Wang, S., Zheng, D., Yin, L., Wang, F., Preparation, activity and structure of cross-linked enzyme aggregates (CLEAs) with nanoparticle, Enzyme Microb. Technol. 107 (2017) 22-31.

Wang, Y., Caruso, F., Mesoporous silica spheres as supports for enzyme immobilization and encapsulation, Chem. Mater. 17 (2005) 953–961.

Wang, Z.G., Wan, L.S., Liu, Z.M., Huang, X.J., Xu, Z.K., Enzyme immobilization on electrospun polymer nanofibers: an overview, J. Mol. Cata. B: Enzym. 56 (2009) 189–195.

Wildgard, L., A comparison of 17 author-level bibliometric indicators for researchers in astronomy, environmental science, philosophy and public health in web of science and google scholar, Scientometrics. 104 (2015) 873-906.

Yaku Arica, M., Soydogan, H., Bayramoglu, G., Reversible immobilization of *Candida rugosa* lipase on fibrous polymer grafted and sulfonated p(HEMA/EGDMA) beads, Bioprocess Biosyst. Eng. 33 (2010) 227-236.

Yoo S.Y., Min, J., Haga, T., Hirakawa, H., Nagamune, T., Choi, J.W., Enzyme Logic Gate with summation function based on putidaredoxin reductase/cytochrome c enzyme reaction, J. Nanosci. Nanotechnol. 17 (2017) 5189-5192.

Yücel, Y., Demir, C., Dizge, N., Keskinler, B., Lipase immobilization and production of fatty acid methyl esters from canola oil using immobilized lipase, Biomass Bioenergy. 35 (2011) 1496-1501.

Zhang, J., Zhang, F., Yang, H., Huang, X., Liu, H., Zhang, J., Guo, S., Graphene oxide as a matrix for enzyme immobilization, Langmuir 26 (2010) 6083–6085.

Zhang, L., Wang, M., Hu, J., Ho, Y., A review of published wetland research, 1991–2008: Ecological engineering and ecosystem restoration. Ecol. Eng. 36 (2010) 973–980.

Zhang, Q., Wu, S., Zhang, L., Lu, J., Verproot, F., Liu, Y., Xing, Z., Li, J., Song, X.M., Fabrication of polymeric ionic liquid/graphene nanocomposite for glucose oxidase immobilization and direct electrochemistry, Biosens. Bioelectron. 26 (2011) 2632-2637.

Zhang, Y., Yao, X., Qin, B., A critical review of the development, current hotspots, and future directions of lake taihu research from the bibliometrics perspective, Environ. Sci. Pollut. Res. 23 (2016) 12811– 12821.

Zhou Y., Wang, L., Wu, T., Tang, X., Pan, S., Optimal immobilization of β-glucosidase into chitosan beads using response surface methodology, Electron. J. Biotechnol. 16 (2013).

Zhou, Z., Hartmann, M., Progress in enzyme immobilization in ordered mesoporous materials and related applications, Chem. Soc. Rev. 42 (2013) 3894-3912.

Zhou, Z., Inayat, A., Schwieger, W., Hartmann, M., Improved activity and stability of lipase immobilized in cage-like large pore mesoporous organosilicas, Microporous Mesoporous Mat. 154 (2012) 133-41.

Zhu, S.T., Canales, A., Bedair, M., Vik, S.B., Loss of complex I activity in the *Escherichia coli* enzyme results from truncating the C-terminus of subunit K, but not from cross-linking it to subunits N or L, J. Bioenerg. Biomembr. 48 (2016) 325-333.

Zsengeller, Z.K., Aljinovic, N., Teot, L.A., Korson, M., Rodig, N., Sloan, J.L., Venditti, C.P., Berry, G.T., Rosen, S., Methylmalonic acidemia: A megamitochondrial disorder affecting the kidney, Pediatr. Nephrol. 29 (2014) 2139-21246.

Table 1. Top 40 most productive journals on enzyme immobilization research ranked by total number of publications in the last 27 years (1991-2017).

Rank	Journals	C	NP(1)	NC(2)	HI(3)	IF(4)	Rank	Journals	C	NP(1)	NC(2)	HI(3)	IF(4)
1	J. Mol. Catal. B: Enzym.	NL	414	12,265	50	1.960	21	Biotechnol. Lett.	NL	78	1,650	20	1.846
2	Enzyme Microb. Technol.	NL	298	12,059	52	2.932	22	Colloids Surf., B	NL	78	1,775	27	3.997
3	Biosens. Bioelectron.	ENG	247	12,033	57	7.291	23	Langmuir	USA	78	2,673	29	3.789
4	Process Biochem.	ENG	219	4,827	37	2.616	24	Appl. Microbiol. Biotechnol.	DE	74	1,532	23	3.340
5	Appl. Biochem. Biotechnol.	USA	211	2,507	24	1.797	25	ACS Appl. Mater. Interfaces	USA	72	1,541	23	8.097
6	Anal. Chim. Acta	NL	199	5,930	41	5.123	26	Biocatal. Biotransform.	ENG	71	782	16	1.060
7	Biotechnol. Bioeng.	DE	188	7,036	49	3.952	27	Biotechnol. Appl. Biochem.	USA	71	1,045	21	1.440
8	Biochem. Eng. J.	NL	163	3,173	29	3.226	28	Bioprocess. Biosyst. Eng.	DE	70	910	18	2.139
9	Sens. Actuators, B	NL	155	4,531	39	5.667	29	J. Chromatogr. A	NL	70	2,054	28	3.716
10	RSC Adv.	ENG	141	1,373	17	3.108	30	Anal. Lett.	USA	68	761	18	1.206
11	Anal. Chem.	USA	133	7,215	54	6.042	31	Analyst	ENG	65	2,228	27	3.864
12	Electroanalysis	DE	121	2,850	30	2.851	32	Molecules	CH	62	631	14	3.098
13	J. Appl. Polym. Sci.	USA	113	1,896	25	1.670	33	Food Chem.	NL	61	2,062	28	4.946
14	Int. J. Biol. Macromol.	NL	112	1,510	23	3.909	34	Chem. Eng. J.	NL	59	1,090	19	6.735
15	Talanta	NL	102	2,542	29	4.244	35	Anal. Biochem.	USA	58	1,610	22	2.275
16	Bioresour. Technol.	NL	100	3,813	34	5.807	36	Ind. Eng. Chem. Res.	USA	56	1,227	17	3.141
17	J. Biotechnol.	NL	100	2,855	30	2.533	37	J. Agric. Food. Chem.	USA	54	1,202	19	3.412
18	Biotechnol. Progr.	USA	95	2,352	27	1.947	38	Electrochim. Acta	ENG	51	1,085	20	5.116
19	J. Chem. Technol. Biotechnol.	USA	93	1,442	20	2.587	39	Anal. Bioanal.Chem.	DE	50	1,566	19	3.307
20	J. Membr. Sci.	NL	89	2,375	29	6.578	40	Microporous Mesoporous Mater.	NL	50	1,981	21	3.649

C= Country; NP(1) = number of publications; NC(2) = number of citations; HI(3) = h-index; IF(4) = Impact Factor. NL= Netherlands; ENG= England; USA= United States of America; DE= Germany; CH= Switzerland.

Table 2. Top 20 most cited articles on enzyme immobilization research in the last 27 years (1991-2017).

R	Authors	Title	Journals	IF	Years	NC(2)
1	Mateo C; Palomo JM; Fernandez-Lorente G; Guisan JM; Fernandez-Lafuente R	Improvement of enzyme activity, stability and selectivity via immobilization techniques	Enzyme Microb. Technol.	2.932	2007	1,621
2	Bhardwaj N; Kundu SC	Electrospinning: A fascinating fiber fabrication technique	Biotechnol. Adv.	11.452	2010	1,466
3	Lee J; Kim J; Hyeon T	Recent progress in the synthesis of porous carbon materials	Adv. Mater.	19.791	2006	1,192
4	Sheldon RA	Enzyme immobilization: The quest for optimum performance	Adv. Synth. Catal.	5.123	2007	1,050
5	Agarwal S; Wendorff JH; Greiner A	Use of electrospinning technique for biomedical applications	Polymer	3.483	2008	805
6	Krajewska B	Application of chitin- and chitosan-based materials for enzyme immobilizations: a review	Enzyme Microb. Technol.	2.932	2004	792
7	Kang XH; Wang J; Wu H; Aksay IA; Liu J; Lin YH	Glucose Oxidase-graphene-chitosan modified electrode for direct electrochemistry and glucose sensing	Biosens. Bioelectron.	7.291	2009	731
8	Kawaguchi H	Functional polymer microspheres	Prog. Polym. Sci.	24.558	2000	717
9	Lakshmi BB; Patrissi CJ; Martin CR	Sol-gel template synthesis of semiconductor oxide micro- and nanostructures	Chem. Mater.	9,890	1997	646
10	Martin CR; Kohli P	The emerging field of nanotube biotechnology	Nat. Rev. Drug Discovery	54.490	2003	636
11	Hanefeld U; Gardossi L; Magner E	Understanding enzyme immobilisation	Chem. Soc. Rev.	40.182	2009	623
12	Rodrigues RC; Ortiz C; Berenguer-Murcia A; Torres R; Fernandez-Lafuente R	Modifying enzyme activity and selectivity by immobilization	Chem. Soc. Rev.	40.182	2013	612
13	Sheldon RA; Van Pelt S	Enzyme immobilisation in biocatalysis: why, what and how	Chem. Soc. Rev.	40.182	2013	605
14	Cosnier S	Biomolecule immobilization on electrode surfaces by entrapment or attachment to electrochemically polymerized films. A review	Biosens. Bioelectron.	7.291	1999	590
15	Garcia-Galan C; Berenguer-Murcia A; Fernandez-Lafuente R; Rodrigues RC	Potential of Different Enzyme Immobilization Strategies to Improve Enzyme Performance	Adv. Synth. Catal.	5.123	2011	588
16	Liang D; Hsiao BS; Chu B	Functional electrospun nanofibrous scaffolds for biomedical applications	Adv. Drug Delivery Rev.	13.660	2007	564
17	Kim J; Grate JW; Wang P	Nanostructures for enzyme stabilization	Chem. Eng. Sci.	3.306	2006	562
18	Diaz JF; Balkus KJ	Enzyme immobilization in MCM-41 molecular sieve	J. Mol. Catal. B: Enzym.	1.960	1996	537

19	Duran N; Esposito E	Potential applications of oxidative enzymes and phenoloxidase-like compounds in wastewater and soil treatment: a review	Appl. Catal., B	11.698	2000	515
20	Svec F; Frechet JMJ	New designs of macroporous polymers and supports: From separation to biocatalysis	Science	35.260	1996	506

R = Rank, IF = Impact Factor, NC(2) = number of citations.

Table 3. Top 30 most influent authors on enzyme immobilization research ranked by number of publications in the last 27 years (1991-2017).

R (NP)(1)	**R (NC)(2)**	**Cluster 1 (Red)**	**C**	**ORG**	**NP(1)**	**NC(2)**	**HI(3)**
6	19	Li J	CHI	CQU	46	882	15
9	10	Wang J	CHI	DICP	41	2,074	18
12	28	Jiang YJ	CHI	HU	38	529	13
14	21	Li Y	CHI	CAS	38	730	14
17	16	Zhang Y	CHI	BUCT	37	995	16
18	24	Jiang ZY	CHI	TU	36	649	16
22	17	Zhang L	CHI	TU	34	928	18
Rank	**R (NC)(2)**	**Cluster 2 (Green)**	**C**	**ORG**	**NP(1)**	**NC(2)**	**HI(3)**
3	8	Arica MV	TUR	GU	61	2,420	30
5	12	Bayramoglu G	TUR	GU	47	1,667	27
16	23	Toppare L	TUR	METU	37	664	17
21	15	Denizli A	CHI	CAS	34	1,114	20
Rank	**R (NC)(2)**	**Cluster 3 (Indian Blue)**	**C**	**ORG**	**NP(1)**	**NC(2)**	**HI(3)**
1	1	Fernandez-Lafuente R	SPA	CSIC	137	9,576	45
15	7	Rodrigues RC	BRA	UFRGS	38	2,721	22
29	27	Goncalves LRB	BRA	UFC	29	583	15

R (NP)(1)	**R (NC)(2)**	**Cluster 5 (Wine)**	**C**	**ORG**	**NP(1)**	**NC(2)**	**HI(3)**
26	26	Wilson L	CH	PUCV	32	593	14
30	30	Illanes A	CH	PUCV	29	466	13
Rank	**R (NC)(2)**	**Cluster 6 (Gray)**	**C**	**ORG**	**NP(1)**	**NC(2)**	**HI(3)**
23	22	Bolivar JM	AUS	GUT	33	693	18
25	25	Nidetzky B	AUS	GUT	32	643	16
Rank	**R (NC)(2)**	**Cluster 7 (Orange)**	**C**	**ORG**	**NP(1)**	**NC(2)**	**HI(3)**
13	5	Kim J	SK	KU	38	3,228	17
20	6	Wang P	CHI	CAS	35	2,765	19
Rank	**R (NC)(2)**	**Cluster 8 (Beige)**	**C**	**ORG**	**NP(1)**	**NC(2)**	**HI(3)**
27	11	Cosnier S	FRA	CNRS	30	2,020	20
Rank	**R (NC)(2)**	**Cluster 9 (Brown)**	**C**	**ORG**	**NP(1)**	**NC(2)**	**HI(3)**
28	20	Gupta MN	IND	IIT	30	879	19
Rank	**R (NC)(2)**	**Cluster 10 (Pink)**	**C**	**ORG**	**NP(1)**	**NC(2)**	**HI(3)**
19	13	Husain Q	IND	AMU	35	1,379	18
Rank	**R (NC)(2)**	**Cluster 11 (Violet)**	**C**	**ORG**	**NP(1)**	**NC(2)**	**HI(3)**
24	14	Minteer SD	USA	UU	33	1,376	17

Rank	R (NC)(2)	Cluster 4 (Yellow)	C	ORG	NP(1)	NC(2)	HI(3)	Rank	R (NC)(2)	Cluster 12 (Blue)	C	ORG	NP(1)	NC(2)	HI(3)
2	2	Guisan JM	SPA	CSIC	114	6,655	39	11	18	Mita DG	ITA	CNR	39	925	20
4	3	Mateo C	SPA	CSIC	52	4,833	30	**Rank**	**R (NC)(2)**	**Cluster 13 (Moss Green)**	**C**	**ORG**	**NP(1)**	**NC(2)**	**HI(3)**
10	4	Fernandez-Lorente G	SPA	CSIC	39	3,720	24	7	29	Pundir CS	IND	MDU	44	468	13
								Rank	**R (NC)(2)**	**Cluster 14 (Purple)**	**C**	**ORG**	**NP(1)**	**NC(2)**	**HI(3)**
								8	9	Xu ZK	CHI	ZU	42	2,087	26

R = Ranking; NP(1) = number of publications; NC(2) = number of citations; HI(3 = h-index; SPA= Spain; CHI= China; BRA= Brazil; USA= United States of America; COL= Colombia; SK= South Korea; AUS= Austria; IND= India; CH= Chile; TUR= Turquia; ITA= Italy; FRA= France; CSIC= Consejo Superior de Investigaciones Científicas; GU= Gazi University; CQU= Chongqing University; UFRGS= Universidade Federal do Rio Grande do Sul; DICP= Dalian Institute of Chemical Physics; HU= Hebei University; BUCT= Beijing University of Chemical Technology; GUT= Graz University of Technology; CAS= Chinese Academy of Sciences; TU= Tianjin University; UFC= Universidade Federal do Ceará; KU= Korea University; PUCV= Pontíficia Universidad Católica de Valparaíso; UU= University of Utah; MDU= Maharshi Dayanand University; ZU= Zhejiang University; CNR= Consiglio Nazionale delle Ricerche; METU= Middle East Technical University; AMU= Aligarh Muslim University; CNRS= National Center for Scientific Research; IIT= Indian Institute of Techonology.

Table 4. Top 50 most frequently used keywords on enzyme immobilization research (Author-Keywords and Keywords Plus) in the last 27 years (1991-2017).

R	Author-keywords	Ocurrences	R	Author-keywords	Ocurrences	R	Keywords Plus	Ocurrences	R	Keywords Plus	Ocurrences
1	immobilization	909	26	enzyme electrode	59	1	enzyme	795	26	hydrogen peroxide	179
2	enzyme immobilization	896	27	trypsin	58	2	enzyme immobilization	688	27	beads	165
3	immobilized enzyme	734	28	glutaraldehyde	57	3	protein	460	28	Escherichia-coli	164
4	biosensor	422	29	glucoamylase	56	4	stability	436	29	films	163
5	Lipase	299	30	flow injection	56	5	immobilization	421	30	surface	154
6	glucose oxidase	237	31	transesterification	55	6	glucose oxidase	413	31	microspheres	153
7	enzyme	235	32	amperometry	55	7	biosensor	399	32	water	144
8	chitosan	156	33	enzime stabilization	55	8	purification	381	33	oxidation	143
9	glucose	144	34	catalase	54	9	electrode	379	34	performance	142
10	adsorption	131	35	enzyme reactor	54	10	hydrolysis	374	35	silica	141
11	biocatalysis	115	36	acetylcholinesterase	54	11	adsorption	360	36	kinetics	140
12	beta-galactosidase	101	37	alpha-amylase	53	12	system	336	37	reactor	135
13	horseradish peroxidase	101	38	alginate	53	13	immobilized enzyme	335	38	chitosan	133
14	Laccase	100	39	biodiesel	51	14	sensor	333	39	Candida-rugosa lipase	129
15	stability	95	40	chemiluminescence	49	15	support	332	40	binding	129
16	covalent immobilization	82	41	hydrolysis	48	16	membrane	300	41	particles	127
17	flow injection analysis	80	42	peroxidase	48	17	stabilization	284	42	beta-galactosidase	126
18	Uréase	79	43	penicillin g acylase	46	18	oxidase	273	43	encapsulation	121
19	sol-gel	66	44	electrospinning	45	19	nanoparticles	239	44	flow injection analysis	115
20	invertase	66	45	carbon nanotubes	44	20	organic-solvents	214	45	optimization	106
21	kinetics	65	46	bioreactor	40	21	acid	212	46	biocatalysis	103
22	esterification	60	47	polyaniline	38	22	lipase	210	47	cytochrome-c	100
23	tyrosinase	60	48	mesoporous materials	38	23	glucose	210	48	amperometric biosensor	96

24	hydrogen peroxide	59	49	lactose hydrolisis	35	24	covalent immobilization	189	49	matrix	95
25	enzyme activity	59	50	enzyme stability	35	25	horseradish peroxidase	187	50	penicillin-g acylase	95

Red color = repeated words or synonymous, R=Rank.

CAPÍTULO 3

Topics related to electronic waste management: trends and perspectives[6]

Abstract

[6] **Submetido em:**

Environmental Science and Pollution Research

Electronic waste (e-waste) is a research topic of industrial and academic interest. However, due to the volume of the present scientific literature on e-waste topics, it is difficult to monitor the research trends in a certain subject of interest. Bibliometric analysis has been one of the most useful tools for measuring the scientific progress in a field of information science. In this study, a pre-assessment of past research and recent trends of researchers and countries related to e-waste between 1998 and 2017 were reported. Documents related to e-waste were retrieved from the Clarivate Analytics Web of Science© (WoS) database. A total of 2776 academic articles having "electronic waste" in the "Title", "Abstract, "Keyword" or "Keyword Plus" were retrieved and analyzed using bibliometric analysis methodology. Waste Management and Environmental Science & Technology were the most sought-after journals to disseminate the studies, and more than a third of the publications were developed from China (992 records). Studies related to "recycling", "printed circuit boards (PCBs)", "leaching and recovery of precious elements (*e.g.*, gold, copper)", and "environmental and human risks in recycling areas" have become the main subjects in recent years and in the present papers under study.

Keywords: e-waste; WEEE; international waste management; VOSviewer; bibliometric map.

1. Introduction

In recent decades, electronic waste (e-waste) has grown significantly in developed and developing countries as a result of several worldwide trends: *(i)* many people today have more than one electronic device, especially those dedicated to communication or information technology, and *(ii)* the lifespans of these devices, such as cell phones, computers, and tablets, are decreasing. The rapid progress of technology regularly provides more advanced devices and equipment. In this way, information and communication technology (ICT) instruments are becoming more affordable, and users change their devices more often to keep up with technological improvements (Baldé et al., 2017).

The global information society has grown very quickly due to the advantages related to communication, transport systems, mobile networks and services, delivery service facilities, and so on (Baldé et al., 2015). Present trends suggest that the generation of e-waste will increase substantially over the next few years (Baldé et al., 2017), and comprehensive studies for understanding these data and presenting trends in e-waste research are needed.

Parallel to the various problems related to electronic waste, management of e-waste has become a research topic in the last two decades (Widmer et al., 2005; Kiddee et., 2013). However, due to the numerous documents available in the scientific literature and the growth of published data in several research fields, it is difficult to provide a comprehensive and systematic overview from this information. Currently, due to progress in the development of new technologies, it is common to observe more attention being paid to computerized methods and tools for assessing the relevant information stored or indexed in big databases (Van Eck and Waltman, 2010). In this context, bibliometric methods have been used as a qualitative and quantitative approach to organizing, monitoring, describing and evaluating the documents from the scientific literature (Zupic and Cater, 2015).

Bibliometrics is a tool by which the state of the art of science and technology can be observed through the general production of scientific literature (Okubo, 1997). Bibliometric analysis involves a measurement of the scientific progress of a given field over time. It helps to explain the social, intellectual, and conceptual structure through bibliographic networks (Batagelj and Cerinsek, 2013), making it possible to examine the performances of countries, co-words, co-citations or co-authors and most trend topics, among others. The results are presented in various forms, such as mappings, to provide an overview of the relationships among participants and expand the means for analysis of a certain topic (Okubo, 1997).

In bibliometrics, there are two main ways to explore scientific literature data: performance analysis and scientific maps (Noyons et al., 1999a). The first approach is based on the productivity impacts and citations of scientific journals through popular metrics such as the *h*-index (author-level metric) (Hirsch, 2005), and the journal impact factor (Garfield, 1972). In the second approach, bibliometric maps show structural and dynamic aspects for visually representing scientific literature based on bibliometric data (Börner et al., 2003).

In this study, the combination of citation analysis and bibliometric maps was used to evaluate the scientific literature on topics related to electronic waste between 1998 and 2017. Presently, there is a lack of studies on the systematic evaluation of electronic waste topics in the scientific literature. In this sense, the goal of this paper was to reflect on the bibliometric analysis of the scientific literature and generate indicators on the "e-waste" topics through the WoS database. Moreover, the relation of these indicators to trends that involve the central theme "e-waste" for the most influential countries in the management of electronic waste was also discussed.

2. Method

2.1 Data retrieval

The dataset used in this research was downloaded from the online database of the Science Citation Index Expanded (SCI-E) in Clarivate Analytics' ISI - Web of Science© (https://webofknowledge.com/) on May 21, 2018. This citation index is usually assessed by academics for bibliometric studies (Milanez et al., 2013; Li et al., 2018; Romanelli et al., 2018), and it has an extensive and multidisciplinary coverage of bibliographic data considering major international and regional scientific journals around the world (Garfield, 2006; Garfield, 2007). In addition, it has been described as the world's leading database of science and technology journals, with a rigorous selection process (Jiupeng et al., 2012). Articles and reviews were predominantly for further analysis because they represent the majority of document types that included entire research ideas and results (Ho et al., 2010).

The first step of this research was to define the set of terms related to the central subject "electronic waste". Search expressions consisted of applying these terms to the "Topic" field, which seeks for publications through their article titles, abstracts, author keywords, and WoS-assigned keywords called Keywords Plus (Boudry et al., 2018). Application of Boolean operators and quotation marks was the key factor for selecting the final dataset (Ştirbu et al., 2015). In total, 2,776 publications were retrieved considering the timespan 1998-2017.

The term "international collaboration network" was designated to describe the number of co-authored publications among countries, organizations and universities in the last 20 years. Articles originating from England, Scotland, North Ireland, and Wales were all considered to be from the United Kingdom (UK). Articles from Hong Kong were included under the heading of China (Fu et al., 2013; Zhang et al., 2010). Impact factors (IFs) were taken from the JCR published in 2018 (Hirsch, 2005). The assessment involved the following information obtained from the collected sample: (1) publication activity – by year, by WoS category and by geographic distribution; (2) main journals – top 20; (3) most-cited papers – in the last 20 years and in the last 5 years; and (4) performance by country – the top 10 countries and author keyword analyses. The synthesis of the systematic literature review employed in this study is presented in Figure 1.

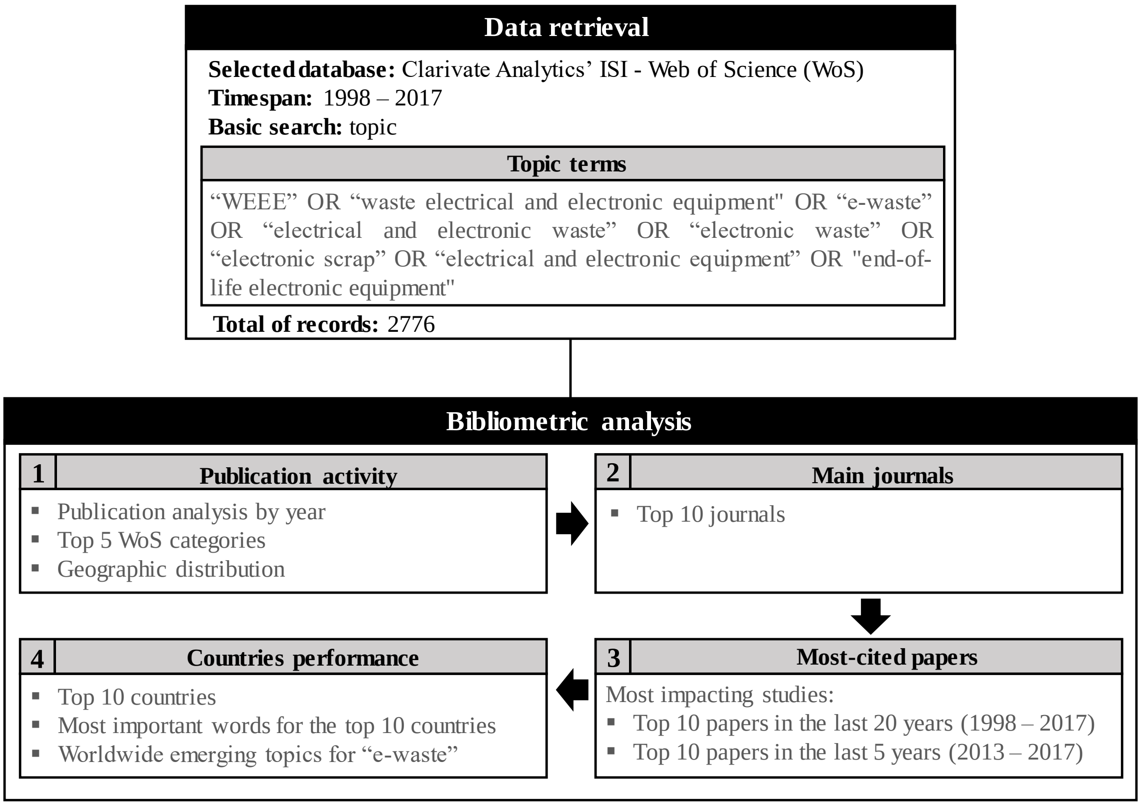

Figure 1. Process of systematic literature review.

2.2 Data analyses

All analyses were performed using the "Analyze Results" tool provided by the Web of Science with the support of MS Excel (v. 2016) to perform calculations and develop charts and tables (indicator visualization). Bibliometric mapping for author keywords was based on co-occurrence analysis using VOSviewer software (version 1.6.8; www.vosviewer.com) to visualize and understand how the 50 main terms are organized around the central term "electronic waste". VOSviewer uses clustering algorithms based on the strengths of the connections among items to help the analysis of the network (Van Eck and Waltman, 2010). Finally, the geographic distribution of the most productive countries was analyzed with support of ArcGIS® (v. 10.5) according to the number of publications to categorize the mapping classes. Repeated words and meaningless words (also called stop words) were not considered.

3. Results and Discussion

3.1 International scientific productivity

Primarily since the year 1990, electronic devices have changed and revolutionized people's lives all around the world. Currently, these devices are found in most countries (Kumar and Dixit, 2018). Many new electronic products are regularly introduced into the market, resulting in increased consumption and waste stream (Heacock et al., 2016). Electronic waste is the world's fastest growing type of waste. The rapid innovation of electronic products associated with the implementation of new functionalities, reduction of prices and increasing variety of options, which tend to reduce the life cycle of existing devices (Lundgren, 2012), has aggravated the world scenario of waste management.

Previous studies that used bibliometric analyses on the topic of environmentally friendly electronic waste have indicated that, from 1980 to 2016, the subject of electronic waste was an important topic on the international agenda (Durmusoglu, 2016). Waste management, recycling, raw material recovery, elemental analysis, and material flow analysis were considered the main emerging topics in the scientific literature and in e-waste statistics (Durmusoglu, 2016). Fig. 2 shows the evolution of the number of publications on electronic waste in relation to five main WoS categories in the last two decades.

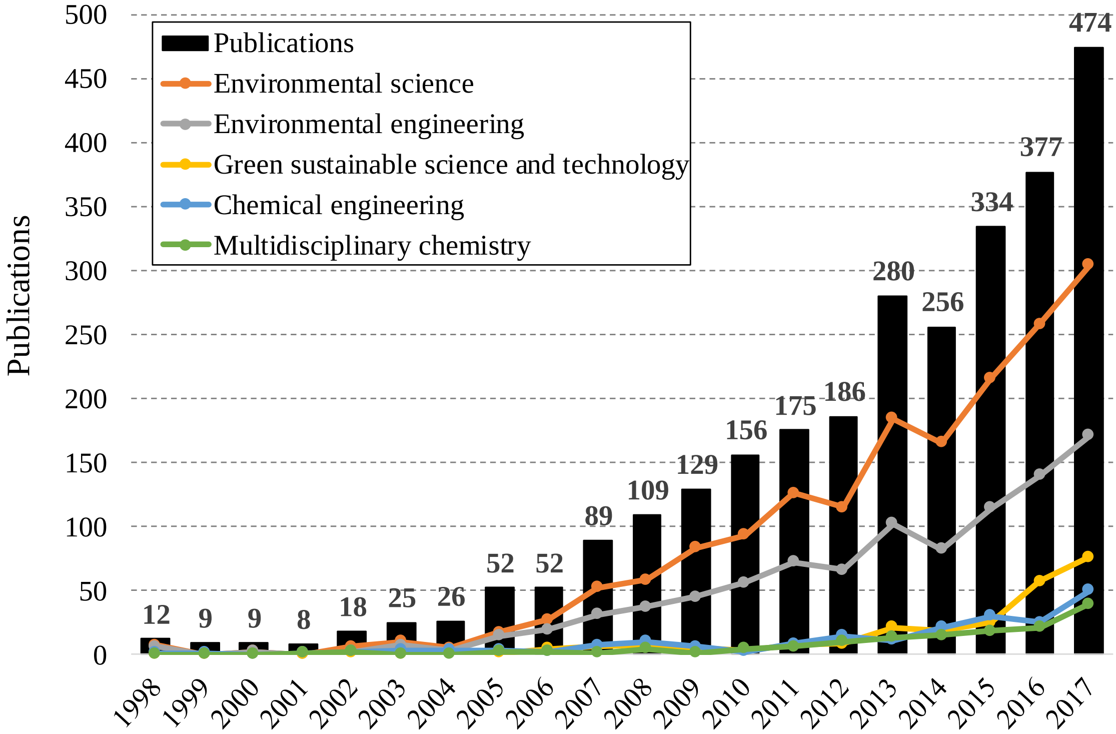

Figure 2. Total number of publications from the online database Web of Science (WoS) involving the topic "electronic waste" from 1998 to 2017 and its association with the growth trends of the top 5 main WoS categories.

In general, the analysis of Fig. 2 reveals three major moments in the development of scientific research on e-waste worldwide (1998 to 2017). From 1998 to 2004, there were fewer than 16 publications/year on average, which is a relatively small number, and the WoS categories cannot be highlighted. However, from 2005 to 2012 there was a linear increase in the annual number of publications, and the average for this time span exceeded 118 publications/year. The main categories were environmental science and environmental engineering. From 2007 to 2012, the number of publications increased at a rate of approximately 22% papers/year. More recently (2013 to 2017), the average number of publications was greater than approximately 336 publication/year, and the trends in the main WoS categories remained the same. The number of publications reached a peak in 2013 (280 papers), approximately 100 more papers than in the previous year (186 papers). In general, the research topics from 1998 to 2017 were primarily in the environmental science and environmental engineering WoS categories. The total of 1728 academic papers in environmental science comprised 62% of the papers retrieved for more than 100 subject categories. More than one third of the publications (35% of the total records) were in the field of environmental engineering, followed by green sustainable science and technology (9% of the total records) and by chemical engineering and multidisciplinary chemistry, with 7% and 5% of the total records, respectively. The category of green sustainable science and technology appears as an emerging topic primarily after 2015, as do chemical engineering and multidisciplinary chemistry.

The increasing number of e-waste studies related to environmental implications in a global scenario may be associated with the main issues posed by e-waste over the last 20 years (Lundgren, 2012):

(i) the large amount generated due to rapid obsolescence;

(ii) hazardous materials and adverse health and environmental problems;

(iii) complex and expensive e-waste treatment that imposes many challenges on the recycling industry;

(iv) a general lack of labor issues (standards and rights), legislation or enforcement surrounding it; and

(v) a general lack of information and financial incentives to cover the costs of correct e-waste management in a responsible way.

E-waste research has been addressed in 83 different countries worldwide. Figure 3 shows the most productive countries in terms of the number of publications. China (PRC), the United States (USA), Germany (GER), the United Kingdom (UK), India (IND), Japan (JPN), Italia (ITA), Australia (AUS), Brazil (BRA) and South Korea (KOR) are the 10 countries that have produced the most publications over the last 20 years. Among them, China has the most e-waste generation indexes and plays a key role in global e-waste management, including the manufacturing, refurbishment, reuse and recycling of e-waste (Baldé et al., 2017). More than 30% of the total number of published academic papers were produced in China (992 records). According to the most recent monitoring of the electronic waste stream published in 2017, most e-waste is generated in Asia. This region is responsible for 18.2 Mt of e-waste, which is equivalent to 4.2 kg/inhabitant (Baldé et al., 2017). In this context, the three other Asian countries with the highest number of papers published were India (149 records), Japan (145 records) and South Korea (81 records).

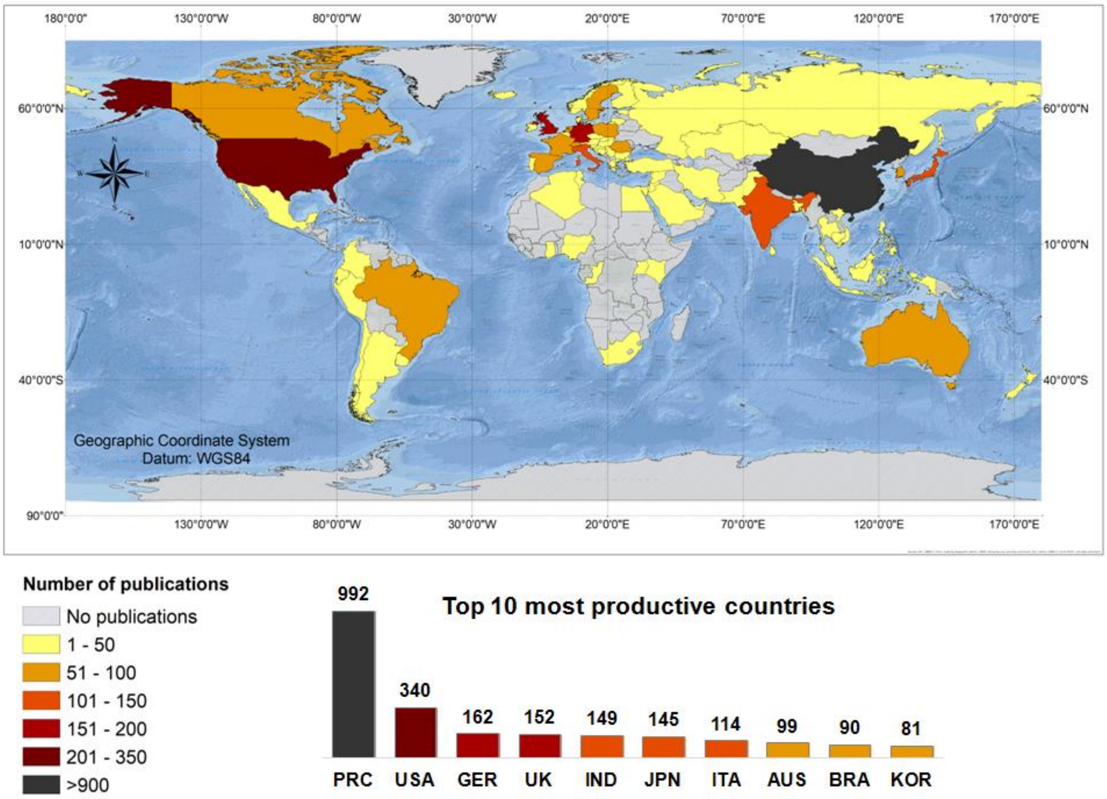

Figure 3. Global country performances according to the total number of publications on e-waste topics. PRC = People's Republic of China, USA = United States, GER = Germany, UK = United Kingdom, IND = India, JPN = Japan, ITA = Italy, AUS = Australia, BRA = Brazil, KOR = South Korea.

The United States (USA) produced 340 documents dedicated to electronic waste research in the last 20 years, the second largest number and approximately 12% of the worldwide total. The Americas generated approximately 11.3 Mt of e-waste in 2016 (7 Mt from North America, 1.2 Mt from Central America, and 3 Mt from South America), and the USA ranked second in e-waste generation around the world (6.3 Mt) (Baldé et al., 2017). Brazil was second in generating electronic waste in the Americas and placed ninth in the number of published studies on this topic, as shown in Fig. 3.

Germany was third in the number of published papers (162 records), followed closely by the United Kingdom, and Italy placed sixth. In total, 428 of the published papers were from European countries, corresponding to approximately 15% of the total number of academic papers retrieved. According to the countries most productive on the e-waste theme and the disposal of electronic waste generated in Europe, the total e-waste generation in 2016 was 12.3 Mt, corresponding to 16.6 kg per inhabitant. Germany generated 1.9 Mt in 2016, which was the highest amount in Europe. In contrast, Oceania generated the smallest amount of e-waste (0.7 Mt) but the largest amount per inhabitant (17.3 kg/inh) (Baldé et al., 2017). Australia was the main contributor to this e-waste amount and had 99 papers published on this topic.

3.2 Description of the main scientific journals

For this topic, it is discussed how the main journals related to e-waste research are organized in terms of the number of publications (ranking). Table 1 shows the 10 journals that have published the most studies on e-waste topics in the last 20 years. These journals represent more than 40% of all publications. The number of citations shows the total number of references cited for all items found in the organized dataset. This is the total sum of citations, including self-citations, which corresponds to the total number of articles cited from 1998 to 2017 for the WoS citation report. Overall, all retrieved papers were published in a wide range of more than 500 different journals. However, most journals (approximately 98%) have published fewer than 75 papers in the last two decades.

Table 1. Top ten journals ranked by the total number of papers published (1998 – 2017).

Rank	Journal	NP[a]	NC[b]	*h*-index[c]	Journal impact factor
1	Waste Management	245	5,237	39	4.723
2	Environmental Science & Technology	139	6,325	49	6.653
3	Journal of Cleaner Production	125	2,090	26	5.651
4	Resources, Conservation and Recycling	111	2,820	29	5.120
5	Environmental Science and Pollution Research	96	933	15	2.800
6	Journal of Hazardous Materials	94	4,330	34	6.434
7	Chemosphere	89	2,776	30	4.427
8	Science of the Total Environment	89	3,093	30	4.610
9	Waste Management & Research	88	1,286	18	1.631
10	Environmental Pollution	75	2,261	25	4.358

[a]Number of publications, [b]Number of citations, [c]*h*-index for these publications

Waste Management is the most popular journal for researchers in the field of electronic waste, with 245 publications. The sum of the citations was 5,237, and 39 papers had effectively 39 citations or more (see the *h*-index). However, *Waste Management* does not have the highest impact factor among the journals listed in Table 1. Importantly, *Environmental Science & Technology* is the most-cited journal, with 6,325 citations. This journal has the highest *h*-index (49) and impact factor (6.653), as well as the second most publications (139 papers published). The third most influential journal is the *Journal of Cleaner Production*, which published 125 papers (4.5% of the total records), followed by *Resources Conservation and Recycling* (4%)

and *Environmental Science and Pollution Research* (3.5%). In addition, other less represented journals published a significant number of papers (see details in Table 1).

3.3 Description of the most impactful papers

Citation analysis in bibliometrics studies has been established as an indicator of a paper's quality and contribution to a specific field (Garfield, 1979). Citation measures demonstrate the main contribution from an individual work. Therefore, the most impactful papers were assessed, and the ten most-cited papers are presented in Table 2. These papers have influenced many related studies, as evidenced by their number of citations. The most-cited paper (542 citations), entitled "Metallurgical recovery of metals from electronic waste: a review", was published in the *Journal of Hazardous Materials* in 2008. This journal was sixth in the ranking (Table 1). In general, the analyses of the most-cited papers revealed that there is no close relationship between the most-cited articles and the most influential journals (see Table 1). It must be emphasized that the longer a scientific article is indexed, the higher the probability that it will be cited. Items that have been recently published and have many citations may indicate new perspectives in the field (Okubo, 1997).

Table 2. Ten most-cited papers in the last 20 years (1998 – 2017)

Rank	Authors	Countries[a]	Title	Journal	Year	NC[b]
1	Cui, J.R. and Zhang, L.F.	NOR	Metallurgical recovery of metals from electronic waste: A review	*Journal of hazardous materials*	2008	542
2	Robinson, B.H.	NZL	E-waste: An assessment of global production and environmental impacts	*Science of the total environment*	2009	516
3	Cui, J.R. and Forssberg, E.	SWE	Mechanical recycling of waste electric and electronic equipment: a review	*Journal of hazardous materials*	2003	467
4	Wong, M.H. et al.	PRC and USA	Export of toxic chemicals - A review of the case of uncontrolled electronic-waste recycling	*Environmental pollution*	2007	408
5	Leung, A.O.W. et al.	PRC and USA	Spatial distribution of polybrominated diphenyl ethers and polychlorinated dibenzo-p-dioxins and dibenzofurans in soil and combusted residue at Guiyu, an electronic waste recycling site in southeast China	*Environmental science & technology*	2007	348
6	Ongondo, F.O. et al.	UK	How are WEEE doing? A global review of the management of electrical and electronic wastes	*Waste management*	2011	297
7	Wilford, B.H. et al.	CAN and UK	Polybrominated diphenyl ethers in indoor dust in Ottawa, Canada: Implications for sources and exposure	*Environmental science & technology*	2005	275
8	Fu, J. et al.	PRC	High levels of heavy metals in rice (*Oryza sativa* L.) from a typical E-waste recycling area in southeast China and its potential risk to human health	*Chemosphere*	2008	246
9	Huo, X. et al.	PRC	Elevated blood lead levels of children in Guiyu, an electronic waste recycling town in China	*Environmental health perspectives*	2007	244
10	Bi, X. et al.	UK and PRC	Exposure of electronics dismantling workers to polybrominated diphenyl ethers, polychlorinated biphenyls, and organochlorine pesticides in South China	*Environmental science & technology*	2007	241

[a]NOR = Norway, NZL = New Zealand, SWE = Sweden, PRC = People’s Republic of China, USA = United States, UK = United Kingdom, CAN = Canada

[b]NC = number of citations

In general, four studies have assessed the global trends in the production and recycling of electronic waste. Cui et al. (2008) presented an overview of the state of the art in the recovery of metals (especially precious metals) from electronic waste by metallurgical processes, including pyrometallurgical, hydrometallurgical, and biometallurgical processing. These authors highlighted two important points: *(i)* samples of electronic scrap for cell phones and printed circuit boards (PCBs) are composed of a large amount of precious metals and *(ii)* recycling of electronic waste is essential for the recovery of valuable elements. Robinson (2009)[30] assessed the present and future production of electronic waste associated with the potential of environmental contaminants and recycling. The author also emphasized that e-waste may contain valuable metals (*e.g.,* Cu and platinum groups), hazardous materials and potentially toxic elements (Pb, Sb, Hg, Cd, and Ni), polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs), dioxins, furans, polycyclic aromatic hydrocarbons (PAHs), polyhalogenated aromatic hydrocarbons (PHAHs), and hydrogen chloride. In this context, several papers have noted the importance of a prior characterization of e-waste before the recycling process. Cui and Forssberg (2003) highlighted that WEEE (waste electrical and electronic equipment) is significantly heterogeneous and complex in terms of composition, size, and shape of components. Furthermore, the mechanical/physical processing of WEEE is considered an indispensable process that provides improvements to a recycling system. A global review of e-waste management and a critical discussion of the generation, treatment, prevention, and regulation of WEEE in various countries and regions was reported by Ongondo et al. (2011).

Among the 10 most-cited papers in the last 20 years are five studies that have evaluated the presence of organic pollutants and heavy metals in different environmental regions of Southeast China (Bi et al., 2007; Fu et al., 2008; Huo et al., 2007; Leung et al., 2007; Wong et al., 2007). Four papers have addressed studies in the Guiyu region (Bi et al., 2007; Huo et al., 2007; Leung et al., 2007; Wong et al., 2007), which has become an intensive e-waste recycling site in China. Persistent organic pollutants, such as flame retardants (PBDEs), organochlorine pesticides (OCPs), polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs), PAHs and PCBs, were analyzed in the air, soil and combusted residue samples of Guiyu (Bi et al., 2007; Leung et al., 2007; Wong et al., 2007). High lead levels in the blood of children in Guiyu were also detected (Huo et al., 2007). Approximately 165 children from Guiyu were found to have a lead concentration ranging from 4.4 to 32.7 μg/dL. Taizhou in Zhejiang Province is another typical e-waste recycling region in China that was the subject of study. The authors who developed this research investigated ten potentially toxic elements (As, Ba, Cd, Co, Cr, Cu, Hg, Mn, Ni, and Pb) in rice samples (Fu et al., 2008). Finally, Wilford et al. (2005) evaluated PDBE indoor air levels in Ottawa, Canada. From the total concentration an average of 42% BDE209 (the major component of the deca-mix PBDE product) was found in all analyzed samples.

More recent publications with a high number of citations may highlight an innovation or new perspectives contained in the article (Okubo, 1997). Considering the increased number of publications between 2013 and 2017 (see Figure 1), a brief analysis was conducted of the 10 most-cited papers published in the last 5 years (see details in Table 3) to verify the recent trends on e-waste research and the study foci.

In the last five years, concerns about non-metallic fraction recycling (*e.g.*, plastic, glass, and PCB fractions) (Law et al., 2013) and estimates of the global transport (export and import) (Breivik et al., 2014) for the amount of e-waste generated around the world have become a prominent issue in the academic literature, which suggests a new trend in e-waste studies. Most of the studies in recent years with a higher number of citations have maintained the context previously observed. The health consequences of exposure to e-waste recycling regions (Law et al., 2014; Kiddee et al., 2013; Ali et al., 2013; Grant et al., 2013; Song and Li, 2014), the state of the art of different WEEE streams (Cucchiella et al., 2015) as well as PCB recycling (Ghosh et al., 2015), and an assessment of handling of e-waste in developed and developing countries were also evaluated (Sthiannopkao and Wong, 2013).

In general, the most impactful papers under study were published in the journals that have the highest number of publications on e-waste (Table 1). *Environmental Science & Technology* is the most frequently cited journal (Table 1) and has published the most impactful articles in recent years (Tables 2 and 3). China, which has an important influence on the academic literature for electronic waste, conducted most of the studies on this topic.

Table 3. Top ten most-cited papers published in the last 5 years (2013 – 2017).

Rank	Authors	Countries[a]	Title	Journal	Year	NC[b]
1	Law, R.J. et al.	UK, BEL, NOR, EGY, CAN, AUS and JPN	Levels and trends of PBDEs and HBCDs in the global environment: Status at the end of 2012	*Environment international*	2014	158
2	Kiddee, P. et al.	AUS and PRC	Electronic waste management approaches: An overview	*Waste management*	2013	133
3	Cucchiella, F. et al.	ITA and UK	Recycling of WEEEs: An economic assessment of present and future e-waste streams	*Renewable & sustainable energy reviews*	2015	106
4	Sthiannopkao, S. and Wong, M.H.	KOR and PRC	Handling e-waste in developed and developing countries: Initiatives, practices, and consequences	*Science of the total environment*	2013	99
5	Ghosh, B. et al.	IND	Waste Printed Circuit Boards recycling: an extensive assessment of current status	*Journal of cleaner production*	2015	84
6	Ali, N. et al.	BEL, KWT and PAK	Levels and profiles of organochlorines and flame retardants in car and house dust from Kuwait and Pakistan: Implication for human exposure via dust ingestion	*Environment international*	2013	84
7	Wang, R.X. and Xu, Z.M.	PRC	Recycling of non-metallic fractions from waste electrical and electronic equipment (WEEE): A review	*Waste management*	2014	77
8	Grant, K. et al.	AUS	Health consequences of exposure to e-waste: a systematic review	*Lancet global health*	2013	75
9	Song, Q.B. and Li, J.H.	PRC	A systematic review of the human body burden of e-waste exposure in China	*Environment international*	2014	74
10	Breivik, K. et al.	NOR, CAN and UK	Tracking the global generation and exports of e-waste. Do existing estimates add up?	*Environmental science & technology*	2014	73

[a]UK = United Kingdom, BEL = Belgium, NOR = Norway, EGY = Egypt, CAN = Canada, AUS = Australia, JPN = Japan, PRC = People's Republic of China, ITA = Italy, KOR = Republic of Korea, IND = India, KWT = Kuwait, PAK = Pakistan

[b]NC = number of citations

3.4 Research emphases: Author's keywords analysis

Author keyword analysis can offer information on research trends (Zhi and Ji, 2012). Garfield (1990) reported that statistical analyses of keyword searches successfully indicate future science directions. Bibliometric analysis using author keywords has been demonstrated recently (Chiu and Ho, 2007). The statistical analysis of author keywords revealed that 5,359 different author keywords have been used from 1998 to 2017. Among them, 1,233 (23%) appeared twice, 633 (12%) appeared three times, and 400 (7%) appeared four times or more. This probably suggests a great diversity of research foci (Chen et al., 2014; Chuang et al., 2007). A bibliometric mapping analyses was developed for the top 50 most influential author keywords in the theme. Fig. 4 shows one network, where the size of the node is proportional to the number of publications and the thickness of the edges. The colors indicate which cluster the item belongs to. In general, the most frequent terms were e-waste, recycling, WEEE and electronic waste, which presented 426, 306, 242, and 186 occurrences, respectively.

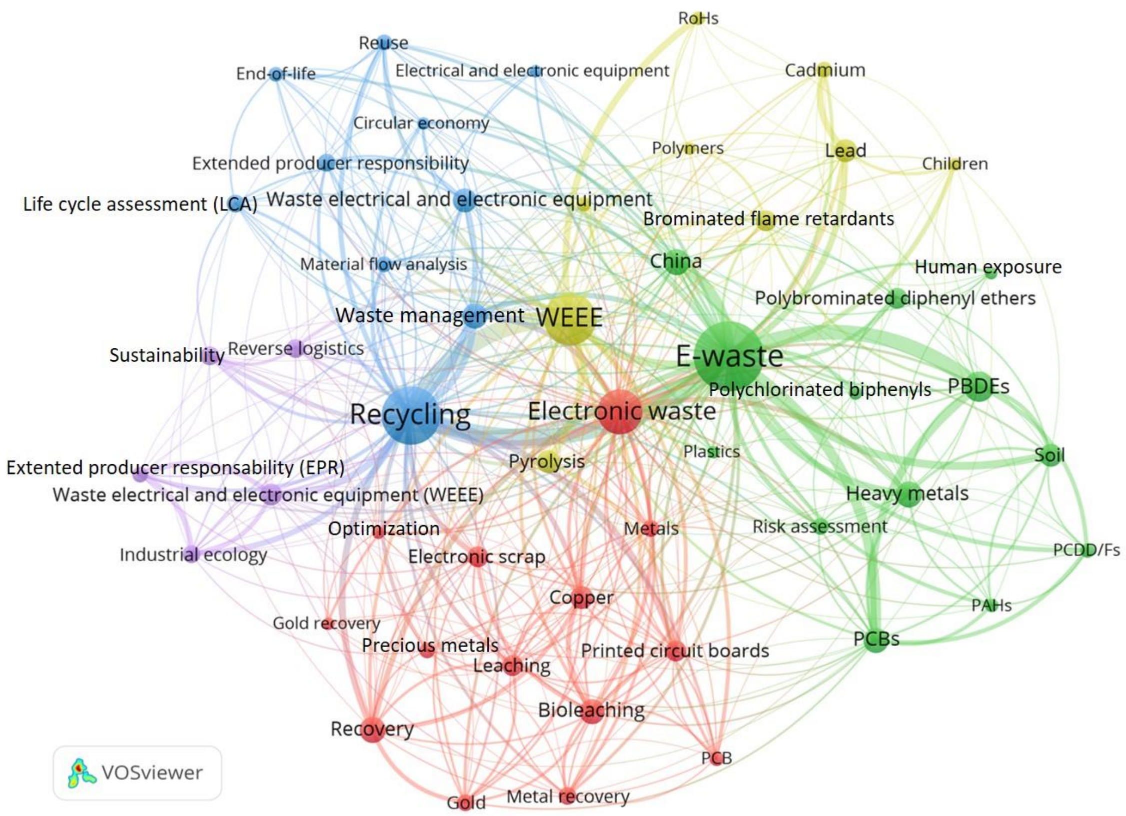

Figure 4. Bibliometric mapping of the 50 most important author keywords.

The cluster analysis of Fig. 4 reveals that these terms are central to the topic of "e-waste management" and link the other fields that are derived from this topic. The terms were divided into clusters according to the co-occurrence and association of terms in the literature. Cluster 1 (red) shows study concepts that are focused on “leaching /bioleaching of printed circuit boards for recovery of valuable metals (*e.g.*, copper and gold)”. In Cluster 2 (green), the “identification of environmental risks and human exposure of persistent organic pollutants such as flame retardants (PBDEs), PCDDs/Fs, PAHs, PCBs and heavy metals” were primarily the focus of research. According to the terms of cluster 3 (blue), the research foci were related to the “assessment of the life cycle and reuse of e-waste”. Topics in “heavy metals/flame retardants and their health risks” were highlighted in cluster 4 (yellow). In cluster 5 (purple), studies were basically focused on issues associated with the “reverse logistics for the life cycle of electronic waste and extended producer responsibility (EPR)”. This last topic is an emerging research field in several countries, especially developing countries (Kiddee et al., 2013). Several strategies presently being used in certain countries, such as life cycle assessment (LCA), material flow analysis (MFA), multicriteria analysis (MCA) and EPR, have been developed to manage e-waste primarily in developed countries (Kiddee et al., 2013). Extended producer responsibility is a good approach to solving the growing e-waste problems. If manufacturers take back items collected by retailers or local governments, there are two important aspects that must be highlighted: *(i)* a correct management and safe destruction of end-of-life (EoL) electronic goods and *(ii)* recovery of materials that can be reused in the production sector of new electronics (Kiddee et al., 2013).

The present study adopted a more limited search criterion because a systematic review of general topics of research is limited to addressing the most relevant trends in the academic literature. Therefore, analyses of the top 50 author keywords were performed through co-occurrence analysis for the top 10 countries (see Supplementary material for detailed information, Appendix A. Figs. 1S-10S). This approach was applied to identify – among other main words – emerging research fields in employment for the most influential countries for e-waste studies.

Table 4 shows the top ten countries, the total number of articles published in the e-waste field, and the ten most important author keywords (highest occurrence number) in the papers from each country. These are the results for the most important topics of each country after discounting words that were search terms (e-waste, electronic waste, WEEE and waste electrical and electronic equipment) or that were terms common to all evaluated datasets, such as recycling, e-waste recycling, flame retardants (PBDEs) and persistent organic pollutants (*i.e.*, PCBs, PBBs, PCDD/Fs and PAHs).

3.4.1 China

For many decades, China has played a role of paramount importance in global waste management. In addition to being a world power in the production of new technologies, it contributes to the most critical scenario of WEEE generation in the world. A few studies indicate that more than half of the e-waste collected for recycling in developed countries is sent to developing countries for processing or final disposal (Sthiannopkao and Wong, 2013). China is generally considered the largest importer and recycler of e-waste globally. China has become the leading destination, among other sites such as India and African countries, due to cheap labor in several regions for informal dismantling and recycling activities (Breivik et al., 2014). Thus, it is not surprising that China is the top country for publishing and research in the e-waste field.

Informal e-waste processing is common in some regions of China. Almost 80% of families in Southeast China work in e-waste recycling (Bi et al., 2007). Guiyu (GY), Qingyuan (QY), Taizhou (TZ), and a set of other cities in China have large regions of e-waste processing (Wang et al., 2011). In this context, the keyword "China" mostly appears in relation to "heavy metals", "contamination by flame retardants (PBDEs) and persistent organic pollutants (*e.g.*, PCBs, PBBs, PCDD/Fs and PAHs)", which have been the focus of research in this country in recent years. The "assessment of risk to human health" (especially children and expectant mothers) of hazardous materials is frequently reported in the scientific literature. The "bioleaching efficiency of copper" – among other metals such as Zn and Al – from waste printed circuit board is a topic with less occurrence in the papers under study, which can be correlated to the subjects of the most recently published papers from China (see Table 4).

3.4.2 USA

For the USA, the author keyword analysis identified research terms such as "extended producer responsibility (ERP)", "industrial ecology", "reverse logistics" and "product take-back" in combination with potentially hazardous elements, *i.e.*, "heavy metals" (Table 4). Currently, problems related to environmental considerations have also become a topic of important discussion and have gained attention from policy makers. Faced with an increase in the amounts of waste, several governments have revised their policies and implemented a post-consumer responsibility for producers.

Table 4. Top 10 countries and the 10 most important words for each country according to thel author keywords analysis.

Rank	Country[a]	NP[b]	Ten most recurrent words
1	PRC	992	China, soil, heavy metals, lead, risk assessment, bioaccumulation, cadmium, children, bioleaching, copper
2	USA	340	lead, extended producer responsibility (EPR), industrial ecology, waste management, reverse logistics, material flow analysis, cadmium, environment, heavy metals, product take-back
3	GER	162	RoHS, industrial ecology, critical metals, rare earth elements, material flow analysis, precious metals, resource recovery, polymer recycling, X-ray fluorescence, reference material
4	UK	152	industrial ecology, pyrolysis, extended producer responsibility (ERP), reuse, sustainability, environment, product take-back, plastic, remanufacturing, mobile phone
5	IND	149	recovery, printed circuit boards (PCBs), metal recovery, leaching, waste management, separation, gold, advance recovery fee, multi-stakeholder analysis, game theory
6	JPN	145	Vietnam, recovery, Ghana, population balance model, steam gasification, hexabromocyclododecanes (HBCDs), dioxins, indium, soil, pyrolysis
7	ITA	114	pyrolysis, life cycle assessment, yttrium, hydrometallurgy, rare earths, printed circuit boards (PCBs), circular economy, indium, leaching, mobile phones
8	AUS	99	bioleaching, soil, heavy metals, copper, waste printed circuit boards (WPCBs), chelator, electronic scrap, phytoremediation, children, sustainability
9	BRA	90	printed circuit boards (PCBs), copper, reverse logistic, mobile phones, mechanical processing, polymers, characterization, leaching, chemometrics, laser-induced breakdown spectroscopy (LIBS)
10	KOR	81	bioleaching, moderate thermophiles, hydrophilization, tin, electronic scrap, extended producer responsibility (EPR), copper, nickel, printed circuit boards, waste management

[a]PRC = People's Republic of China, USA = United States, GER = Germany, UK = United Kingdom, IND = India, JPN = Japan, ITA = Italy, AUS = Australia, BRA = Brazil, KOR = South Korea
[b]NP = **number of** publications.

The main result of this project was the guidance manual for governments that was published in 2001 (OECD, 2016). In this guide, the EPR program sets the key role in the management of products. According to the Organization for Economic Co-operation and Development (OECD), EPR is a concept whereby producers and importers of products must take a degree of responsibility for the environmental impact of a product, especially regarding collecting, dismantling, and recycling in the post-consumer phase. Since then, in the last decade, there has been a substantial increase in implementation and interest in EPR programs (Kaffine and O'Reilly, 2013).

Comparing the regional distribution of EPR programs, almost 50% of EPR systems have been implemented in North America, followed by Europe with 42% (Kaffine and O'Reilly, 2013). Regarding the policy instrument used, a vast majority of EPR programs use take-back requirements as their key policy instrument, sometimes in combination with advance disposal fees (ADFs). Most EPR systems focus on the extensive damage due to potentially hazardous electronic waste. Within the US, 50%, 8%, 24% and 7% of the policies cover electronics, packaging, tires, and vehicles/batteries, respectively (Kaffine and O'Reilly, 2013).

3.4.3 Germany

The most important topics among the published studies of German researchers and collaborators were cited as economically relevant metals, such as Cu and Au ("precious metals"), "critical metals", such as Ga, Ge, In, and Pd, and "rare earths". The context of these elements is related to the worldwide supply of raw materials for industrial sectors that is vulnerable due to diminishing natural reserves and political conflicts in countries that exploit such resources (Zhang et al., 2017). To enable a continuous and sustainable supply, studies of "resource recovery" from secondary sources have been increasing and offer promising potentials. However, although WEEE contains precious metals and important non-metallic fractions (polymers), it also contains hazardous substances. The term "RoHS" (restriction of hazardous substances) is highly associated with the use of brominated substances as flame retardants in polymers, such as PBB and PBDE, that are limited in European countries by Directive 2011/65/EU (EC, 2011).

In addition, emerging separation technologies are discussed in the literature to improve recycling results. The processes can be combined with spectroscopic techniques, such as near-infrared (NIR) spectroscopy and "X-ray fluorescence" (XRF). "Reference materials" can be used to validate and evaluate the accuracy of developed methods. However, when reporting the use or preparation of reference materials, most studies are related to polymer analysis (Altwaiq et al., 2003; Pohlein et al, 2009; Roth et al., 2015). Presently, there is a lack of comprehensive reference samples for WEEE.

3.4.4 United Kingdom

The most highlighted words for studies from the UK are related to sustainable e-waste recycling, which is important not only for the e-waste treatment and to avoid “environmental impacts” but also for recovery of valuable elements. These are essential points for manufacturers engaging in programs such as “reverse logistics, industrial ecology, and product take-back projects in a sustainable practice”. Producers that expand their businesses and enter into product recovery projects are seeking, among other aspects, to generate profits for their company by replacing raw material inputs (recycling and recovery of valuable materials) or inserting themselves into new segments in the market by using reprocessed products (“reuse”, “remanufacturing”, and reconditioning) (Stindt and Sahamie, 2014). “Extended producer responsibility (EPR)” has also captured the attention of most European contributors following the introduction of EU directives. Producers with economic incentives to reduce the environmental impact of their products have implemented the directives of EPR, and 34% cover electronics (Kaffine and O’Reilly, 2013).

3.4.5 India

Many scientists have been involved in “leaching processes and recovery of valuable metals from electronic waste”. “Printed circuit boards (PCBs)” have been the subject of several works over the last 20 years. This is not surprising because valuable substances are in PCBs, making PCB waste an economically attractive urban ore for recycling (Ghosh et al., 2015). On the other hand, topics in “game theory for analysis of the strategies of the stakeholders” for creating the best situation for waste management for manufacturers, consumers and the environment were also highlighted in the author keyword analysis. The game theoretic approach is based on a mathematical tool (Von Neumann and Morgenstern, 1944) responsible for analyzing the strategies by identifying the equilibrium points for various scenarios simultaneously. As an example, this approach may be used to formulate economically viable and environmentally friendly solutions to issues related to e-waste streams, as discussed by Kaushal and Nema (2013).

3.4.6 Japan

Japan has conducted studies on environmental issues primarily associated with chemical contamination in Asian countries. Due to activities in the areas of e-waste recycling, studies investigated whether chemical pollutants – among them, halogenated flame retardants and "hexabromocyclododecanes (HBCDs)" – have spread to other countries in the region. In Asia, particularly in China, activities primarily related to the recycling of electronic waste and damage to the environment by flame retardants and persistent organic pollutants have been extensively reported, as mentioned before. However, there is little relevant information on Asian countries that surround this region, such as Japan, South Korea, "Vietnam" and India (Li et al., 2017). In addition, a concern of other developing countries, such as "Ghana", has emerged in recent years. Accra (Ghana) has a large informal e-waste recycling center, and studies on environmental exposure to chemicals/substances emitted from e-waste recycling sites and their effects on human health have been reported (Tokumaru et al., 2017; Tue et al., 2017).

Monitoring the amount of an e-waste stream is essential for many sectors, but it is not a simple step to run. Faced with a large amount of e-waste generated annually and a wide variety of complex materials found in this waste, it is difficult to monitor the flow of e-waste. In addition, some countries do not have official statistics on this type of waste. The "population balance model (PBM)" based on the WEEE generated has been used to understand the e-waste production estimates. In addition, the amount of critical raw materials (*e.g.*, "indium" content in LCD monitors) in WEEE has also been projected using the PBM (Yamasue et al., 2007).

The term "steam gasification" is most closely related to effective processes for producing clean hydrogen from WEEE content. The reaction usually proceeds through an initial "pyrolysis" of the e-waste and a later gasification of char (Zhang et al., 2013).

3.4.7 Italy

Pyrolysis has been a traditional process for metal recovery from electronic waste equipment. However, the main challenges of this process are dehalogenation, avoidance of the emission of highly toxic pollutants (*i.e.*, PBDEs, PBDD/Fs, PAHs, PCBs, and heavy metals) and the preparation, accumulation and separation of the metals in the recycling process. In this context, in recent decades, a greater attention to hydrometallurgical processes based on the leaching of a variety of elements has been reported (Cui and Zhang, 2008).

Compared to pyrometallurgy processes, hydrometallurgical methods are more accurate, more predictable, and easier to control (Andrews et al., 2000). For leaching, various agents can be used, including cyanide, halide, thiourea, and thiosulfate, followed by a recovery process using methods such as cementation, solvent extraction, adsorption on activated carbon, and ion exchange (Cui and Zhang, 2008). Due to the increasing demand for critical elements, the current applications have been the “recovery of critical materials like indium, yttrium, and rare earths, among other materials less exploited” (Dodson et al., 2015; Venkatesan et al., 2018).

The recycling of e-waste is one of the measures that helps to maintain the economic model based on resource optimization while promoting the use of waste as a resource. A “circular economy (EC)” is a regenerative system in which the consumption of raw material input and the generation of residue are minimized through measures such as e-waste maintenance, repair, reuse, remanufacturing, refurbishing, and recycling. To achieve models that are economically and environmentally sustainable, the “life cycle assessment (LCA)” method can be used to support the analysis of the impacts and benefits associated with recycling and bring significant gains to the regenerative system.

3.4.8 Australia

“Bioleaching” is a process that has been explored for many years for metal extraction from ores. On the other hand, the use of microbiological processes for extraction of copper and valuable elements in e-waste has been less explored/investigated until the present day (Cui and Zhang, 2008).

In addition, the highlighted terms "soil, heavy metals and copper" are associated with "phytoremediation" processes. The decontamination of the soil in regions that have suffered environmental impacts from an e-waste recycling site has been recently reported (Luo et al., 2017a; Luo et al., 2017b).

3.4.9 Brazil

PCBs are one of the components of electronic waste for which reuse and recycling has not been effectively solved. However, there is an extensive literature on PCB recycling (Marques et al., 2013). The composition of these materials is very rich and complex due to the diversity of materials, and in general, a PCB board is composed of 40 wt.% metals, 30 wt.% plastic and 30 wt.% ceramic. It is reported that approximately one-third of the weight of PCBs is copper, which is recoverable by chemical methods (Marques et al., 2013), and if a suitable treatment and recovery process is applied, waste PCBs might serve as a secondary copper source.

However, in Brazil, the recovery processing of metals contained in PCBs – among other electronic wastes – has primarily been developed by foreign companies (Europe, Asia and

North America) (Neto et al., 2017). The main barrier for Brazilian producers to adopt WEEE reverse logistics measures for recycling and reuse is the lack of technology to handle PCBs. Presently, the main recycling activity involves polymers, which requires a simpler technology (Neto et al., 2017). In this context, the recycling of PCBs is a relatively new opportunity for Brazil in terms of processes related to the extraction and reuse of raw materials (precious metals).

In addition, search topics in "e-waste characterization, chemical analysis by laser-induced breakdown spectroscopy (LIBS), and chemometrics" have emerged as a common trend in the field of e-waste research in recent years. LIBS is an emerging technique in analytical chemistry and has demonstrated a great potential for different applications. In this sense, several researchers have proposed methods applying the LIBS technique to the analysis of different materials in electronic waste, such as polymers (Costa et al., 2017a; Costa et al., 2017b), flame retardants and hazardous elements (Stepputat and Noll, 2003), PCBs (Carvalho et al., 2015), rare earth elements in magnets (Martin et al., 2015) and scraps of mobile phones (Aquino et al., 2015), among other applications. Chemometrics has been frequently reported with LIBS applications, as it is often better for data analysis when extracting and visualizing the information inherent in chemical data by application of suitable mathematical and statistical methods. In addition, experimental design, for planning and performing experiments to obtain the resulting data with maximum information, can also be performed (Wold, 1991).

3.4.10 South Korea

As discussed previously, most hydrometallurgy techniques for e-waste metal recovery involve cyanide and halide leaching of valuable elements (Zupic and Cater, 2015). However, “bioleaching” has been reported as an environmentally friendly technique for recovering metals from primary and secondary metal sources. The use of microorganisms for metal extraction offers a number of advantages compared to conventional methods. These include a low operating cost (an economic method), lower generation of waste, and high efficiency in detoxifying effluents (Cui and Zhang, 2008). Bioleaching using “moderate thermophilic bacteria” for maximal extraction of metals from electronic scraps has been frequently reported in the published articles under study (Ilyas et al., 2013; Ilyas et al., 2014; Xia et al., 2017).

Regarding the non-metallic fraction, different techniques for separating polymers have been developed, such as electrostatic separation, gravitational separation, selective dissolution, and automated sorter systems based on laser scanning (*e.g.*, LIBS (Costa et al., 2017a) and Raman (Sommer and Rich, 2001)) and infrared or X-ray spectroscopy (Schlummer, 2014). In addition, the froth flotation technique has received attention as an alternative method due its efficiency in separating a mix of waste polymers having similar characteristics, such as density, surface hydrophobicity, and dielectric constant (Wang et al., 2014). Recently, several studies have shown progress in selective surface "hydrophilization of plastics" to allow separation of different polymers (Mallampati et al., 2017; Truc and Lee, 2017).

4. Conclusions

Over the last two decades, much has been developed for and learned about the management of electronic waste. A general review of the body of literature on e-waste reveals that a rapid development on this subject has occurred primarily in the past decade, when more than 100 articles were published per year. On the other hand, we must recognize that due to the large amount of e-waste generated year-by-year and the complexity of the e-waste, this research topic still has a long way to go.

The journal that published the most articles on the topic of electronic waste did not introduce the most impactful papers in the field. *Waste Management* is the most sought-after journal among researchers, but *Environmental Science & Technology* has the papers with the highest number of citations. In addition, among the total number of articles published between 1998 and 2017, the most active country, with more than one third of the publications, was the China (PRC). This fact may be linked to China having the highest indexes of e-waste generation and playing a key role in global e-waste management, including the manufacturing, refurbishment, reuse and recycling of e-waste.

Given the sheer volume of the scientific literature, the bibliometric mapping was a powerful tool for studying the connections and occurrences of the most influential terms in the electronic waste domain. The most important research focuses were on "leaching/bioleaching and recovery of valuable metals", "environmental and human risks after exposure to hazardous materials", "assessment of the life cycle, reverse logistics and reuse of e-waste" and "extended producer responsibility (EPR)".

Developing countries are beginning catch up on issues once touched upon by the most influential countries in the field of e-waste, and they are beginning to see "electronic waste" no longer as a solid waste but as a "source of resources". After individual analysis of the author keywords for the top ten countries, it was observed that some of them presented concerns related to waste management (the UK and USA, for example). Other countries, such as China and Japan, presented studies about the environmental impact. Germany and Brazil were the only two countries that presented studies related to analytical techniques for waste characterization (X-ray fluorescence and laser-induced breakdown spectroscopy).

Search topics such as “printed circuit boards”, “leaching and recovery of precious metals”, “recycling”, “environmental and human damages in recycling areas”, “EPR programs” and “life cycle assessment” began to enter the agenda of researchers in recent years, and they are also current topics of research in different countries. In addition, emerging separation technologies to help the recycling process are discussed in the scientific literature. These processes can be combined with analytical techniques, such as near-infrared (NIR) spectroscopy, X-ray fluorescence (XRF) spectrometry, and laser-induced breakdown spectroscopy (LIBS).

Finally, the results and the analysis of the emerging topics in e-waste research suggest that future studies should be devoted to *(i)* critical materials (*e.g.*, In, Ga, Pd and rare earth elements) due to the scarcity and demand for these year-by-year; *(ii)* electronic devices that have a short lifespan and make up an important source of valuable materials (*e.g.*, mobile phones, tablets, and laptops); *(iii)* establishment of directives to restrict toxic elements in e-waste, especially developing countries that have not been implemented such policies; and *(iv)* certified reference materials (CRMs), as there is presently a lack of comprehensive reference samples for WEEE. In addition, other specific topics may appear upon a more in-depth search of more advanced studies on each topic.

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Supplemental Data

Avalilable (temporarily) at:

https://drive.google.com/open?id=1SdKFKqqKLKiqe-i4TH2AMq49JEfq9NKX

References

Ali N, Ali L, Mehdi T, Dirtu AC, Al-Shammari F, Neels H, Covaci A (2013) Levels and profiles of organochlorines and flame retardants in car and house dust from Kuwait and Pakistan: Implication for human exposure via dust ingestion. Environ. Int. 55:62–70.

Andrews D, Raychaudhuri A, Frias C (2000) Environmentally sound technologies for recycling secondary lead. J. Power Sources 88:124–129.

Aquino FWB, Santos J M, Carvalho RRV, Coelho JAO, Pereira-Filho ER (2015) Obtaining information about valuable metals in computer and mobile phone scraps using laser induced breakdown spectroscopy (LIBS). RSC Adv. 5:67001–67010.

Baldé CP, Kuehr R, Blumenthal K, Gill SF, Kern M, Micheli P, Magpantay E, Huisman J (2015) E-waste statistics: Guidelines on classifications, reporting and indicators. United Nations University (UNU), IAS - SCYCLE, Bonn, Germany.

Baldé CP, Forti V, Gray V, Kuehr R, Stegmann P (2017) The global e-waste monitor – 2017. United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn, Geneva, Vienna.

Batagelj V, Cerinsek M (2013) On bibliographic networks. Scientometrics 96:845–864.

Bi X, Thomas GO, Jones KC, Qu W, Sheng G, Martin FL, Fu J (2007) Exposure of electronics dismantling workers to polybrominated diphenyl ethers, polychlorinated biphenyls, and organochlorine pesticides in South China. Environ. Sci. Technol. 41:5647–5653.

Börner K, Chen C, Boyack KW (2003) Visualizing knowledge domains. Annu. Rev. Inf. Sci. Technol. 37:179–255.

Boudry C, Baudouin C, Mouriaux F (2018) International publication trends in dry eye disease research: A bibliometric analysis. Ocul. Surf. 16:173–179.

Breivik K, Armitage JM, Wania F, Jones KC (2014) Tracking the global generation and exports of e-waste. Do existing estimates add up? Environ. Sci. Technol. 48:8735–8743.

Carvalho RRV, Coelho JAO, Santos JM, Aquino FWB, Carneiro RL, Pereira-Filho ER (2015) Laser-induced breakdown spectroscopy (LIBS) combined with hyperspectral imaging for the evaluation of printed circuit board composition. Talanta 134:278–283.

Chen H, Yang Y, Zhou J (2014) Global trends of compost research from 1997 to 2012: A bibliometric analysis based on SCI database. Asian J. Chem. 26:5242–5248.

Chiu WT, Ho YS (2007) Bibliometric analysis of tsunami research. Scientometrics 73:3-17.

Chuang KY, Huang YL, Ho YS (2007) A bibliometric and citation analysis of stroke-related research in Taiwan. Scientometrics 72:201–212.

Costa VC, Aquino FWB, Paranhos CM, Pereira-Filho ER (2017a) Identification and classification of polymer e-waste using laser-induced breakdown spectroscopy (LIBS) and chemometric tools. Polym. Test. 59:390–395.

Costa VC, Aquino FWB, Paranhos CM, Pereira-Filho ER (2017b) Use of laser-induced breakdown spectroscopy for the determination of polycarbonate (PC) and acrylonitrile-butadiene-styrene (ABS) concentrations in PC/ABS plastics from e-waste. Waste Manage. 70:212–221.

Cucchiella F, D'Adamo I, Koh SCL, Rosa P (2015) Recycling of WEEEs: An economic assessment of present and future e-waste streams. Renewable Sustainable Energy Rev. 51:263–272.

Cui JR, Forssberg E (2003) Mechanical recycling of waste electric and electronic equipment: a review. J. Hazard. Mater. 99:243–263.

Cui JR, Zhang LF (2008) Metallurgical recovery of metals from electronic waste: A review. J. Hazard. Mater. 158:228–256.

Dodson JR, Parker HL, García AM, Hicken A, Asemave K, Farmer TJ, He H, Clark JH, Hunt AJ (2015) Bio-derived materials as a green route for precious & critical metal recovery and re-use. Green Chem. 17:1951-1965.

Durmusoglu A (2016) A pre-assessment of past research on the topic of environmental-friendly electronics. J. Cleaner Prod. 129:305–314.

EC (2011) Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast). European Commission.

Fu J, Zhou Q, Liu J, Liu W, Wang T, Zhang Q, Jiang G (2008) High levels of heavy metals in rice (Oryza sativa L.) from a typical e-waste recycling area in southeast China and its potential risk to human health. Chemosphere 71:1269–1275.

Fu H, Wang M, Ho Y (2013) Mapping of drinking water research: A bibliometric analysis of research output during 1992–2011. Sci. Total Environ. 443:757–765.

Garfield E (1972) Citation analysis as a tool in journal evaluation. Science 178:417–479.

Garfield E (1979) Is citation analysis a legitimate evaluation tool? Scientometrics 1:359–375.

Garfield E (1990) KeyWords Plus Takes You Beyond Title Words. Part 2. Expanded Journal Coverage for Current Contents on Diskette Includes Social and Behavioral Sciences. Curr. Contents 33:5–9.

Garfield E (2006) Citation indexes for science. A new dimension in documentation through association of ideas. Int. J. of Epidemiol. 35:1123–1127.

Garfield E (2007) The evolution of the Science Citation Index. Int. Microbiol. 10:65–69.

Ghosh B, Ghosh MK, Parhi P, Mukherjee PS, Mishra BK (2015) Waste Printed Circuit Boards recycling: an extensive assessment of current status. J. Clean. Prod. 94:5-19.

Grant K, Goldizen FC, Sly PD, Brune MN, Neira M, Van den Berg M, Norman RE (2013) Health consequences of exposure to e-waste: a systematic review. Lancet Glob. Health 1:E350–E361.

Heacock M, Kelly CB, Asante KA, Birnbaum LS, Bergman AL, Bruné M, Buka I, Carpenter DO, Chen A, Huo X, Kamel M, Landrigan PJ, Magalini F, Diaz-Barriga F, Neira M, Omar M, Pascale A, Ruchirawat M, Sly L, Sly PD, Berg MV, Suk WA (2016) E-waste and harm to vulnerable populations: a growing global problem. Environ. Health Perspect. 124:550–555.

Hirsch J (2005) An index to quantify an individuals scientific research output. Proc. Natl. Acad. Sci. 102:16569–16572.

Ho YS, Satoh H, Lin SY (2010) Japanese lung cancer research trends and performance in Science Citation Index. Intern. Med. 49:2219–2228.

Huo X, Peng L, Xu X, Zheng L, Qiu B, Qi Z, Zhang B, Han D, Piao Z (2007) Elevated blood lead levels of children in Guiyu, an electronic waste recycling town in China. Environ. Health Perspect. 115:1113–1117.

Ilyas S, Lee JC, Chi RA (2013) Bioleaching of metals from electronic scrap and its potential for commercial exploitation. Hydrometallurgy 131–132:138–143.

Ilyas S, Lee JC, Kim BS (2014) Bioremoval of heavy metals from recycling industry electronic waste by a consortium of moderate thermophiles: process development and optimization. J. Cleaner Prod. 70:194–202.

Jiupeng MA, Hui-zhen FU, Yuh-shan HO (2012) The top-cited wetland articles in science citation index expanded: characteristics and hotspots. Environ. Earth Sci. 70:1039–1046.

Kaffine D, O'Reilly P (2013) What have we learned about extended producer responsibility in the past decade? A survey of the recent EPR economic literature. Organization for Economic Co-operation and Development (OECD). Available at: http://spot.colorado.edu/~daka9342/OECD_EPR_KO.pdf.

Kaushal RK, Nema AK (2013) Multi-stakeholder decision analysis and comparative risk assessment for reuse–recycle oriented e-waste management strategies: a game theoretic approach. Waste Manage. Res. 31:881–895.

Kiddee P, Naidu R, Wong MH (2013) Electronic waste management approaches: An overview. Waste Manage. 33:1237–1250.

Kumar A, Dixit G (2018) Evaluating critical barriers to implementation of WEEE management using DEMATEL approach. Resour., Conserv. Recycl. 131:101–121.

Law RJ, Covaci A, Harrad S, Herzke D, Abdallah MAE, Femie K, Toms LML, Takigami H (2013) Levels and profiles of organochlorines and flame retardants in car and house dust from Kuwait and Pakistan: Implication for human exposure via dust ingestion. Environ. Int. 55:55–62.

Law RJ, Covaci A, Harrad S, Herzke D, Abdallah MAE, Femie K, Toms LML, Takigami H (2014) Levels and trends of PBDEs and HBCDs in the global environment: Status at the end of 2012. Environ. Int. 65:147–158.

Leung AOW, Luksemburg WJ, Wong AS, Wong MH (2007) Spatial distribution of polybrominated diphenyl ethers and polychlorinated dibenzo-p-dioxins and dibenzofurans in soil and combusted residue at Guiyu, an electronic waste recycling site in southeast China. Environ. Sci. Technol. 41:2730–2737.

Li WL, Ma WL, Zhang ZF, Liu LY, Song WW, Jia HL, Ding YS, Nakata H, Minh NH, Sinha RK, Moon HB, Kannan K, Sverko E, Li YF (2017) Occurrence and Source Effect of Novel Brominated Flame Retardants (NBFRs) in Soils from Five Asian Countries and Their Relationship with PBDEs. Environ. Sci. Technol. 51:11126−11135.

Li K, Rollins J, Yan E (2018) Web of Science use in published research and review papers 1997–2017: a selective, dynamic, cross-domain, content-based analysis. Scientometrics 115:1–20.

Lundgren K (2012) The global impact of e-waste: Addressing the challenge. International Labour Organization, Programme on Safety and Health at Work and the Environment (SafeWork), Sectoral Activities Department (SECTOR), Geneva.

Luo J, Cai L, Qi S, Wu J, Gu XWS (2017a) A multi-technique phytoremediation approach to purify metals contaminated soil from e-waste recycling site. J. Environ. Manage. 204:17–22.

Luo J, Cai L, Qi S, Wu J, Gu XWS (2017b) Improvement effects of cytokinin on EDTA assisted phytoremediation and the associated environmental risks. Chemosphere 185:386–393.

Mallampati SR, Lee BH, Mitoma Y, Simion C (2017) Selective sequential separation of ABS/HIPS and PVC from automobile and electronic waste shredder residue by hybrid nano-Fe/Ca/CaO assisted ozonisation process. Waste Manage. 60:428–438.

Marques AC, Cabrera JM, Malfatti CF (2013) Printed circuit boards: A review on the perspective of sustainability. J. Environ. Manage. 131:298–306.

Martin MZ, Fox RV, Miziolek AW, DeLucia FC, André N (2015) Spectral analysis of rare earth elements using laser-induced breakdown spectroscopy. Next-generation spectroscopic technologies VIII. Series of books: Proceedings of SPIE. Vol. 9482.

Milanez DH, Schiavi MT, Amaral RM, Faria LIL, Gregolin JAR (2013) Development of carbon-based nanomaterials indicators using the analytical tools and data provided by the web of science database. Mater. Res. 16:1282–1293.

Mnim Altwaiq A, Wolf M, Van Eldik R (2003) Extraction of brominated flame retardants from polymeric waste material using different solvents and supercritical carbon dioxide. Anal. Chim. Acta 491:111–123.

Neto GCO, Correia AJC, Schroeder AM (2017) Economic and environmental assessment of recycling and reuse of electronic waste: Multiple case studies in Brazil and Switzerland. Resour., Conserv. Recycl. 127:29–41.

Noyons E, Moed H, Luwel M (1999) Combining mapping and citation analysis for evaluative bibliometric purposes: A bibliometric study. J. Am. Soc. Inf. Sci. 50:115–131.

Okubo Y (1997) Bibliometric Indicators and Analysis of Research Systems: Methods and Examples. OECD Science, Technology and Industry Working Papers, 1997/01, OECD Publishing, Paris.

Ongondo FO, Williams ID, Cherrett TJ (2011) How are WEEE doing? A global review of the management of electrical and electronic wastes. Waste Manage. 31:714–730.

OECD (2016) Extended Producer Responsibility: Updated Guidance for Efficient Waste Management. OECD publishing, Paris. Available at: https://doi.org/10.1787/9789264256385-en.

Pohlein M, Bertran RU, Wolf M, Van Eldik R (2009) Preparation of reference materials for the determination of RoHS-relevant flame retardants in styrenic polymers. Anal. Bioanal. Chem. 394:583–595.

Robinson BH (2009) E-waste: An assessment of global production and environmental impacts. Sci. Total Environ. 408:183–191.

Romanelli JP, Fujimoto JT, Ferreira MD, Milanez DH (2018) Assessing ecological restoration as a research topic using bibliometric indicators. Ecol. Eng. 120:311–320.

Roth T, Bertran RU, Latza A, Andörfer-Lang K, Hügelschäffer C, Pöhlein M, Puchta R, Placht C, Maid H, Bauer W, Van Eldik R (2015) Preparation of candidate reference materials for the determination of phosphorus containing flame retardants in styrene-based polymers. Anal. Bioanal. Chem. 407:3023–3034.

Schlummer M (2014) Recycling of postindustrial and postconsumer plastics containing flame retardants. Polym. Green Flame Retard. 25:869–889.

Sommer EJ, Rich JT (2001) Application of Raman spectroscopy to identification and sorting of post-consumer plastics for recycling. U.S. Patent 6313423.

Song QB, Li JH (2014) A systematic review of the human body burden of e-waste exposure in China. Environ. Int. 68:82–93.

Stepputat M, Noll R (2003) On-line detection of heavy metals and brominated flame retardants in technical polymers with laser-induced breakdown spectrometry. Appl. Opt. 42:6210–6220.

Sthiannopkao S, Wong MH (2013) Handling e-waste in developed and developing countries: Initiatives, practices, and consequences. Sci. Total Environ. 463–464:1147–1153.

Stindt D, Sahamie R (2014) Review of research on closed loop supply chain management in the process industry. Flex. Serv. Manuf. J. 26:268–293.

Ştirbu S, Thirion P, Schmitz S, Haesbroeck G, Greco N (2015) The utility of Google Scholar when searching geographical literature: comparison with three commercial bibliographic databases. J. Acad. Librariansh. 41:322–329.

Tokumaru T, Ozaki H, Onwona-Agyeman S, Ofosu-Anim J, Watanabe I (2017) Determination of the Extent of Trace Metals Pollution in Soils, Sediments and Human Hair at e-Waste Recycling Site in Ghana. Arch. Environ. Contam. Toxicol. 73:377–390.

Truc NTT, Lee BK (2017) Selective separation of ABS/PC containing BFRs from ABSs mixture of WEEE by developing hydrophilicity with ZnO coating under microwave treatment. J. Hazard. Mater. 329:84–91.

Tue NM, Goto A, Takahashi S, Itai T, Asante KA, Nomiyama K, Tanabe S, Kunisue T, (2017) Soil contamination by halogenated polycyclic aromatic hydrocarbons from open burning of e-waste in Agbogbloshie (Accra, Ghana). J. Mater. Cycles Waste Manage. 19:1324–1332.

Van Eck NJ, Waltman L (2010) Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 84:523–538.

Venkatesan P, Hoogerstraete TV, Hennebel T, Binnemans K, Sietsma J, Yang Y (2018) Selective electrochemical extraction of REEs from NdFeB magnet waste at room temperature. Green Chem. 20:1065–1073.

Von Neumann J, Morgenstern O (1944) Theory of Games and Economic Behavior. Princeton University Press, Princeton, NJ.

Wang C, Wang H, Liu Q, Fu J, Liu Y (2014) Separation of polycarbonate and acrylonitrile-butadiene-styrene waste plastics by froth flotation combined with ammonia pretreatment. Waste Manage. 34:2656–2661.

Wang LL, Hou ML, An J, Zhong YF, Wang XT, Wang YJ, Wu MH, Bi XH, Sheng GY, Fu JM (2011) The cytotoxic and genetoxic effects of dust and soil samples from e-waste recycling area on L02 cells. Toxicol. Ind. Health 27:831−839.

Widmer R, Oswald-Krapf H, Sinha-Khetriwal D, Schnellmann M, Boni H (2005) Global perspectives on e-waste. Environ. Impact Assess. 25:436–458.

Wilford BH, Shoeib M, Harner T, Zhu JP, Jones KC (2005) Polybrominated diphenyl ethers in indoor dust in Ottawa, Canada: Implications for sources and exposure. Environ. Sci. Technol. 39:7027–7035.

Wold S (1991) Chemometrics, why, what and where to next? J. Pharmaceut. Biomed. Anal. 9:589–596.

Wong MH, Wu SC, Deng WJ, Yu XZ, Luo Q, Leung AOW, Wong CSC, Luksemburg WJ, Wong AS (2007) Export of toxic chemicals - A review of the case of uncontrolled electronic-waste recycling. Environ. Pollut. 149:131–140.

Xia MC, Wang YP, Peng TJ, Shen L, Yu RL, Liu YD, Chen M, Li JK, Wu XL, Zeng WM (2017) Recycling of metals from pretreated waste printed circuit boards effectively in stirred tank reactor by a moderately thermophilic culture. J. Biosci. Bioeng. 123:714–721.

Yamasue E, Nakajima K, Daigo I, Hashimoto S, Okumura H, Ishihara KN (2007) Evaluation of the Potential Amounts of Dissipated Rare Metals from WEEE in Japan. Mater. Trans. 48:2353–2357.

Zhang L, Wang M, Hu J, Ho Y (2010) A review of published wetland research, 1991–2008: Ecological engineering and ecosystem restoration. Ecol. Eng. 36:973–980.

Zhang S, Ding Y, Liu B, Chang C (2017) Supply and demand of some critical metals and present status of their recycling in WEEE. Waste Manage. 65:113–127.

Zhang S, Yoshikawa K, Nakagome H, Kamo T (2013) Kinetics of the steam gasification of a phenolic circuit board in the presence of carbonates. Appl. Energy 101:815–821.

Zhi W, Ji G (2012) Constructed wetlands, 1991–2011: A review of research development, current trends, and future directions. Sci. Total Envir. 441:19–27.

Zupic I, Cater T (2015) Bibliometric Methods in Management and Organization. Organizational Research Methods 18:429–472.

CAPÍTULO 4

GEOLIBS: a bibliometric review and application on Ecological Restoration[7]

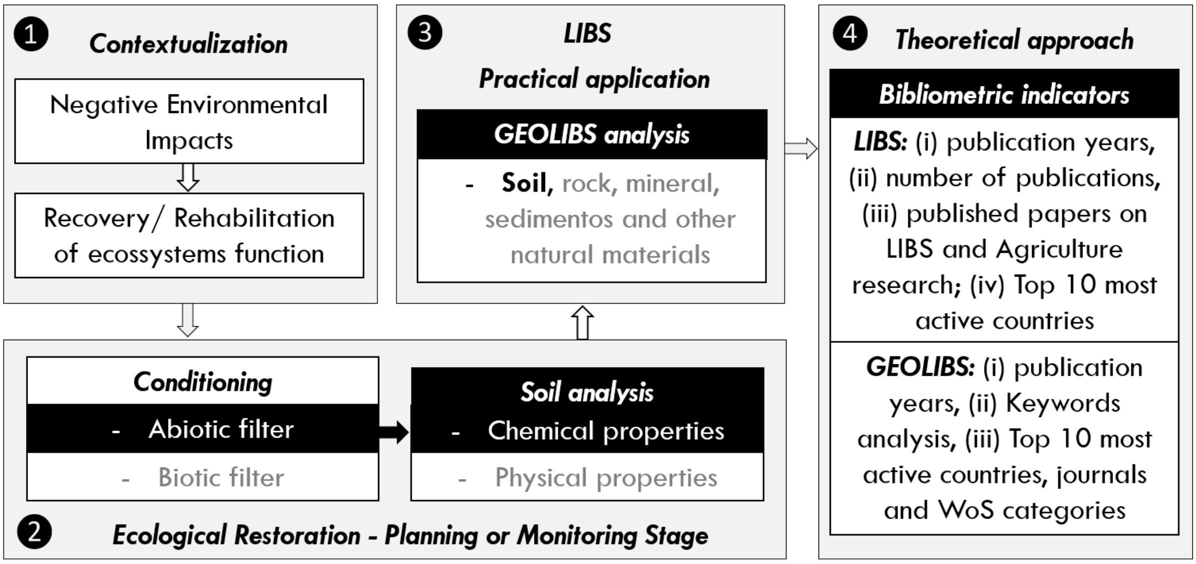
[7] **A ser submetido em:**

Science of the Total Environment

Abstract

Ecological restoration has been considered a global priority in the face of negative environmental impacts from human activities. From this perspective, preliminary assessment and monitoring of soil chemical properties in degraded areas may support environmental intervention and conservation strategies. It is in this sense that laser-based spectroscopic techniques can be used as strategic analysis tools because of the broad approach they offer. In this study, we present an overview of the Laser-Induced Breakdown Spectroscopy (LIBS) technique used in the qualitative chemical analysis of soils (GEOLIBS). Through bibliometric indicators provided by the Web of Science (WoS) database, we discuss the recent status of research involving this technique and present its potential for use in environmental analyzes from a practical application in the context of ecosystems restoration. The bibliometric results indicated that among the 3,377 records of scientific publications on LIBS, only about 18% (622 publications) refer specifically to the domain of GEOLIBS. The research categories (WoS Categories) *Food Science and Technology* and *Environmental Sciences* represent only 4.5% and 3.9%, respectively, of the total publications on GEOLIBS, which clearly shows that the use of LIBS in environmental applications and especially in agriculture is still incipient. In the international scenario, USA and China have been accumulating most publications on LIBS and GEOLIBS research. The results of the practical application indicated that GEOLIBS is effective to characterize the qualitative chemical variation of the soil, being able to detect elements of difficult determination by conventional methods. The LIBS spectra of the analyzed samples show that the elements Fe, Mg, Si, K, Al, and O represented homogeneously the soil of the study area through the *Principal Component Analysis* (PCA). In general, the chemical attributes of the soil did not vary in qualitative terms, but the quantitative aspect represented indirectly by the intensity of the spectral signal, shows differences in the quantity of these elements in the samples according to the land use types.

Graphical Abstract



Keywords: restoration ecology; ecological restoration; VOSviewer; bibliometric map; Laser-induced breakdown spectroscopy; tropical ecosystems

1. Introduction

Anthropogenic changes in the landscape have been considered the greatest threats to biodiversity worldwide (Thomas et al., 2004), especially in tropical regions (Gibson et al., 2011). Fragmentation of forest habitats, for example, has the potential to cause a decline in species of fauna and flora and favor invasion by exotic ruderal species (Tilman et al., 2017). Thus, there are two main alternatives to overcome the negative impacts of human actions under the natural environment: conserving remaining habitats or recovering the ecosystem functions of degraded sites through the practice of ecosystem restoration (da Silva et al., 2017).

Deforestation of tropical forests can trigger substantial carbon losses to the atmosphere (Fearnside and Barbosa, 1998; Pan et al., 2011) and lead to significant changes in soil physicochemical characteristics and the biogeochemical cycle (Paul et al., 2010). For this reason, the restoration of degraded ecosystems has been considered a global priority (Romanelli et al., 2018). There is a consensus in the scientific literature that ecological restoration projects successfully recover many aspects of long-term biogeochemical cycles, as well as ecosystem services (Rasiah et al., 2004; Scowcroft et al., 2004; Paul et al., 2010).

The establishment and self-perpetuation of restoration projects, however, can be strongly limited by factors such as soil compaction, aeration reduction, absorption capacity, availability of water and nutrients for vegetation (Clark et al., 2003), and also the heavy metal phytotoxicity (Li et al., 2016). Not every plant species is able to adapt to soils with high levels of environmental contamination (Couinc et al., 2018). In addition to these aspects, the socioeconomic context, the regional precipitation regime, the topographic position in the landscape (Guo and Gifford, 2002; Silver et al., 2004) and the properties of the local geological matrix (Chazdon, 2003) are also factors that can interfere with the success of forest restoration.

The geological matrix, specifically, can influence the ecological restoration trajectory differently due to its elemental geochemical composition (Smith et al., 2016, dos Santos et al., 2017). Soils derived from sandstones, gneisses or basalts, for example, may present different geogenic characteristics and potential for contamination, especially when they are close to the rocks rich in metals (Santos et al., 2017). For this reason, in many countries, the geochemical fund has been investigated in evaluations prior to environmental interventions, in order to plan the actions that will be developed (Gloaguen and Passe, 2017).

Preliminary assessment and monitoring of areas can guide planning and strategies for environmental management and conservation (Chen et al., 2014). It is in this context that spectroscopic techniques based on laser can be used as strategic tools of environmental analysis, due to the wide perspective that they provide. Laser-Induced Breakdown

Spectroscopy (LIBS) technique is one of them. LIBS is a versatile technique that allows analysis of the spectral signal of a sample and enables the multi-elemental detection of any material - solid, liquid or gas (Miziolek et al., 2006; Noll, 2012). Minimum sample preparation for LIBS analysis is a valuable and advantageous way of avoiding the need for high purity reagents, exhaust hoods, laboratory safety requirements, and extremely clean material, as well as being relatively simple to handle (Bauer and Buckley, 2017).

The field of LIBS has been transformed as a consequence of the interest in real-time (*in situ*) analysis, the wide demand of applied sciences and the recent development of analytical systems by the commercial sector (Harmon et al., 2013). This technique is relatively recent (Bauer and Buckley, 2017) but has already been sufficiently validated to solve several practical problems, such as quality control of industrial products (Gaudiuso et al., 2010), water resources (De Giacomo et al., 2004), agricultural and food samples, geological and archaeological measurements (Anglos, 2001; De Giacomo et al., 2008) biological samples (Trevizan et al., 2009), among other applications. LIBS has also been widely used in analyzes of agricultural chemistry, to determine soil carbon content, humus content, nutrient and toxic elements for plants (Barakov et al., 2010; Bricklemyer et al., 2011; Ayyalasomayajula et al., 2012).

The use of the LIBS technique for the analysis of soils, mineral and other related natural materials has been developing mainly since the last decades (Harmon et al., 2013, Kim et al., 2018). Specifically for these types of materials, this technique has become an attractive analytical tool due to its versatility, high analytical frequency and breadth of chemical detection, sensitivity to the detection of light elements (He, Li, Be, B, C, N and O), simultaneous multi-elemental analysis, reduced amount of samples for analysis and ease combination with other techniques such as Raman spectroscopy (Sharma et al., 2007), hyperspectral imaging optics (Melessanaki et al., 2001) or inductively coupled plasma optical emission spectroscopy (ICP-OES) (Andrade and Pereira-Filho, 2016).

The LIBS technique has been increasingly used in environmental and agricultural analyzes, and several literature reviews have been published to cover these advances (as reviewed by Peng et al., 2016). However, there is a shortage of studies that have bothered to present bibliometric indicators to contextualize the tendencies, potentialities and possible knowledge gaps that involve the application of this technique, especially on what has been designated by some authors as "GEOLIBS" (as proposed by Harmon et al., 2013 and Connores et al. 2016).

Understanding the breadth of a specific field of science such as GEOLIBS through bibliometric analysis is important because this type of information has the potential to support management and decision support in scientific and technological policy (Ravichandran, 2012; Zhao, 2013), as well as allowing the introduction of new perspectives among different areas of science. Bibliometrics can be understood in a broad context as a statistical technique that treats registered information from scientific publications and integrates these results into analyzes of specific fields of science or whole disciplines (Liao and Huang, 2014; Zhang et al., 2016, Romanelli et al., 2018).

In this sense, considering the importance of the restoration of degraded ecosystems and the previous evaluation of the physical environment for the planning of restoration actions, and the potential of the LIBS technique to support this process, this study aims at: i) presenting a theoretical approach on the LIBS technique and more specifically on what has been designated as "GEOLIBS", through bibliometric indicators; and (ii) presenting a practical application of the GEOLIBS technique in the context of restoring ecosystems and discuss their advantages and limitations.

2. Materials and Methods

2.1 Bibliometric analysis

Bibliometric indicators were developed considering the bibliographic data of publications indexed in the online database of the Science Citation Index Expanded (SCI-E) - ISC - Clarivate Analytics - Web of Science © (WoS) (https://webofknowledge.com/). The database is commonly used for both academic and bibliometric studies (Bozares and Azevedo, 2014; Romanelli et al., 2018). The search terms were applied to the "Topic" field, which searches for publications through the title, abstract, keywords of the author and keywords designated by WoS, called Keywords Plus (Boudry et al., 2018). In the first search a comprehensive term ("Laser-induced Breakdown Spectroscopy") was used to retrieve the largest number of publications on the LIBS technique. Subsequently, specific terms were used to retrieve publications related to the application of LIBS in geological and environmental materials analyzes - GEOLIBS, as proposed by Harmon et al. (2013). These specific terms were: "soil *", "sediment *", "mineral *" and "rock *", where the asterisk is a wildcard for any letter or group of letters after the main word (Palencia et al., 2009). This was done mainly to include the terms in the plural. Application of Boolean Operators and quotation marks was also critical for selecting the final dataset (Fig 1).

Only articles and reviews were considered in this analysis since they represent the majority of the documents with complete research results (Fu et al., 2013, Romanelli et al., 2018). The database was analyzed and collected on August 22, 2018. The bibliometric indicators were developed through the (1) years of publication, (2) Web of Science categories, (3) journals, (4) countries and (5) keywords. All analyzes were performed using the "Analyzing Results" tool provided by the database (WoS) with MS Excel support (v. 2016) to perform calculations and to develop indicators graphs. The bibliometric mapping was developed through VOSviewer software (version 1.6.6; www.vosviewer.com), considering the criterion of co-occurrence of keywords.

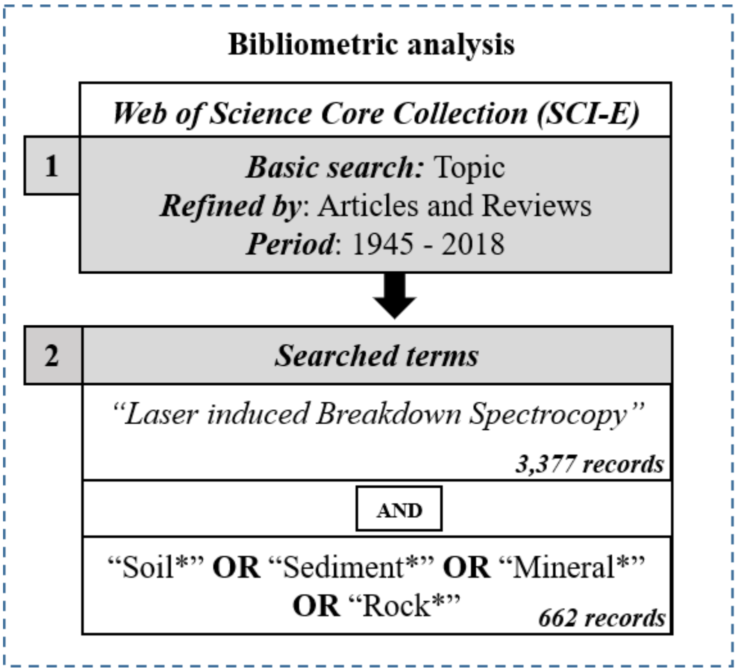


Fig 1. Synthesis of the employed bibliometric methodology on Web of Science (WoS).

2.2 GEOLIBS analysis

Study area

The study area is located in the municipality of São Carlos, the central region of the State of São Paulo, between the coordinates 195026.52m E and 206132.63m E, and 7569004.51m S and 7555497.76m S, approximately 230 km from the city of São Paulo. This area occurs between two Units of Water Resources Management: Tietê-Jacaré Basin and Mogi-Guaçu Basin (Pugliese et al., 2012). The study area is inserted in Itaqueri Formation, Tietê-Jacaré hydrographic basin (Fig. 2). The Itaqueri Formation is quite heterogeneous in relation to the pedological cover, presenting Latosols of medium texture to clayey and Litholic Neosols (Oliveira and Prado, 1989), although restricted spots of Nitosols, Argisols and Quartzite Neosols can also be found (Pinheiro et al., 2016).

According to Soares et al. (2003), the original vegetation composition in the region was comprised about 27% of savanna (savanna sensu strict, short-shrub savanna, and wet meadows), 16% of arboreal savanna, 55% of semi-deciduous and riparian forest, and 2% of semi-deciduous forests. According to the Köppen climatic classification, the area is classified as Cwa and Aw, which is characterized by a tropical climate with a humid summer and dry winter and an average temperature above 22 °C for the hottest month (Mendonça and Danni-Oliveira 2007; Costa et al., 2018).

Sampling

Soil analysis from the LIBS technique occurred from the five-point field sampling in three different land use types: Reference Forest, Restored Area and Degraded Pasture (Figure 2). At each point, composite soil samples were collected at six different depths (0-10, 10-20, 20-40, 40-60, 60-80 and 80-100 cm), totaling 90 samples. All types of land use occur under the same soil type (Latosol) and similar microtopography (flat to the smooth undulating slope, declivity <8%).

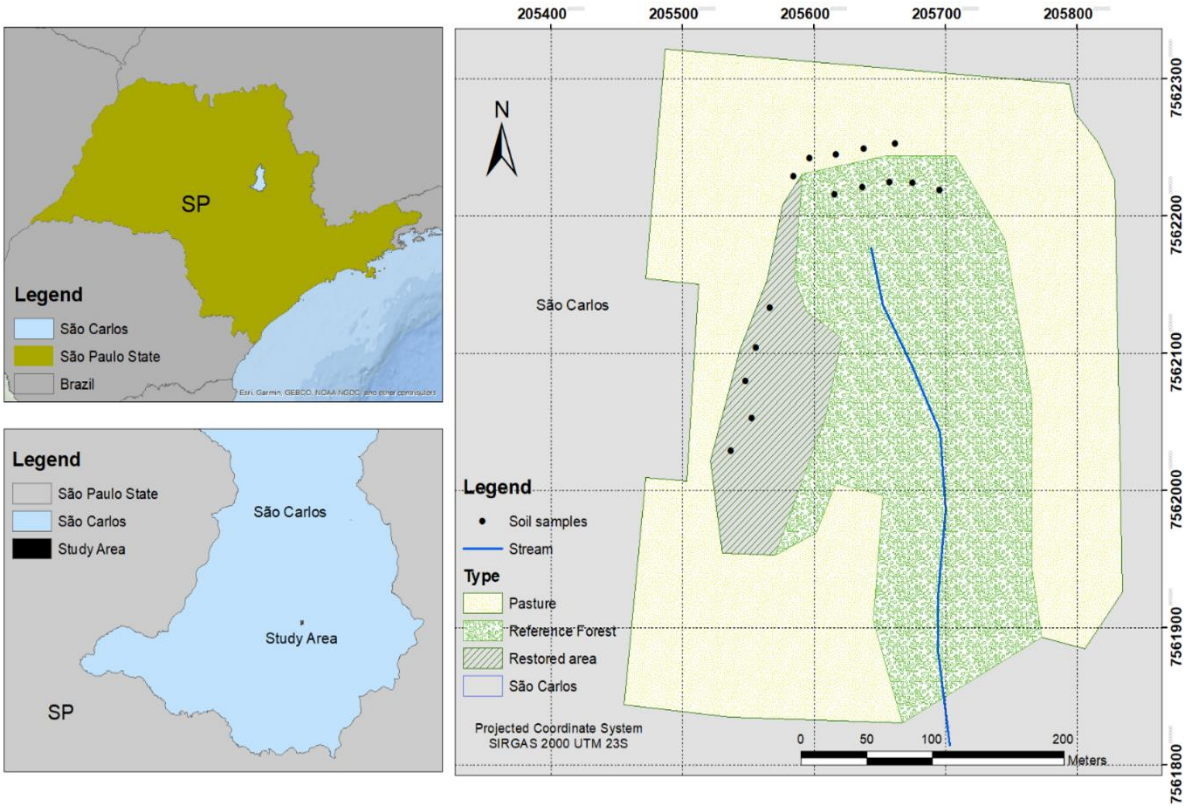


Fig. 2. Study area (São Carlos – São Paulo State). Degraded pasture, Restored Area and Reference Forest: riparian zone in a micro basin under Itaqueri Formation.

2.3 LIBS settings

Soil samples were air-dried and passed through a stainless steel 100 mesh (0.149 mm). A sample mass of 500 mg was pressed under 10 t inch^{-1} to form pellets with 12 mm in diameter. The LIBS spectra were recorded using a commercial LIBS instrument (Applied Spectra, J200 model, Fremont, CA, USA) equipped with a Q-switched Nd:YAG laser at 1064 nm with a single laser pulse with a duration of 8 ns at a frequency of 10 Hz. Experiments were carried out by recording 50-point scans in 10 horizontal lines, with a total of 500 spectra *per* sample. Additional laser settings were as follow: laser fluence of 1019 mJ/cm^2 (80 mJ of laser pulse energy on a 100 µm of spot size), at a 5 Hz repetition rate and a 1 mm/s ablation rate. The data acquisition time was 1.05 ms and the delay time was 0.5 µs. All operational parameters were controlled by Axiom software with an automated XYZ stage and a 1280 × 1024 complementary metal-oxide-semiconductor (CMOS) color camera imaging system. The spectrometer consists of a six-channel CCD with an average resolution of 70 pm and ranges from 186 to 1042 nm with 12,288 pixels.

2.4 Data handling

For data processing and evaluation, the following computer programs were used:

• VOSviewer: to elaborate bibliometric mapping;

• ArcGIS® (version 10.5): to elaborate the geographic localization map of the study area;

• Aurora (Applied Spectra): to identify the emission lines of the analytes under LIBS determination;

• Microsoft Excel®: to data matrices processing and evaluation;

• MATLAB® 2018a (The Mathworks Inc., Natick, MA, USA) and Pirouette (Infometrix, Bothell, WA, USA) software package (version 4.5 rev. 1): preliminary dataset inspection, standardization, and principal component analysis (PCA) calculation.

3. Results and Discussion

3.1 Theoretical approach: a bibliometric analysis

There is a great demand in environmental and earth sciences for an analytical technique that can be used in the field in fast mineral identification and in the chemical analysis of the soils, which is not yet fully supplied by other spectroscopy techniques such as X-ray fluorescence and raman spectroscopy, developed over the past decade (Harmon et al., 2013).

Traditionally, some analytical techniques such as inductively coupled plasma mass spectrometry (ICP-MS), inductively coupled plasma optical emission spectroscopy (ICP-OES) and atomic absorption spectrometry (AAS) have been used to detect potential toxic elements and soil nutrients (Falandysz et al., 2007; Ismail and Yoo, 2010). However, these methods are limited by complex sampling steps and may not meet the demands of real-time measurement in certain types of environmental analyzes (Peng et al., 2016).

The applications of LIBS for natural material analysis began to be described in the literature in the mid-1990s (Fig. 3), to detect toxic metallic pollutants in soils and to track pollutants in the air (Harmon et al., 2013). In the last two decades, however, this technique has been employed in a wide range of studies involving the analysis of sediments, soils and other natural materials, which has been designated by some authors as GEOLIBS (Harmon et al., 2013; Connors et al., 2016). Much of these advances are due to the demand for agriculture, which is increasingly using sophisticated sensors to provide better data and process control in the field (Bauer and Buckley, 2017). Nevertheless, it is possible to verify that few scientific papers published in the field of GEOLIBS are associated to Food Science and Technology (4.5%) and, in general, to Environmental Sciences (3.9%) (Fig. 3).

The application of the LIBS technique in these areas is more challenging than in other fields of science, mainly due to difficult to understanding the complex interaction between the nature of the samples and adverse working conditions, generally external to the laboratory environment, which can jeopardize on the detection of chemical elements and the LIBS performance (Peng et al., 2016). Therefore, further research is needed to support the demand for more reliable and robust instruments and the development of more suitable methods for LIBS analysis.

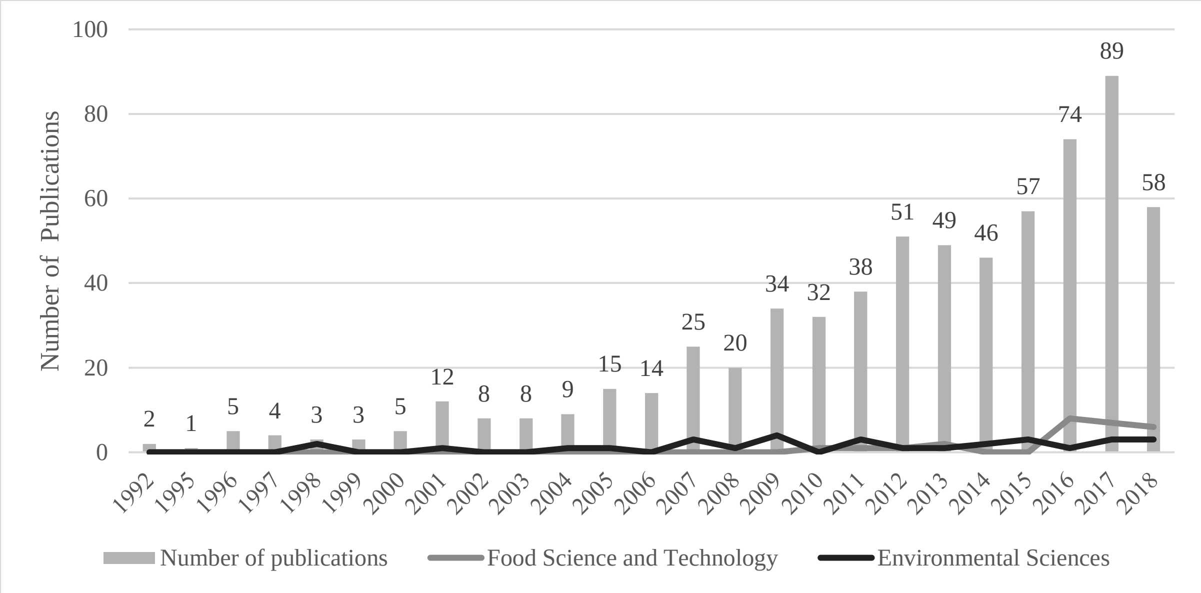


Fig 3. Total publications from WoS Core Collection (SCI-E) involving "GEOLIBS research" from 1992 to 2018, associated with WoS Categories: Food Science Technology and Environmental Sciences.

Much of the development effort to produce a portable field LIBS instrument was stimulated by the detection of environmental contamination, seeking to reconcile the simplicity of this technique with its analytical speed (Harmon et al., 2013). Contamination by toxic elements and the detection of nutrients in the soil are two issues of great importance in agriculture, and in general, in the Environmental Sciences and Earth Sciences. Soil provides the nutrients (micronutrients and macronutrients) for plant growth and also it may contain potencially toxic elements that represents a potential source of impact to the environment as it can be absorbed by plants and affect human health, directly or indirectly (Hattab et al., 2019). In this sense, elemental chemical analysis of soil is important both for environmental monitoring of areas (e.g., reclaimed mining areas) and for planning actions of environmental interventions (e.g., ecological restoration).

The contamination of the soil by potential toxic elements is a common problem around industrial and military installations, and a great deal of effort has been directed towards the detection and quantification of these contaminants (Perlati et al., 2015; Aihemaiti et al., 2018; Yun et al., 2018). High levels of toxic elements, commonly denotated as heavy metals, in the soil can be a direct consequence of anthropogenic actions such as agricultural irrigation waters, soil alterations with agrochemicals and limestone, burial of residues, atmospheric deposition of vehicle emissions and mining activities (Harmon et al., 2013). In the Amazon rainforest, for example, gold mining activities, which occurred for several decades, have led to cumulative environmental impacts, including acid mine drainage and soil and water pollution by arsenic, cyanide, and mercury (Senesi et al., 2018).

In the context of the use and application of the LIBS technique for the analysis of environmental contamination, the bibliometric analysis of the main author's keywords (minimum of five occurrences) used to describe the published scientific works on this subject (between 1992 and 2018) revealed that the detection of heavy metals in the soil, and especially the detection of lead and chromium (Fig. 4), were some of the main issues addressed by these studies (cluster in dark blue). This information is consistent with what was presented by Santos et al. (2012), Harmon et al. (2013), Qiao et al. (2015), Yu et al. (2016) and Peng et al. (2016).

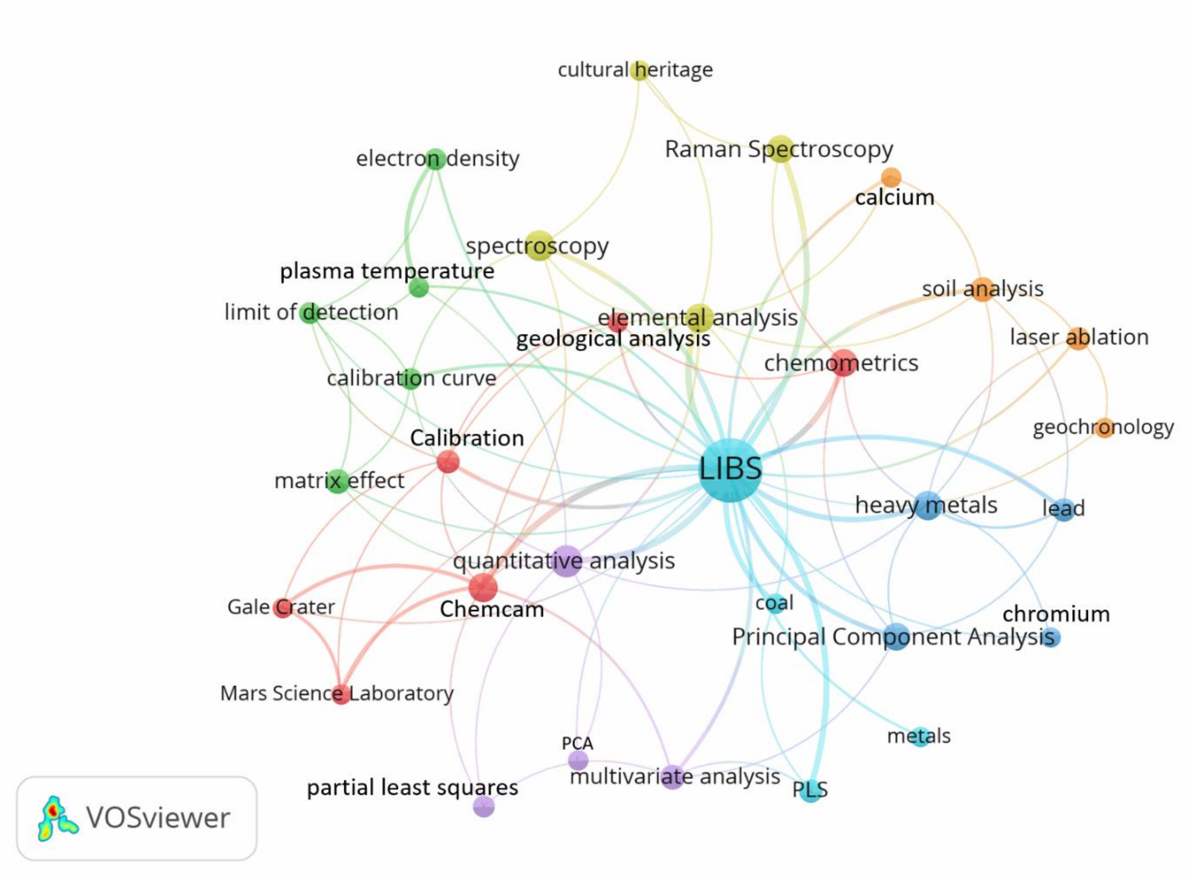


Fig. 4 Network visualization map for the main author’s keywords (minimum of five occurrences) on GEOLIBS research. The size of the node is proportional to the number of citations as well as the thickness of the edges between nodes. The colors indicate which cluster of subjects the item belongs to.

Most studies on LIBS show that this technique is adequate to detect most of the potencially toxic elements in the soil (i.e., Pb, Cu, Cd, Ni, Ag, Mo, Zn, Hg, and Cr) and the results are in accordance with reference (for example, *Atomic Absorption Spectroscopy - AAS*) (Dong et al., 2013; Badday et al., 2015; Peng et al., 2016). The results for the LIBS analysis of heavy metal content in a number of reference soil samples were compared with the results obtained using ICP spectroscopy by Galiova et al. (2011). In this study, LIBS shows a high potential not only for qualitative measurement but also for the quantitative analysis of heavy metals and nutrients in soils.

LIBS technique has also been used to analyze various soil nutrients, including Ca, Mg, Zn, Ba, N, P, K, C and other trace elements (Cousin et al., 2011). In addition, some specific measurements of elements such as silicon are especially interesting as the more traditional approaches to determining this element in environmental matrices are laborious and problematic. For example, digestion methods with HNO_3, H_2O_2, and HF has been reported *prior* to ICP analysis (Bauer and Buckley, 2017). In contrast, LIBS reduce sample processing to a minimum (no sample solubilization is required), thereby minimizing the introduction of errors due to sample preparation step, the use of concentrated acids, waste generation, and so on. Direct analysis and determination of silicon in plants by LIBS were described in greater detail by de Souza et al. (2015).

GEOLIBS: bibliometric indicators

At the first search for publications in the WoS, 3,377 bibliographical data were retrieved from general scientific publications on LIBS research, on which 97% are articles and 3% are reviews. After refining this database by the terms that specifically refer to GEOLIBS (Fig. 1), 662 bibliographic data of scientific publications were collected, on which 95% are represented by articles and 5% by reviews, covering the advances of the LIBS technique in the analysis of geological materials and other types of natural materials (for complete information on the main review papers on GEOLIBS research, see supplemental material).

In this context, to understand how countries have organized themselves as players that conduct researches on LIBS and, specifically, on GEOLIBS research, an assessment of international collaboration based on co-authorship was carried out, considering the accumulated number of publications along the years. In general, research on LIBS has been developed in 72 different countries since 1981 (Fig. S1 - see supplemental material for detailed information) which shows the relevance of the subject for all around the word. Research on GEOLIBS, however, has been developed in 51 countries. The term "GEOLIBS" was first used and published by Harmon et al. (2013) and subsequently mentioned by Connors et al. (2016). The first paper that envolved this subject was registered in 1992 and after 2012 were registered more than 45 publications *per* year on this domain (Fig. 3). This fact reveals that this field is emerging as a research topic recently, as was pointed out by other authors (Harmon et al., 2013; Bauer e Buckley, 2017). In the international scenario, EUA and China have been accumulating most publications on LIBS research (in general) and also on GEOLIBS research. The top 10 most active countries in this field of science are present in Table 1.

Table 1. Top 10 most active countries on LIBS and GEOLIBS research ranked by the number of accumulated publications (NP).

LIBS			GEOLIBS		
Rank	**Country/Region**	**NP**	**Rank**	**Country/Region**	**NP**
1	USA	847	1	USA	194
2	People’s R China	760	2	People’s R China	140
3	Italy	236	3	France	71
4	France	235	4	Italy	51
5	Spain	229	5	Brazil	36
6	Germany	189	6	Spain	34
7	India	141	7	Germany	25
8	Japan	134	8	South Korea	23
9	South Korea	101	9	Canada	19
10	Brazil	100	10	India	19

Overall, all retrieved papers on GEOLIBS research were published in a wide range of 165 different journals. However, most journals (about 95%) have accumulated fewer than 10 papers along the years. The top 10 most active journals on this subject, which represent about 52% of all publications, are listed in Table 2. This list of journals was associated with the top 10 main *WoS Categories* in order to present what areas of science have been publishing studies on GEOLIBS research.

Table 2. Top 10 most active journals on GEOLIBS research and top 10 main WoS Categories ranked by the number of accumulated publications (NP).

Rank	Journals	NP	Rank	WoS Categories	NP
1	Spectrochimica Acta Part B Atomic Spectroscopy	144	1	Spectroscopy	312
2	Applied Spectroscopy	45	2	Chemistry Analytical	116
3	Applied Optics	34	3	Optics	75
4	Spectroscopy and Spectral Analysis	34	4	Instruments Instrumentation	66
5	Journal of Analytical Atomic Spectrometry	33	5	Geochemistry Geophysics	38
6	Analytical Methods	12	6	Physics Applied	33
7	Journal of Applied Spectroscopy	12	7	Environmental Sciences	30
8	Analytical and Bioanalytical Chemistry	11	8	Food Science Technology	27
9	Journal of Geophysical Research Planets	10	9	Astronomy Astrophysics	16
10	Talanta	9	10	Chemistry Multidisciplinary	16

Most of these studies are still being directed to specific areas of spectroscopy, which can be evidenced both by the title of the main journals that published these studies and by the *WoS Categories* associated to this set of works. These results clearly show that the use of LIBS in environmental applications and especially in agriculture is incipient, and that there is a large field of research that can still be developed to support planning and analysis of natural materials (for complete information on the list of the main published works on LIBS and their application in agriculture, see supplementary material).

3.2 Theoretical approach: ecological restoration

Forest ecosystems retain large amounts of nutrients in the soil that are often significantly diminished by changes in land use and occupation (Ahirwal and Maiti, 2016). The natural recovery of these environments is slow due to the unfavorable characteristics of the spoilage (Castro-Romero et al., 2014; Roa-Fuentes et al., 2015; Ahirwal et al., 2017). However, the adoption of adequate restoration practices, such as reforestation, can favor the recovery process and improve site conditions, leading to an increase in nutrient stocks, for example (Singh et al., 2002). The ultimate goal of restoring ecosystems, therefore, is to improve the characteristics of the degraded site, so that the restored ecosystem becomes self-sustaining and resilient over time (Miller et al., 2016; Ahirwal et al., 2017).

Environmental pollution and adverse soil physicochemical properties restrict vegetation development and species establishment until it is properly managed (Maiti, 2012). Poor nutritional soils affect plant growth, and unfavorable physical properties also represent an important environmental threshold for vegetation establishment (Maiti, 2007; Anawar et al., 2013; Ahirwal et al., 2014).

Reforestation is recognized as one of the least costly techniques to restore soil fertility and improve micro-climatic conditions, in addition to supporting ecological succession (Santos et al., 2008; Dhar et al., 2008). Trees can improve soil quality through numerous processes, including maintenance or enhancement of soil organic matter (SOM), nitrogen fixation, and improvements in soil physical-chemical and biological properties (Jha and Singh, 1991; Frouz et al., 2009). In this process, the implication of the arboreal component under soil fertility depends on the intrinsic characteristics of each species (Byard et al., 1996). The development of nutrient stocks, specifically, begins with the litter fall and its decomposition (Akala and Lal, 2000), and this is important because the supply of organic matter and nutrients is a basic prerequisite for the growth of plants and their establishment over time (Williamson et al., 2011).

From this context, we investigated how LIBS could be used in the restoration and monitoring of degraded ecosystems, aiming to subsidize intervention actions and environmental assessment. In this analysis, we investigated the behavior of soil chemical attributes in different land use types (Reference Forest, Restored area and Pasture) and different depths. We present a broad view of scenarios using the LIBS technique and PCA. The results of this analysis are expressed in qualitative terms, which can be converted to quantitative data through specific calibration methods, which were not determined in this study, but are discussed.

GEOLIBS: results of practical application

Figure 5 shows LIBS average emission spectra (around 500 spectra recorded per sample, n = 90) and the elemental composition of the three analyzed land use types (Reference Forest, Restored area and Pasture). The emission signals for Fe, Mg, Si, K, Al, and O represented, in general (and homogeneous), the soil of the study area. No contaminating elements (heavy metals) were identified by LIBS, although there are industrial activities in the vicinity of the studied area and the history of the prior use of forest restoration in the area is agricultural activity. These results are the same for all analyzed depths (0-100 cm).

In general, the chemical attributes of the soil did not vary in qualitative terms due to the land use type, but the quantitative aspect of the main elements found, which is represented directly by the intensity of the spectral signal (Table 3), shows that the different types of soil cover significantly influenced the amount of these elements in the soil.

The intensity of the emission signal of Fe in the soil was similar in the Reference Forest and Pasture, and around 2-fold higher than the signal for Restored Area. Likewise, Al and Si presented similar behavior in terms of the intensity of the spectral signal in the samples. These elements were expected in large quantities in this type of soil due to the intrinsic characteristics of the Latosols, which are deep, highly weathered, with Fe oxide being one of the major components of the clay fraction, generally with low natural fertility and high acidity (Schaefer et al., 2008). In the coarser fractions (sand and silt) there is a predominance of quartz (Si). The lower intensity of the spectral signal of Fe and Si may be indicative of variation in the type and content of oxides found in the Latosols of the site. In Schaefer et al. (2008), it is possible to verify the difference in Si, Fe and Al oxide contents as a function of the type of Latosol.

The other elements with a lower spectral signal in the Restored Area can be attributed to lower soil cover (approximately 5 years old) in relation to other types of vegetation cover (Reference Forest and Pasture). The low soil cover in Restored Area may have promoted changes in soil chemistry dynamics, mainly in the superficial layer, resulting from the loss of organic matter and other elements by leaching or surface runoff. On the other hand, the improvements in the chemical characteristics of the soil, represented by the greater amount of nutrient in the soil (higher emission signalsfor Mg and K) can be an indirect indicator of the development and recovery of the ecosystem.

In some cases, the ultimate goal of restoration is to accelerate the recovery of disturbed sites and bring them back to a condition similar to natural sites (Derhe et al., 2016). In this situation, one of the project success indicators can be determined by assessing soil nutrient recovery over time (Banning et al., 2008), which may be associated with recovery of nutrient cycling, for example (Koch and Hobbs, 2007, Suganuma et al., 2018).

The PCA calculated for all soil samples assessed are shown in the Figure 6. The explained variance due to the fist and the second principal components (PC) was 59% (PC1 31%; PC2 28%). The analysis of the score plots shows three predominant segregations related to each land use type. In the case of the Mg and K (macronutrients) elements, the highest intensities were verified in the Reference Forest. This result may be associated with the higher nutrient cycling rates that the vegetation of this type of phytophysiognomy promotes, especially for element K (Fig. 6). Das and Mondal (2016) reported that the levels of N, K and P are the main limiting nutrients returned by litterfall and play an important role in soil fertility and tree growth in subtropical regions. Also, in this context, the high intensity of the element O in this phytophysiognomy may be associated with organic matter, since this fragment of the forest has the same history of use and occupation for more than 20 years, and therefore had a greater accumulation of plant material in the soil over the years.

In general, the raw spectra of the Reference Forest was characterized by higher intensities of Mg and K when compared to the other phytophysiognomies, whereas Restored area and Pasture were characterized mainly by high Fe intensities (Fig 5).

The estimation of the presence of these nutrients in the soil revealed that the superficial layers (0-40 cm) presented the greater availability of the elements Mg, Ca, and K in the types Restored area and Pasture, compared to the deeper layers. In the Reference Forest, the depths were not well separated by the PCA analysis, which indicates a greater homogeneity of elements along the soil profile (Fig. S4). We associate this trend of distribution of results (Reference Forest) with the greater cycling of nutrients that must occur in this type of vegetation cover. This information could be validated from the analysis of the other PCAs, which compared the different types of cover (land use type) at all depths (0-10, 10-20, 20-40, 40-60, 60-80, 80-100 cm) (for detailed information, see supplemental data Fig. S5 to Fig. S10).

Zhao et al. (2015) studying a chronosequence of secondary forests in China reported that half of the nutrient stock at these sites were stored in the soil surface horizons, as evidenced in this study. The higher root density, higher microbial activity and higher deposition of organic matter in the upper layers can also explain the trend of the results presented in this study.

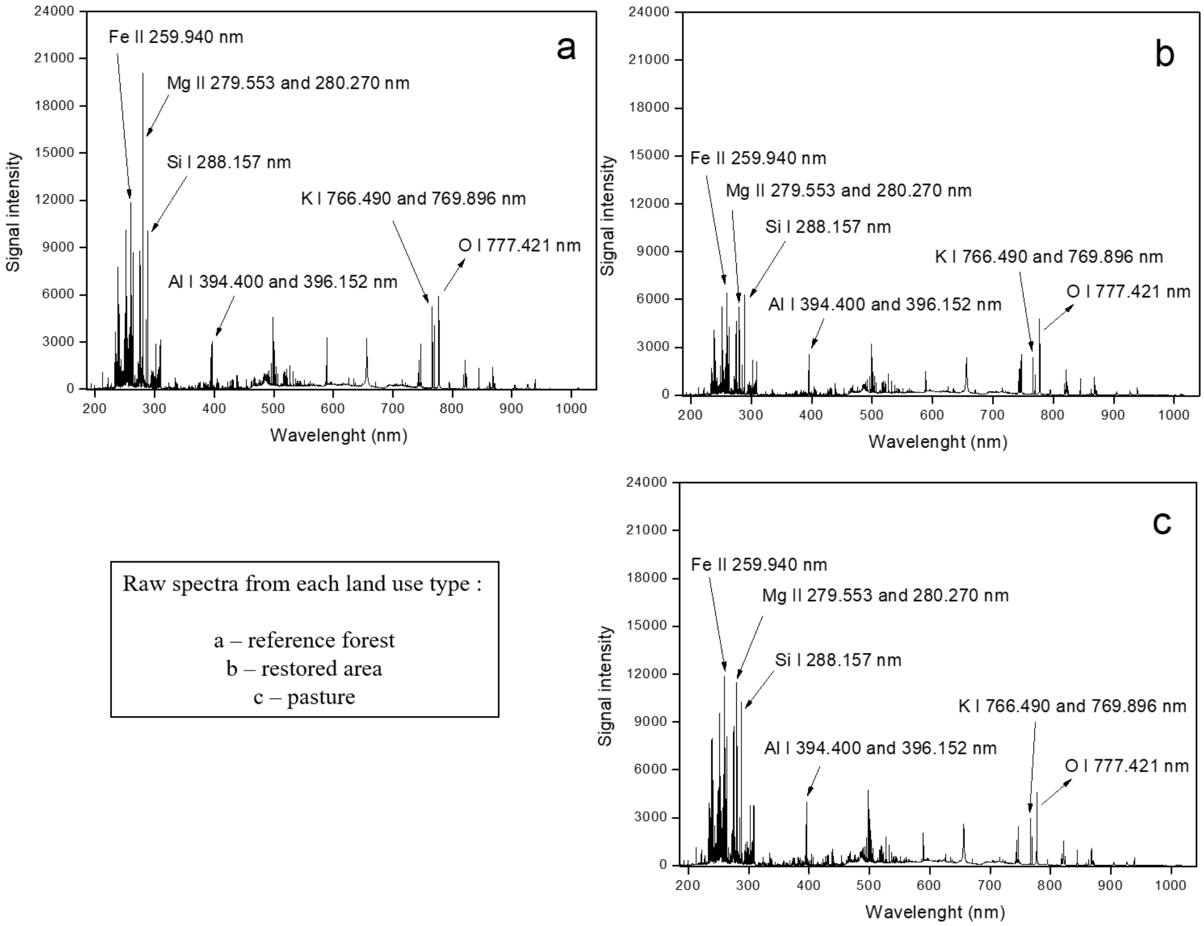


Fig. 5 Raw spectra of soil samples from each land use type and main elements.

Table 3. Signal intensity from the main elements detected on soil samples on each land use type (raw spectra).

Element	Reference Forest	Restored Area	Pasture
	Signal Intensity		
Fe	12,000	6,000	12,000
Mg	20,000	5,800	11,800
Si	10,000	6,000	10,000
Al	3,000	2,800	4,300
K	5,000	2,500	3,000
O	6,000	4,500	4,500

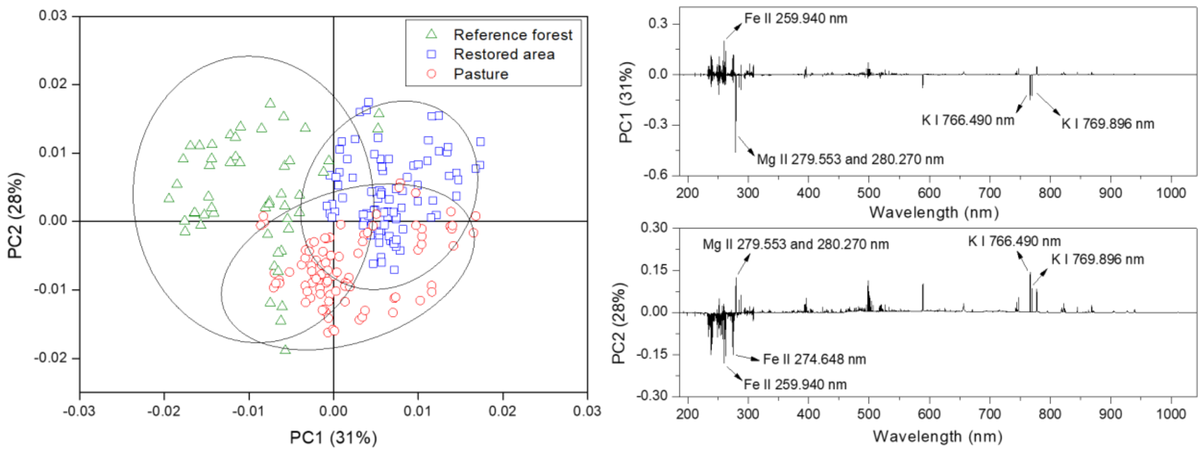


Fig. 6 Score and loadings plots for PCA using the raw spectra from each land use type (Reference Forest, Restored Area, and Pasture).

3.3 Quantitative LIBS

It is possible to promote quantitative analyzes using LIBS since the intensity of the plasma emission is proportional to the abundance of a certain element in the sample (Harmon et al., 2013). Quantitative analysis, however, is an incipient issue in the context of GEOLIBS due to its complex laser sample and plasma particle procedure. Quantification may be the main issue that researchers should continue to investigate to promote the application of this technique in the context of Environmental Sciences and Earth Sciences. Some methodological approaches, including univariate, multivariate and calibration-free analysis (CF), have been proposed to improve the reproducibility and precision of the technique, combined also with the aim of eliminating the matrix effect (Peng et al., 2016, Tempesta et al., 2018).

For solid samples, the character of the generated microplasma is determined by several interrelated factors: the nature of the material (i.e. its composition, crystallinity, optical reflectivity, optical transmissivity and surface morphology), laser pulse energy and the environment in which the LIBS plasma is formed (Liu et al., 2005; McMillan et al., 2006; He et al., 2008). By monitoring the position and intensity of emission lines in the optical spectrum of LIBS, information can be obtained on both the chemical species present in the plasma and their abundance. Elemental abundance in a sample can be quantified by measuring the intensity of the light captured at specific wavelengths (Radziemski and Cremers, 1989; Harmon et al., 2013). The light emitted by the plasma, created by the interaction of a laser beam with the surface of the sample, is always subject to the self-absorption (SA) of its cold outer region. This phenomenon may affect the accuracy and uncertainty of quantitative analysis by LIBS.

To overcome this inherent failure of spectroscopy, different correction methods have been proposed in the literature (as revised by Kadachi et al., 2018).

Like all analytical methodologies, the ability to perform quantitative analyzes is based on the quality of the standards. Optimum conditions depend on the sample, on the availability of calibration or reference materials and, more importantly, on the purpose of the analysis (Harmon et al., 2013). Quantification of the elemental content in soils with LIBS is challenging due to matrix effects that strongly influence the formation of the plasma and the signal of LIBS. In addition, soil heterogeneity on the micrometric scale may affect the accuracy of the analytical results (Rühlmann et al., 2018). In the ideal case, when matrix reference materials exist, LIBS can provide a quantitative analysis. This is more difficult when there are no reference standards, as is often the case with geological materials (Harmon et al., 2013).

4. Conclusions

In this study, we present an overview of the LIBS technique associated with the chemical analysis of minerals, rocks, sediments, soils and other natural materials (GEOLIBS). By means of bibliometric indicators and a GEOLIBS application in the context of Environmental Sciences, we discuss the potential and limitations of this technique in the qualitative chemical analysis of soils. In general, LIBS proved to be efficient to characterize the chemical variation in different land use types and also in depth, being able to detect elements difficult to determine by conventional methods, such as Si and O. Although our results provide indirect information on the quantity of elements in the samples, through the spectral signal strength, no specific calibration models were used to achieve precisely the elemental quantitative analysis similar to conventional methods.

As an analytical tool, LIBS has shown to be promising in the rapid detection of toxic elements and nutrients in the soil, which has great potential to subsidize the planning and monitoring of restoration projects and the determination of agricultural chemistry. The development of portable LIBS systems seems to be a bridge to take this technique to the greater practical application, but the performance of these systems still needs to be improved and the equipment must become compact for use in the field. In addition, a number of instrumental limitations and matrix effect problems still need to be convincingly solved to make LIBS a powerful quantitative chemical analysis technique that meets the demand of applied sciences.

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Supplemental material

Avalilable (temporarily) at:
https://drive.google.com/open?id=1ZXJTY0ymcHdNubtHFuxaBvVnnwmo9BwB

References

Ahirwal J, Maiti S, Satyanarayana Reddy M. (2017). Development of carbon, nitrogen and phosphate stocks of reclaimed coal mine soil within 8 years after forestation with Prosopis juliflora (Sw.) Dc. CATENA 156:42-50.

Ahirwal, J., Maiti, S.K., 2016. Assessment of soil properties of different land uses generated due to surface coal mining activities in tropical Sal (Shorea robusta) forest, India. Catena 140, 155–163.

Ahirwal, J., Singh, A.K., Maiti, S.K., 2014. The importance and future challenges of ecological restoration of abandoned coalmine degraded lands: an Indian scenario. J. Mines Met. Fuels 62, 277–285.

Aihemaiti, A., Jiang, J., Li, D., Liu, N., Yang, M., Meng, Y., Zou, Q., 2018. The interactions of metal concentrations and soil properties on toxic metal accumulation of native plants in vanadium mining area. J. Environ. Manage. 222, 216–226.

Akala, V., Lal, R., 2000. Potential of mine land reclamation for soil organic carbono sequestration in Ohio. Land Degrad. Dev. 11, 289–297.

Anawar H, Canha N, Santa-Regina I, Freitas M. (2013). Adaptation, tolerance, and evolution of plant species in a pyrite mine in response to contamination level and properties of mine tailings: sustainable rehabilitation. *Journal of Soils and Sediments* 13:730-741.

Andrade D, Pereira-Filho E. (2016). Direct Determination of Contaminants and Major and Minor Nutrients in Solid Fertilizers Using Laser-Induced Breakdown Spectroscopy (LIBS). *Journal of Agricultural and Food Chemistry* 64:7890-7898.

Andrade, Daniel F.; Sperança, Marco Aurelio, Pereira-Filho, Edenir Rodrigues. Different sample preparation methods for the analysis of suspension fertilizers combining LIBS and liquid-to-solid matrix conversion: determination of essential and toxic elements. Anal. Methods, 2017, 9, 5156.

Anglos, D. 2001. Laser-Induced Breakdown Spectroscopy in Art and Archaeology. Applied Spectroscopy 55: 186A-205A.

Ayyalasomayajula, K., Yu-Yueh, F., Singh, J., McIntyre, D. and Jain, J. 2012. Application of laser-induced breakdown spectroscopy for total carbon quantification in soil samples. Applied Optics 51: B149.

Banning, N.C., Grant, C.D., Jones, D.L., Murphy, D.V., 2008. Recovery of soil organic matter, organic matter turnover and nitrogen cycling in a post-mining forest rehabilitation chronosequence. Soil Biol. Biochem. 40, 2021–2031.

Bauer, A. and Buckley, S. 2017. Novel Applications of Laser-Induced Breakdown Spectroscopy. Applied Spectroscopy 71: 553-566.

Blouin M., M. E.Hodson, E. A. Delgado, G. Barker, L. Brussaard, K. R. Butt, J. Dai, L. Dendooven, G. Pérès, and J. E. Tondoh. 2013. A review of earthworm impact on soil function and ecosystem services. Eur. J. Soil Sci. 64:161–182.

Bolin, B., & Sukumar, R. (2000). Global Perspective. In R. T. Watson, I. R. Noble, B. Bolin, N. H. Ravindranath, D. J. Verardo & D. J. Dokken (Eds.), Land use, land-use change, and forestry. A special report of the Intergovernmental Panel on Climate Change (pp. 25–51). Cambridge, UK: Cambridge University Press.

Boudry, C., Baudouin, C., Mouriaux, F., 2018. International publication trends in dry eye disease research: a bibliometric analysis. Ocular Surf. 16, 173–179. http://dx.doi. org/10.1016/j.jtos.2017.10.002.

Bricklemyer, R., Brown, D., Barefield, J. and Clegg, S. 2011. Intact Soil Core Total, Inorganic, and Organic Carbon Measurement Using Laser-Induced Breakdown Spectroscopy. Soil Science Society Of America Journal 75: 1006.

Burakov, V., Raikov, S., Tarasenko, N., Belkov, M. and Kiris, V. 2010. Development of a laser-induced breakdown spectroscopy method for soil and ecological analysis (review). Journal Of Applied Spectroscopy 77: 595-608.

Byard, R., Lewis, K.C., Montagnini, F., 1996. Leaf litter decomposition and mulch performance from mixed and monospecific plantations of native tree species in Costa Rica. Agric. Ecosyst. Environ. 8, 145–155.

Castro-Romero M, Valdés-López C, Barrera-Cataño J. (2014). Prioridades de restauración ecológica del suelo y sus servicios ecosistémicos asociados, degradados por uso agropecuario en la microcuenca Santa Helena (Suesca-Cundinamarca). Caldasia 36:37-52.

Chazdon R. (2003). Tropical forest recovery: legacies of human impact and natural disturbances. Perspectives in Plant Ecology, Evolution and Systematics 6:51-71.

Chazdon, R. L. (2014). Second Growth: The promise of tropical forest regeneration in an age of deforestation. Chicago, IL and London, UK: The University of Chicago Press.

Clark LJ, Whalley WR, Barraclough PB (2003) How do roots penetrate Strong soil? Plant and Soil 255:93–104.

Clemens S. (2006). Toxic metal accumulation, responses to exposure and mechanisms of tolerance in plants. Biochimie 88:1707-1719.

Costa C, Lorandi R, de Lollo J, Imani M, Dupas F. (2018). Surface runoff and accelerated erosion in a peri-urban wellhead area in southeastern Brazil. Environmental Earth Sciences 77.

Couic, E., Grimaldi, M., Alphonse, V., Balland-Bolou-Bi, C., Livet, A., Giusti-Miller, S., Sarrazin, M. and Bousserrhine, N. 2018. Mercury behavior and C, N, and P biogeochemical cycles during ecological restoration processes of old mining sites in French Guiana. Environmental Science: Processes & Impacts 20: 657-672.

Cousin A, Forni O, Maurice S, Gasnault O, Fabre C, Sautter V et al. (2011). Laser-induced breakdown spectroscopy library for the Martian environment. *Spectrochimica Acta Part B: Atomic Spectroscopy* 66:805-814.

Das, C., Mondal, N.K., 2016. Litterfall, decomposition and nutrient release of Shorea robusta and Tectona grandis in a sub-tropical forest of West Bengal, Eastern India. J. For. Res. 27, 1055–1065.

De Giacomo, A., Dell'Aglio, M. and De Pascale, O. 2004. Single Pulse-Laser Induced Breakdown Spectroscopy in aqueous solution. Applied Physics A 79: 1035-1038.

De Giacomo, A., Dell'Aglio, M., Bruno, D., Gaudiuso, R. and De Pascale, O. 2008. Experimental and theoretical comparison of single-pulse and double-pulse laser induced breakdown spectroscopy on metallic samples. Spectrochimica Acta Part B: Atomic Spectroscopy 63: 805-816.

de Pierri Castilho S, Cooper M, Dominguez A, Bedano J. (2016). Effect of Land Use Changes in Eastern Amazonia on Soil Chemical, Physical, and Biological Attributes. *Soil Science*181:133-147.

Derhé M, Murphy H, Monteith G, Menéndez R. (2016). Measuring the success of reforestation for restoring biodiversity and ecosystem functioning. *Journal of Applied Ecology*53:1714-1724.

Dhar A, Comeau P, Karst J, Pinno B, Chang S, Naeth A et al. (2018). Plant community development following reclamation of oil sands mine sites in the boreal forest: a review. *Environmental Reviews* 26:286-298.

Dong D, Zhao C, Zheng W, Zhao X, Jiao L. (2013). Spectral Characterization of Nitrogen in Farmland Soil by Laser-Induced Breakdown Spectroscopy. Spectroscopy Letters 46:421-426.

dos Santos R, Citadini-Zanette V, Leal-Filho L, Hennies W. (2008). Spontaneous Vegetation on Overburden Piles in the Coal Basin of Santa Catarina, Brazil. *Restoration Ecology*16:444-452.

dos Santos, L.M.R., Gloaguen, T.V., Fadigas, F., de, S., Chaves, J.M., Martins, T.M.O., Martins, O., 2017. Metal accumulation in soils derived from volcano sedimentary rocks, Rio Itapicuru Greenstone Belt, northeastern Brazil. Sci. Total Environ. 601e602, 1762e1774. http://dx.doi.org/10.1016/j.scitotenv. 2017.06.035.

Douterlungne D, Ferguson B, Siddique I, Soto-Pinto L, Jímenez-Ferrer G, Gavito M. Microsite determinants of variability in seedling and cutting establishment in tropical forest restoration plantations. Restoration Ecology 2015; 23:861-871.

Falandysz J, Kunito T, Kubota R, Bielawski L, Mazur A, Falandysz J et al. (2007). Selected elements in Brown Birch Scaber Stalk Leccinum scabrum. *Journal of Environmental Science and Health, Part A* 42:2081-2088.

Fearnside, P.M., Barbosa, R.I., 1998. Soil carbon changes from conversion of forest to pasture in Brazilian Amazonia. For. Ecol. Manage. 108, 147–166.

Frouz, J., Pižl, V., Cienciala, E., Kalčík, J., 2009. Carbon storage in post-mining forest soil, the role of tree biomass and soil bioturbation. Biogeochemistry 94, 111–121.

Fu, H.Z., Wang, M.H., Ho, Y.S., 2013. Mapping of drinking water research: a bibliometric analysis of research output during 1992–2011. Sci. Total Environ. 443, 757–765. http://dx.doi.org/10.1016/j.scitotenv.2012.11.061.

Gaudiuso, R., Dell'Aglio, M., Pascale, O., Senesi, G. and Giacomo, A. 2010. Laser Induced Breakdown Spectroscopy for Elemental Analysis in Environmental, Cultural Heritage and Space Applications: A Review of Methods and Results. Sensors 10: 7434-7468.

Gibson, L., Lee, T.M., Koh, L.P., Brook, B.W., Gardner, T.A., Barlow, J. et al. (2011) Primary forests are irreplaceable for sustaining tropical biodiversity. Nature, 478, 378–381.

Gloaguen, T. and Passe, J. 2017. Importance of lithology in defining natural background concentrations of Cr, Cu, Ni, Pb and Zn in sedimentary soils, northeastern Brazil. Chemosphere 186: 31-42.

Guo, L. B., & Gifford, R. M. (2002). Soil carbon stocks and land use change: A meta analysis. Global Change Biology, 8, 345–360.

H.C. Liu, X. Mao, S. Mao, R. Greif, R.E. Russo, Particle size dependent chemistry from laser ablation of brass, Anal. Chem. 77 (2005) 6687–6691.

Harmon, R., Russo, R. and Hark, R. 2013. Applications of laser-induced breakdown spectroscopy for geochemical and environmental analysis: A comprehensive review. Spectrochimica Acta Part B: Atomic Spectroscopy 87: 11-26.

Hattab, S., Bougattass, I., Hassine, R., Dridi-Al-Mohandes, B., 2019. Metals and micronutrients in some edible crops and their cultivation soils in eastern-central region of Tunisia: A comparison between organic and conventional farming. Food Chem. 270, 293–298.

He, Y., Liu, X., Lv, Y., Liu, F., Peng, J., Shen, T., Zhao, Y., Tang, Y. and Luo, S. 2018. Quantitative Analysis of Nutrient Elements in Soil Using Single and Double-Pulse Laser-Induced Breakdown Spectroscopy. Sensors 18: 1526.

Huang, Z., Han, L., Zeng, L., Xiao, W., Tian, Y., 2016. Effects of land use patterns onstream water quality: a case study of a small-scale watershed in the Three Gorges Reservoir Area, China. Environ. Sci. Pollut. R. 23, 3943–3955.

IPCC, 2000. Intergovernmental Panel on Climate Change 2000. Land Use, Land Use Change and Forestry. Special report Cambridge Univ. Press, Cambridge, U.K.

Ismail N, Jong Yoo. (2010). Determination of Lead (Pb) concentration level in solder finished product using Laser Induced Breakdown Spectroscopy (LIBS). *2010 12th Electronics Packaging Technology Conference*.

Jha, A.K., Singh, J.S., 1991. Spoil characteristics and vegetation development of an age series of mine spoils in a dry tropical environment. Vegetation 97, 63–76.

Kadachi, A., Al-Eshaikh, M. and Ahmad, K. 2018. Self-absorption correction: an effective approach for precise quantitative analysis with laser induced breakdown spectroscopy. Laser Physics 28: 095701.

Koch J, Hobbs R. (2007). Synthesis: Is Alcoa Successfully Restoring a Jarrah Forest Ecosystem after Bauxite Mining in Western Australia?. *Restoration Ecology* 15:S137-S144.

L.J. Radziemski, D.A. Cremers (Eds.), Laser-Induced Plasmas and Applications, Marcel Dekker, New York, 1989.

Liao, J., Huang, Y., 2014. Global trend in aquatic ecosystem research from 1992 to 2011. Scientometrics 98, 1203–1219. http://dx.http://dx.doi.org/10.1007/s11192-013- 1071-z.

Lin, Z.J., Anar, M.J., Zheng, H., 2015. Hydrologic and water-quality impact of agricultural land use changes incurred from bioenergy policies. J. Hydrol. 525,429–440.

M. Galiova, J. Kaiser, K. Novotny, M. Hartl, R. Kizek, P. Babula, Utilization of laser-assisted analytical methods for monitoring of lead and nutrition elements distribution in fresh and dried Capsicum annuum l. leaves, Microsc. Res. Tech. 74 (9) (2011) 845–852 <http://dx.doi.org/10.1002/jemt.20967>.

M.A. Badday, N. Bidin, Z.H. Rizvi, R. Hosseinian, Determination of environmental safety level with laser-induced breakdown spectroscopy technique, Chem. Ecol. 31 (4) (2015) 379–387 <http://dx.doi.org/10.1080/ 02757540.2014.961436>.

Maiti, S.K., 2012. Ecorestoration of the Coalmine Degraded Lands. Springer, India.

Maiti, S.K., Shee, C., Ghose, M.K., 2007. Selection of plant species for the reclamation of mine-degraded land in the Indian context. Land Contam. Reclam. 15, 55–65.

Martínez-Garza C, Campo J, Ricker M, Tobón W. (2016). Effect of initial soil properties on six-year growth of 15 tree species in tropical restoration plantings. *Ecology and Evolution* 6:8686-8694.

Melessanaki, K., Papadakis, V., Balas, C., Anglos, D. Laser induced breakdown spectroscopy and hyper-spectral imaging analysis of pigments on an illuminated manuscript, Spectrochim. Acta Part B 56 (2001) 2337–2346.

Mendonça F, Danni-Oliveira IM (2007) Climatologia: noções básicas e climas do Brasil. São Paulo: Oficina de textos, p 206 (in Portuguese).

Miller B, Sinclair E, Menz M, Elliott C, Bunn E, Commander L et al. (2016). A framework for the practical science necessary to restore sustainable, resilient, and biodiverse ecosystems. *Restoration Ecology* 25:605-617.

Miziolek, A.W., Pallesch, V., Schechter, I. (Eds.), Laser Induced Breakdown Spectroscopy, Cambridge University Press, Cambridge, 2006.

Mueller R, Rodrigues J, Nüsslein K, Bohannan B. (2016). Land use change in the Amazon rain forest favours generalist fungi. *Functional Ecology* 30:1845-1853.

N.J. McMillan, C.E. McManus, R.S. Harmon, F.C. DeLucia, A.W. Miziolek, Laser-induced breakdown spectroscopy analysis of complex silicate minerals — beryl, Anal. Bioanal. Chem. 385 (2006) 263–271.

Noll, R. Laser-Induced Breakdown Spectroscopy: Fundamentals and Applications, Springer, New York, 2012.

Oliveira, J. B.; Prado, H. Carta pedológica semidetalhada do Estado de São Paulo – Folha Piracicaba. São Paulo, IA – Instituto Agronômico / IGC – Instituto Geográfico e Cartográfico. Escala 1:100.000. 1989.

Palencia C, Castro A, Giaiotti D, Stel F, Vinet F, Fraile R. (2009). Hailpad-based research: A bibliometric review. Atmospheric Research 93:664-670.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the world's forests. Science 333, 988–993.

Paul, M., Catterall, C., Pollard, P. and Kanowski, J. (2010). Does soil variation between rainforest, pasture and different reforestation pathways affect the early growth of rainforest pioneer species?. Forest Ecology and Management, 260(3), pp.370-377.

Paz C, Goosem M, Bird M, Preece N, Goosem S, Fensham R et al. (2016). Soil types influence predictions of soil carbon stock recovery in tropical secondary forests. *Forest Ecology and Management* 376:74-83.

Peng, J., Liu, F., Zhou, F., Song, K., Zhang, C., Ye, L. and He, Y. 2016. Challenging applications for multi-element analysis by laser-induced breakdown spectroscopy in agriculture: A review. Trac Trends In Analytical Chemistry 85: 260-272.

Perlatti, F., Ferreira, T.O., da Costa Roberto, F.A., Romero, R.E., Sartor, L.R., Otero, X.L., 2015. Trace metal/metalloid concentrations in waste rock, soils and spontaneous plants in the surroundings of an abandoned mine in semi-arid NE-Brazil. Environ. Earth Sci. 74, 5427–5441.

Pugliese, E., Almeida Leite, Wcd., Castro, Mcaad.,Schalch, V., 2012. Exigências para o licenciamento ambiental de áreas para a implantação de aterros sanitários no Brasil: a experiência do município de São Carlos, SP. In VII Congreso de Medio Ambiente de la AUGM, 2012. La Plata, Argentina. La Plata: Facultad de Ciencias Naturales y Museo.

Rasiah,V., Florentine, S. K., Williams, B. L., Westbrooke, M. E., 2004. The impact of deforestation and pasture abandonment on soil properties in the wet tropics of Australia. Geoderma 120,35–45.

Ravichandran, P., 2012. Bibliometric analysis on publication trends in the biodiversity research: a study. J. Adv. Library Inf. Sci. 1, 94–99.

Rivera, M.B., Giraldez, M.I., Fernanndez-Caliani, J.C., 2016. Assessing the environmental availability of heavy metals in geochemically contaminated soils of the Sierra de Aracena Natural Park (SW Spain). Is there a health risk? Sci. Total Environ. 560 e 561, 254 e 265. http://dx.doi.org/10.1016/j.scitotenv.2016.04.029.

Roa-Fuentes L, Martínez-Garza C, Etchevers J, Campo J. (2013). Recovery of Soil C and N in a Tropical Pasture: Passive and Active Restoration. *Land Degradation & Development*26:201-210.

Romanelli, J., Fujimoto, J., Ferreira, M. & Milanez, D. Assessing ecological restoration as a research topic using bibliometric indicators. Ecological Engineering 120, 311-320 (2018).

Rühlmann, M., Büchele, D., Ostermann, M., Bald, I. and Schmid, T. 2018. Challenges in the quantification of nutrients in soils using laser-induced breakdown spectroscopy – A case study with calcium. Spectrochimica Acta Part B: Atomic Spectroscopy 146: 115-121.

Schaefer, C.E.G.R., Fabris, J.D., Ker, J.C., 2008. Minerals in the clay fraction of Brazilian Latosols (Oxisols): a review. Clay Miner. 43, 137–154.

Scowcroft, P.B. ,Haraguchi,J.E., Hue,N.V.,2004. Reforestation and topography affect montane soil properties, nitrogen pools, and nitrogen transformations in Hawaii. Soil Science Society of America Journal 68,959–968.

Sharma, S.K., Misra, A.K., Lucey, P.G., Weins, R.C., Clegg, S.M. Combined remote LIBS and Raman spectroscopy at 8.6 m of sulfur-containing minerals, and minerals coated with hematite or covered with basaltic dust, Spectrochim. Acta Part B 68 (2007) 1036–1045.

Silver, W. L., Kueppers, L. M., Lugo, A. E., Ostertag, R., & Matzek, V. (2004). Carbon sequestration and plant community dynamics following reforestation of tropical pasture. Ecological Applications, 14, 1115–1127.

Singh, A.N., Raghubansh, A.S., Singh, J.S., 2002. Plantations as a tool for mine spoil restoration. Curr. Sci. 82, 1436–1441.

Soares JJ, Silva DW, Lima MIS (2003) Current state and projection of the probable original vegetation of the São Carlos region of São Paulo State, Brazil. Braz J Biol 63(3):527–536.

Song, Y., Zhao, T., 2013. A bibliometric analysis of global forest ecology research during 2002–2011. Springerplus 2, 204. http://dx.doi.org/10.1186/2193-1801-2-204.

Steinfeld, H., Hann, O., & Black Burn, H. (2013). Livestock-environment interactions, issues and options. Rome, Italy: FAO of United Nations.

Suganuma M, Torezan J, Durigan G. (2017). Environment and landscape rather than planting design are the drivers of success in long-term restoration of riparian Atlantic forest. *Applied Vegetation Science* 21:76-84.

Tempesta, G., Senesi, G., Manzari, P. and Agrosì, G. 2018. New insights on the Dronino iron meteorite by double-pulse micro-Laser-Induced Breakdown Spectroscopy. Spectrochimica Acta Part B: Atomic Spectroscopy 144: 75-81.

Thomas, C.D., Cameron, A., Green, R.E., Bakkenes, M., Beaumont, L.J., Collingham, Y.C. et al. (2004) Extinction risk from climate change. Nature, 427, 145–148.

Trevizan, L., Santos, D., Samad, R., Vieira, N., Nunes, L., Rufini, I. and Krug, F. 2009. Evaluation of laser induced breakdown spectroscopy for the determination of micronutrients in plant materials. Spectrochimica Acta Part B: Atomic Spectroscopy 64: 369-377.

Williamson J, Rowe E, Hill P, Nason M, Jones D, Healey J. (2018). Alleviation of both water and nutrient limitations is necessary to accelerate ecological restoration of waste rock tips. Coreacuk. https://core.ac.uk/display/381926 (Accessed November 8, 2018).

Yun, S.W., Baveye, P.C., Kim, D.H., Kang, D.H., Lee, S.Y., Kong, M.J., Park, C.G., Kim, H. Do, Son, J., Yu, C., 2018. Analysis of metal(loid)s contamination and their continuous input in soils around a zinc smelter: Development of methodology and a case study in South Korea. Environ. Pollut. 238, 140–149.

Zhang, Y., Yao, X., Qin, B., 2016. A critical review of the development, current hotspots, and future directions of lake taihu research from the bibliometrics perspective. Environ. Sci. Pollut. Res. 23, 12811–12821.

Zhao, Y., Liu, X., Wang, Z., Zhao, S., 2015. Soil organic carbon fractions and sequestration across a 150-yr secondary forest chronosequence on the Loess Plateau, China. Catena 133, 303–308.

CAPÍTULO 5

The legacy of Elinor Ostrom on common forests research assessed through bibliometric analysis[8]

[8] **A ser submetido em:**

Forest Policy and Economics

Abstract

A bibliometric analysis was performed to evaluate the research on management of the common forests that were influenced by the seminal work of Elinor Ostrom (*Governing the Commons*) from 1990 to 2018. This analysis was based on the online database of the Science Citation Index Expanded – Web of Science©. Six main aspects of the retrieved publications were evaluated: (1) publication years; (2) journals; (3) countries (or regions); (4) study approach type; (5) authors; and (6) keywords. The results indicate that the way the theme has been approached is, mainly, through case studies. From the analysis proposed we find both the relevance and the global coverage of the theme, which is subject of research among authors from 34 different countries. *Forest Policy and Economics* and *Ecology & Society* were the two most widely used journals to disseminate research results. The main concepts addressed by the body of literature, represented by the author's keywords, were: "*Forest governance"*; "*Institutional analysis and development framework"*; "*Property rights*"; "*Socio-ecological systems"*; "*Community-based forest management"*; "*Co-management"*; "*Design principles"*; "*Institutions"*; "*Common-pool resource"* and; "*Sustainability"*. Overall, this framework has proved to be effective in assessing the research trends surrounding the theme and contributing to researchers and governments with information on forest management.

Keywords: VOSviewer; bibliometric analysis; Ostrom's systemic approach; common-pool resources; forest management; forest governance.

1. Introduction

Forests are widely recognized as important providers of ecosystem services (Pohjanmies *et al.*, 2017). These services include food production, wood products, and fuel; the conservation of water quality and regulation; nutrient retention; carbon sequestration; climate regulation; ecotourism and socio-cultural values (MA, 2005; Martín-López *et al.*, 2016). Forests also provide habitat for many species of economic interest and maintain the biodiversity, structure, and functioning of biological systems (Bowen *et al.*, 2007; Vespa *et al.*, 2018). In general, forest ecosystems play important roles in protecting the very landscapes that humans depend on (Lopez and Moran, 2016).

The sustainability of forest ecosystems, on the other hand, can be influenced by several factors, such as the expansion of agricultural cropping areas and urbanization, the adverse effects of climate change and forest management (Sharitz *et al.*, 1992; Stolte, 2001; Lopez and Moran, 2016). Forests and their transformations, as well as ways of sustaining them, are some of the main research topics of Elinor Ostrom (1990). The author investigated the management of common forests through a series of studies in organizations of which she was founder and co-founder (Lopez and Moran, 2016). In her seminal book (Governing the Commons), Ostrom investigated different types of common resources, including forests, and concluded, unlike Hardin (1968), that some local communities were able to manage their forest resources sustainably (Gautam *et al.*, 2004; Nagendra *et al.*, 2005; Roy *et al.*, 2012; Andersson *et al.*, 2014).

Her achievements has nourished a new and growing body of literature on the management of common forests around the world. In addition to the importance of climate issues, population growth and the need for a new model of sustainable management, scientific publications on forest ecosystem services have been boosted (Aznar-Sánchez *et al.*, 2018). Hence, the number of journals on the issue has also increased (Malesios and Arabatzis, 2012) and this is specially important for our analysis. Despite this spreading of the subject, there is a lack of studies (specifically) dedicated to the analysis of the dynamics and systematic organization of the publications on the management of common forests under the bias of the Ostrom systemic concepts was evidenced. This study aims to fill this knowledge gap through a bibliometric analysis. Studies with this characteristic can provide new insights in forests management research and point to its access points.

Analysis of research trends through bibliometric studies has received considerable attention in recent decades. Bibliometric research provides information on changes and trends in the course and content of scientific research (Klenk *et al.*, 2010; Liu *et al.*, 2011; Zhang *et* *al.*, 2017). Bibliometric techniques make use of statistical and mathematical tools to measure researchers' contributions to the literature (Rostaing *et al.*, 2007; Şenel and Demir, 2018). Thus, bibliometric studies can be used in specific fields of study (Vain, 2007) or even in whole disciplines (Bullock, 2015). This field of research is relatively recent (Şenel and Alkan, 2017). The precursor of this methodology was Garfield in the mid-twentieth century (Huang *et al.*, 2014).

Among the more traditional approaches of bibliometric analysis are the co-occurrence analysis, co-citation and the bibliographic coupling applied to the metadata of a given database, such as the *Web of Science.* These metadata generally refer to publication years, number of publications and authorship, institutions and countries, categories of topics, number of citations, main journals, and keywords (Durieux and Gevenois, 2010; Suominen and Toivanen, 2016). Publication years may indicate changes in research activity, interests and even the availability of funding (Liu *et al.*, 2011, Blank *et al.*, 2013, Robinson *et al.*, 2013). The number of published articles addressed and explored issues over time, reflecting the evolution of government policies, non-governmental initiatives or other relevant fields. The diversity of journals titles, in turn, can delineate the breadth of potential audiences and readers (Bonnell, 2012), as well as indicating the main sources used to disseminate results (Hu *et al.*, 2010). Keywords (in general or authors' keywords) can provide an overview of the main issues addressed by the authors according to their frequency of occurrence (Leipold, 2014; Liu *et al.*, 2011) and can also be used to predict future research directions (Hu *et al.*, 2010). Finally, counting the number of citations can demonstrate the potential and impact of these publications (Klenk *et al.*, 2010, Bonnell, 2012, Castro e Silva and Teixeira, 2011).

The evolution of bibliometrics techniques has led to the development of several visualization tools (Zhang *et al.*, 2017), tables of analysis (Robinson *et al.*, 2013), bibliometric mappings (Rafols *et al.*, 2010), automated software (Suominen and Toivanen, 2016; Zhang *et al.*, 2017), among other advances. The results obtained through these kinds of resources can be useful for several users. Researchers starting in a given area, for example, may have access to key research topics and know their strands, identify the most influential authors, and the trends of the area. On the other hand, Senior researchers, can use this feature to keep up-to-date (Zhang *et al.*, 2017).

Bibliometric research has already been used in several fields of science (Van Raan 2006, van Eck *et al.*, 2010), including studies concerning forest ecosystems (Aznar-Sánchez *et al.*, 2018). In Aleixandre-Benavent *et al.* (2018), for example, the authors have analyzed trends in global deforestation research; and Song and Zhao (2013) have used this resource to analyze research on forest ecology. Romanelli *et al.* (2018) also have used bibliometrics to analyze research on the ecological restoration of forest ecosystems worldwide.

Considering the importance of forest ecosystems for global environmental sustainability and the advantages of bibliometric analysis to systematize metadata research and analysis data, the main objective of this study is to provide an overview of available scientific knowledge on the management of common forests that were influenced by the work of Elinor Ostrom after the publication of *Governing the Commons* in 1990. Bibliometric analysis was performed through the *Web of Science* database (timespan: 1990-2018), aiming at: (1) examining the main topics and concepts of research on common forests through keyword analysis; (2) presenting the content and main characteristics of the publications retrieved, according to countries/regions where the studies were conducted, main journals and authors, publication years, number of citations and type of study approach.

2. Materials and Methods

Bibliometric indicators were developed considering the bibliographic data of publications indexed in the online database of the Science Citation Index Expanded (SCI-E) – ISC – Clarivate Analytics – *Web of Science*© (WoS) (https://webofknowledge.com/). The database is often used in the development of academic and bibliometric studies (Azevedo *et al.*, 2005; Boanares and Azevedo, 2014; Romanelli *et al.*, 2018). It was used two sets of data, which were retrieved by different search strategies in WoS. These searches were designated as *first search* and *second search* (Fig. 1). Only articles and reviews were considered in this analysis, since they represent the majority of documents with complete research results (Fu *et al.*, 2013; Romanelli *et al.*, 2018). Datasets were downloaded on November 15, 2018.

At the first search, the search terms were applied to the Topic field, which searches for publications through the title, abstract, keywords of the authors and Keywords Plus (Boudry *et al.*, 2018). Keywords Plus augmented the title-word and author keyword indexing by supplying additional search terms extracted from the titles of article references on WoS (Garfield, 1990). Keywords Plus has been proven effective in research concerning the knowledge structure of scientific fields in terms of bibliometric analysis (Zhang *et al.*, 2016; Fu *et al.*, 2018), but it may also bring some unwanted results. Publications retrieved through Keywords Plus were analyzed in detail and the publications that moved away from the central theme were excluded from the analysis. The terms used in the first search were combined to retrieve the publications that addressed the theme of common forests and also because the term explicitly refers to the Ostrom's work. In this way, it was used the term “Ostrom” (instead of “Elinor Ostrom”) in the first row of search because it is more comprehensive and almost all publications refer to the author only by her last name. In the second row, it was used the terms “Common*” OR “Resource*” OR “Governance*” to refer to the book entitled as Governing the Commons. The asterisk is a wildcard character for any letter or group of letters after the main word (Palencia *et al.*, 2009). In the third and last row, it was considered term “Forest*” to finalize the selection of the publications. These records were later separated between case studies and non-case studies. In the second search, the search terms were applied to the “Author” field to retrieve the author’s own publications on common forests, but they will not be discussed in this work. The terms “Elinor Ostrom” OR “Ostrom E” AND “Forest*” were used, retrieving 8 records. Publications retrieved by the second search are presented as supplementary material (Table S.1.). The final database represents a sample of 24 records with the theme on common forests. Bibliometric indicators analyzed were: (i) publication years; (ii) journals; (iii) countries (or regions); (iv) type of study approach; (v) authors; and (vi) keywords.

All analyzes were performed using the “Analyzing Results” tool provided by the database (WoS) with MS Excel support (v. 2016) to perform calculations and to draw indicator graphs. The bibliometric mapping was developed through VOSviewer (software version 1.6.6; www.vosviewer.com), considering the criterion of co-occurrence of keywords.

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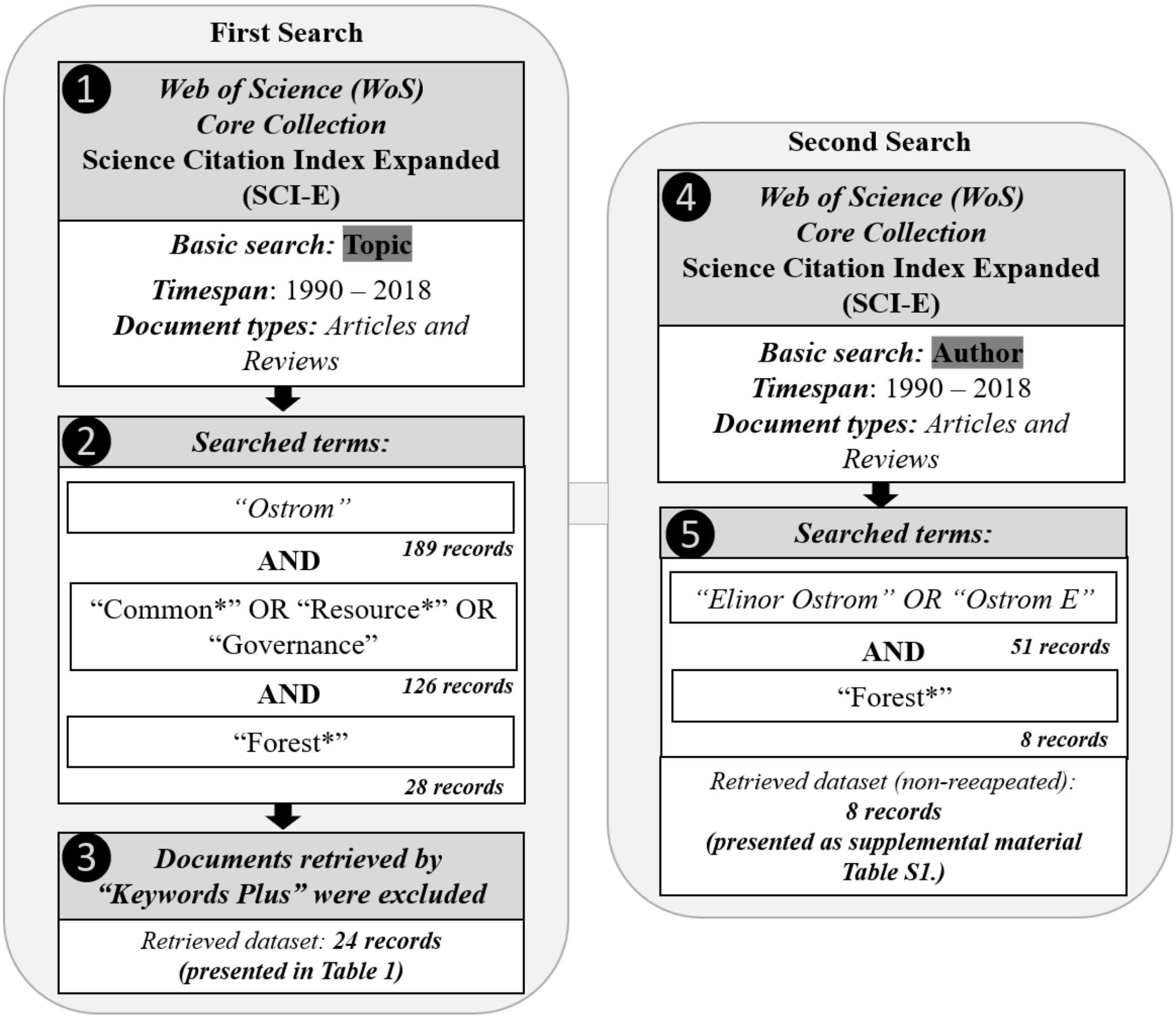

Fig. 1. Synthesis of the employed methodology.

3. Results and Discussion

3.1 Keywords analysis

To investigate the most common search topics among the selected publications, an author's keywords evaluation was performed. Keywords provide information synthesized on the research (Garfield, 1990), and include important terms that were addressed by the authors (Boudry *et al.*, 2018). The terms considered as keywords can be used to analyze the trends of a research area and to show the existing gaps (Guo *et al.*, 2016). In this analysis, repeated words or terms, and meaningless words (also called stopwords) were not taken into account (Fig. 2). It is estimated that 115 author's expressions have been used to describe the retrieved bibliometric sample of this study, which may suggest the wide diversity of subjects covered within this domain (Chuang *et al.*, 2007). Keywords with at least two occurrences among the selected publications (Fig. 2) are presented and discussed under the bias of the common forest resources.

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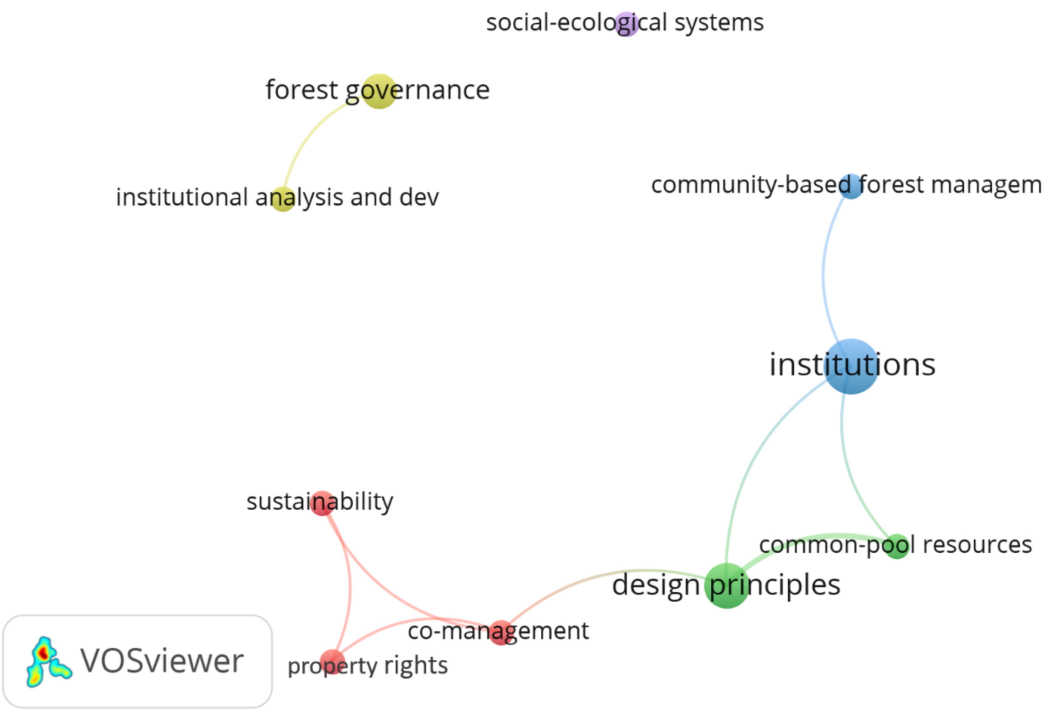

Fig. 2 Network visualization map for the main author's keywords on "Ostrom" and "Forest commons" research. The size of the node is proportional to the number of citations as well as the thickness of the edges between nodes. The colors indicate which cluster of subjects the item belongs to. The absence of links between items refers to the non-co-occurrence of the terms in the retrieved publications.

Common-pool resources (CPR)

Common-pool resources (CPR) are defined as natural or artificial resources large enough to not exclude multiple users. They are systems that generate finite quantities of resource units, so that one person's use subtracts the amount of resource units available to others (Lopez and Moran, 2016). Communal forests are classified as CPR according to Ostrom (1994) for two main reasons: i) the exclusion of users through the development of institutions is difficult and expensive; and ii) when individuals subtract these resources through use (in general), fewer resources remain available to the rest of the group (Állo and Laureiro, 2016), which has been designated by some authors as "rival". When resource units are highly valued and many actors benefit from appropriation for consumption, exchange, or as a factor in the production process, appropriations made by an individual are likely to create negative externalities for other users (Ostrom, 1994).

As described by Gordon (1954), Olson (1965) and Hardin (1968), it is assumed that when individuals use common resources together, each individual is driven to withdraw many units (and/or invest less in maintenance resource), which would not be ideal from a group point of view. Individuals jointly using a common resource are presumed to face a tragic situation of maintaining this resource. However, it is important to consider the assumptions under which these predictions are made (Alló and Laureiro, 2016).

The "Tragedy of the Commons" (Hardin, 1968) will therefore occur in open access common areas where those involved (users and/or external authorities) have not established an effective governance regime. These governance regimes tend to regulate one or more of the following factors: i) who is allowed to appropriate the units of resources; ii) the timing, quantity, location and technology of appropriation; iii) who is obliged to contribute resources to supply or maintain the resource system itself; iv) how appropriation and obligation activities should be monitored and applied; v) how conflicts over appropriation activities and obligations should be resolved; and vi) how the rules that affect it will change over time with changes in resource system performance and participant strategies (Ostrom, 2002).

Forest governance

Around the world, different types of forest governance are used to manage forests. There are a number of strategies for managing them, such as: national parks (for the purpose of preservation), private landowners, rural communities (which have demonstrated the ability to create administrative rules) and, in other situations, forests may also be co-administered by different actors. In this sense, it is necessary to identify the existing institutions that manage forests to understand their social, ecological, political and economic performance (Lopez and Moran, 2016).

Ostrom investigated forests through a series of organizations at Indiana University: the Center for the Study of Institutions, Population and Environmental Change (CIPEC), the International Forest Resources and Institutions Program (IFRI) and the Workshop on Political Theory and Policy Analysis. Research conducted by CIPEC and IFRI has shown that to have good forest governance, regardless of the type of institution that manages the forest, it is necessary to have a common goal and a shared approach, respected among different stakeholders, in addition to the direct forest users (Lopez and Moran, 2016).

Institutions

Institutions, as defined by Ostrom (1990), are formal and informal rules in use; and determine what people can do, must do or cannot do in specific situations. Also, in Ostrom (1990), the author postulated a set of eight general design principles that seemed to characterize the effectiveness of these multiple types of rules and sets of rules. In Crawford and Ostrom (1995), the authors define institutions as regulators of human actions, constituted and reconstituted by rules, norms and shared strategies. Finally, in Hess and Ostrom (2007) the authors bring the concept of institutions as: formal and informal rules that are understood and used by a given community. Ostrom is considered a representative of the New Institutional Economy (Łapniewska, 2016).

Institutional analysis and development (IAD) framework

Ostrom's Institutional Analysis and Development (IAD) framework has been widely used in research to study the local management of common resources, such as forests (Benson *et al.*, 2013, Clement and Amezaga, 2013). The framework is one of many approaches to conducting institutional analysis (Ostrom, 1986; Ostrom, 1990). In their paper, Bartles et al. (1998) have shown that this framework has been widely used in scientific research to investigate the planning and management of forests around the world (Fleischman *et al.* 2017). From the IAD framework it is possible to obtain a guidance on the main insights of institutional, technical and participatory aspects of collective interventions, or the common problem and its resulting effects (Nigussie *et al.*, 2018).

The IAD framework (Fig. 3) can be defined as a general language for analyzing and testing behavioral hypotheses in various situations and at multiple levels of analysis. It refers to how the rules, physical and material conditions, and attributes of the community affect the structure of arenas of action, the incentives that individuals face, and the results. The center of this structure characterizes the "arena of action", which is composed of a situation of action and actors. The action situation refers to a social space where the actors interact, solve the common problem and exchange goods and services. The actors, in turn, are those who participate in the situation (Ostrom *et al.*, 1994; Ostrom, 2007). When the stages of the IAD structure (Fig. 1) are followed using the action arena as the unit of analysis, it is possible to systematically follow the path of decision making, from pre-planning to planning, execution, and also the sustainability scenario of a project.

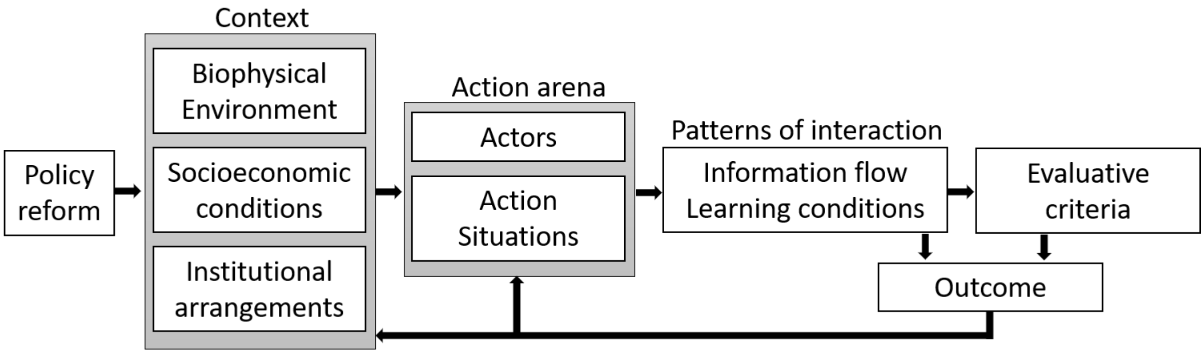

Fig. 3. The IAD framework.
Source: Ostrom *et al.* (1994).

Community-based forest management

The failure of centralized approaches to natural resource management has propelled the search for a viable and sustainable alternative approach to achieving sustainable management (Nabane and Matzke, 1997; Milupi *et al.*, 2017). Thus, the approach to property rights granted to local communities to manage natural resources became common in the 1960s, which was recognized as Community-based Natural Resource Management (CBNRM). According to Songorwa (1999), this type of management was aimed to create conditions where most members of the community would benefit from the sustainable use and management of natural resources. According to the same author, this should occur through a participatory approach from the "bottom-up", considering several principles, which include: meeting basic needs of local populations, local and non-state control, delivery and equitable sharing of benefits and resources and commitment of members of the community and institutions for the management and conservation of natural resources (Milupi *et al.*, 2017).

Ostrom sought to understand in her work how some communities use to be succeeded in managing their common resources, while others are not able to. Unlike Hardin (1968), Ostrom (1990) found that some local communities were able to manage their resources, which include forests in a sustainable way, while resources managed by private or state law did not always lead to sustainable management. Ostrom identified the existence of a set of "design principles" that were common to the communities that are self-governed in a sustainable way (Lopez and Moran, 2016). All these communities have created different institutional arrangements at the local level that have been respected by community members (Chhatre and Agrawal, 2008). Ostrom described this phenomenon as the "emergence" of collective action to manage the common resource. Community-based conservation promotes the idea that long-term conservation success required engagement and provision of benefits to local communities (Brooks *et al.*, 2013; Bannett and Dearden, 2014; Gurneya *et al.*, 2016).

Co-management

Many governments have adopted the forest co-management framework as a process of decentralization and deconcentration of management; usually, where costs and benefits are shared with communities within a defined structure of property rights (Baland and Platteau, 1996). Empirical research has shown that co-management succeeds when there are defined property rights to ensure an equitable distribution of resources and benefits (Behera, 2009; Behera and Engel, 2006; Shahabuddin and Rao, 2010). In this sense, Plummer and Fitzgibbon (2004) define co-management as "the distribution of rights and responsibilities belonging to a particular resource".

The scientific literature on forest sustainability and property rights presents co-management as a key instrument for sustainable forest management (Plummer and Fitzgibbon, 2004; Matum, 2006; Jumbe and Angelsen, 2007). However, co-management (as a model of cooperative management) does not always present achieve results, even though the different forest communities are under the same physical environment and management institutions (Zhu *et al.*, 2014). In China, for example, some co-management initiatives have resulted in economic progress and social development, while others have stoped progressing at the beginning of project implementation (Zhu *et al.*, 2011; Chen *et al.*, 2012; Zhu *et al.*, 2012). These contradictory cases show that more studies about this issue are demanded, also point out the need to investigate other management factors in the success or failure of co-management of forest resources.

Property rights

Property rights can be understood as all kinds of relation between actors and objects (Schlager and Ostrom, 1992; von Benda-Beckmann and von BendaBeckmann, 1999; Sikor *et al.*, 2017). The right to access, use, manage, protect and transfer of resources composes the individual or community property rights package (Schlager and Ostrom, 1992). The focus on property rights, as they are applied in practice, provides an important "bottom-up" perspective on governance of common resources that is complementary to the relationships centered on different government actors (Agrawal and Ribot, 1999; Sikor *et al.*, 2017).

In the case of common forests, the policy framework of each country can establish co-management systems in which government partially transfers the rights over these resources to local users, but retains a certain supervisory authority (Guariguata, 2017). In these co-management schemes, governments need to provide property rights that define who has the rights and responsibilities to manage and encourage sustainable management practices (Cronkleton *et al.*, 2012, Cronkleton *et al.*, 2013, Hlaing *et al.*, 2013). While granting property rights is an important path for maintaining common resources, national and local governments still need to monitor them to ensure the involvement of all stakeholders (Hlaing *et al.*, 2013, Guariguata, 2017).

In the last decades, research has shown that property rights, whether legally or implicitly recognized by the state, are important components of the sustainable use and management of resources by rural communities (Nagendra 2002, Nagendra *et al.*, 2004). Although some authors point out legal rights (*de jure*) being essential for long-term sustainability in locally accessed forests, in some cases, informal recognition rights (*de facto*) can maintain stability in these systems (Gautam *et al.*, 2004; Dorji *et al.*, 2006).

Design principles (DP)

Ostrom defined Design Principles (DP) as “an essential element or condition that helps explain the institutions’ success in sustaining common-pool resources (CPR) and gaining generation-after-generation conformity of appropriators to the rules in use” (Ostrom, 2010). The author argues that the expression “design principles”, which means, literally, a collection of terms, may have confused many readers, and that perhaps the expression “best practices” might better reflect the idea of rules or the structure of institutions (Ostrom 2010, Holden and Tilahun, 2018).

Ostrom’s eight design principles for common-pool resource (CPR) institutions proved to be influential (Saunders, 2014). The author's work is popular because there are many empírical examples drawn from institutions around the world and her work presents an alternative to the pessimistic prediction that man can not cooperate effectively with natural resource management (Saunders, 2014; Tilahun, 2018). The Ostrom’s Design Principles were first listed in her book (Ostrom, 1990) and later refined in Ostrom (2010).

Social-ecological systems (SES)

All the resources used by the human population are embedded in complex social and ecological systems (SES). SES are composed of multiple subsystems and internal variables within these multi-level subsystems that are analogous to the biological hierarchies of living systems (Bertalanffy, 1969; Pennisi, 2003; Ostrom, 2009). In a complex SES, subsystems such as: resource system, resource units, users, and governance systems are relatively separable but interact with each other and provide feedback to affect subsystems and their compartments as well as other larger and smaller SES (Ostrom, 1990). Structurally, SES resemble von Bertalanffy's (1969) systemic assumptions and other approaches updated under this author's precepts (Drack, 2009; Drack and Wolkenhauer, 2011).

While it is recognized that science must increase its efforts to sustain SES, the ecological and social sciences have developed independently and do not easily combine to facilitate sustainability promoting process (The Drama of the Commons, 2002). In addition, scholars tend to develop simple theoretical models to analyze aspects of resource problems and prescribe universal solutions (Ostrom, 2009).

An important contribution of the Ostrom researches in this context was the proposal of a socio-ecological systems structure that reflects the hierarchical qualities of complex SES (Lopez and Moran, 2016). The main components of this system framework, in other words, what she characterizes as the first-line variables of an SES system are: i) resource systems; ii) units of resources; iii) actors; iv) governance systems; v) external social, economic and political scenarios; and vi) related ecosystems. In addition, the SES structure shows how the components interact and what the results of these interactions are (Ostrom, 2009; Lopes and Moran, 2016).

Sustainability

In 1987, the World Commission for Environment and Development (WCED) published its seminal report, Our Common Future, which raised up the question about discussion on how the world population should engage in sustainable development, including how they can address the global resource systems, or “commons” (WCDE, 1987; Ostrom, 2008). In this report, the commission noted that: “Humanity has the capacity to make development sustainable - to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs”.

Although many policy analysts think that private ownership of a common resource is a guaranteed method for sustainability, it can fail to assure long-term protection. Proof of this is that much of deforestation occurs when farmers promote the clearing of their private land for agricultural purposes. Therefore, effective monitoring of employees and users is an essential ingredient of sustainable CPR institutions (Ostrom, 2008).

Scholarship on forest commons certainly examined how commons resources act in relation to their institutional arrangements to achieve desired societal goals, such as conservation, sustainability, and resource condition improvements (Agrawal 1996; Arnold

1998; Somanathan *et al.*, 2005; Agrawal 2007). In this sense, some scholars have pointed to the interdependence of different forms of property rights and institutional arrangements and implicitly questioned whether the terms private, common, and state are distinct domains of governance or complementary systems and are, therefore, best viewed as mixed forms (Antinori and Bray 2005; Bray *et al.*, 2006; Grafton, 2000). Additional comparative research involving different governance systems attempting to identify their specific strengths under specific circumstances would certainly be welcomed by forest patrimony scholars (Agrawal, 2007).

3.2 Publications contents

In general, all publications retrieved by bibliometric analysis were published in 16 different journals (Table 1). Most of these journals (about 75%), however, only published one paper within the theme addressed by this research. The two most influential journals that disseminated most of the research associated with Ostrom's legacy and the management of common forest resources were: *Forest Policy and Economics* and *Ecology & Society*, which account for about 30% and 21% of all publications, respectively. The third most influential journal in this field is the *Journal of Environmental Management* (8% of the retrieved publications).

Please, insert Table 1. Here

Forest Policy and Economics (Impact Factor: 2.496 - JCR 2017) is a leading scientific journal that publishes research on politics and economics related to forests, forest landscapes, forest-related industries, and other aspects. The journal's scope also includes contributions to the social sciences and humanities perspectives related to forests and land use systems. *Ecological & Society*, (Impact factor: 3,256- JCR 2017), in turn, publishes applied and theoretical contents related to the ecological, political and social bases for sustainable socioecological systems. Due to the focus and scope of these journals, as well as their considerable scientific impact, the journals *Forest Policy and Economics* and *Ecology & Society* stood out in the dissemination of information on politics, economics and social contents associated with forests.

This research topic has proved to be relevant in various parts of the world, involving authors from 34 different countries. Most part of the publications were conducted from case studies. Publications that did not involve case studies were concerned with presenting broader approaches and discussing Ostrom's concepts from a more general perspective. The main research topics investigated by the retrieved publications in the first search (Table 2) are presented below and discussed in detail under the bias of the commons forests management, and according to the precepts of Ostrom and other authors that were influenced by her works.

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Table 1. Retrieved publications by the *first search* ranked by publication years; followed by title, authors and journal.

Year	Title	Authors	Journal
2017	*Revisiting the 'cornerstone of Amazonian conservation': a socioecological assessment of Brazil nut exploitation*	Guariguata *et al.*	*Biodiversity and Conservation*
2017	*Forest recreation as a governance problem: four case studies from Switzerland*	Wilkes-Allemann *et al.*	*European Journal of Forest Research*
2017	*A review of community-based natural resource management*	Milupi *et al.*	*Applied Ecology and Environmental Research*
2016	*Evaluating the fulfillment of the principles of collective action in practice: A case study from Galicia (NW Spain)*	Alló and Loureiro	*Forest Policy and Economics*
2016	*REDD plus implementation in the Ecuadorian Amazon: Why land configuration and common-pool resources management matter*	Loaiza *et al.*	*Forest Policy and Economics*
2016	*The legacy of Elinor Ostrom and its relevance to issues of forest conservation*	Lopez and Moran	*Current Opinion In Environmental Sustainability*
2016	*Building local institutions for national conservation programs: lessons for developing Reducing Emissions from Deforestation and Forest Degradation (REDD plus) programs*	Collen *et al.*	*Ecology and Society*
2015	*Institutional factors and opportunities for adapting European forest management to climate change*	Bouriaud *et al.*	*Regional Environmental Change*
2015	*From restitution to revival: A case of commons re-establishment and restitution in Slovenia*	Premrl *et al.*	*Forest Policy and Economics*
2015	*Disturbances, robustness and adaptation in forest commons: Comparative insights from two cases in the Southeastern Alps*	Gatto and Bogataj	*Forest Policy and Economics*
2015	*Institutional Change and Institutional Performance Under Decentralized Forest Management in Babati District, Tanzania*	Babili *et al.*	*Small-Scale Forestry*
2015	*Putting the "E" in SES: unpacking the ecology in the Ostrom social-ecological system framework*	Vogt *et al.*	*Ecology and Society*
2014	*Institutional diversity and local forest governance*	Andersson *et al.*	*Environmental Science & Policy*
2014	*Enhancing the Ostrom social-ecological system framework through formalization*	Hinkel *et al.*	*Ecology and Society*
2014	*Co-management implementation in forested national reserves: Contradicting cases from China*	Zhu *et al.*	*Forest Policy and Economics*
2013	*Economics of the external and the extended orders of markets and politics and their application in forestry*	Deegen	*Forest Policy and Economics*
2013	*Community perceptions of state forest ownership and management: A case study of the Sundarbans Mangrove Forest in Bangladesh*	Roy *et al.*	*Journal of Environmental Management*
2013	*Challenges for Community-Based Forest Management in the KoloAla Site Manompana*	Urech *et al.*	*Environmental Management*
2012	*A review of the role of property rights and forest policies in the management of the Sundarbans Mangrove Forest in Bangladesh*	Roy *et al.*	*Forest Policy and Economics*
2010	*A Review of Design Principles for Community-based Natural Resource Management*	Cox *et al.*	*Ecology and Society*
2010	*Disturbance, Response, and Persistence in Self-Organized Forested Communities: Analysis of Robustness and Resilience in Five Communities in Southern Indiana*	Fleischman *et al.*	*Ecology and Society*
2007	*Design principles and common pool resource management: An institutional approach to evaluating community management in semi-arid Tanzania*	Quinn *et al.*	*Journal of Environmental Management*
2006	*Forest property rights under nationalized forest management in Bhutan*	Dorji *et al.*	*Environmental Conservation*
2001	*Organized participatory resource management: insights from community forestry practices in India*	Sekher	*Forest Policy and Economics*

Table 2. Retrieved publications by the *first search* classified in case studies (followed by the country/region where the study was conducted) and non-case studies.

Case Studies				***Non-case studies***
Authors	**Country/Region**	**Authors**	**Country/Region**	**Authors**
Guariguata *et al*., 2017	Brazil	Vogt *et al.*, 2015	United States	Lopez and Moran, 2016
Wilkes-Allemann *et al.*, 2017	Switzerland	Andersson *et al.*, 2014	Bolivia	Hinkel *et al*., 2014
Milupi *et al.*, 2017	*Many countries*	Zhu *et al.*, 2014	China	Deegen, 2013
Allo and Loureiro, 2016	Spain	Roy *et al*., 2013	Bangladesh	Cox *et al.*, 2010
Loaiza *et al.*, 2016	Ecuador	Urech *et al.*, 2013	Madagascar	
Collen *et al.*, 2016	Ecuador	Roy *et al.*, 2012	Bangladesh	
Bouriaud *et al.*, 2015	*European region*	Fleischman *et al.*, 2010	United States	
Premrl *et al.*, 2015	Slovenia	Quinn *et al.*, 2007	Tanzania	
Gatto and Bogataj, 2015	Slovenia and Italy	Dorji *et al.*, 2006	Bhutan	
Babili *et al.*, 2015	Tanzania	Sekher, 2001	India	

Case Studies

In the context of the publications that were conducted from case studies, the authors Guariguata *et al.* (2017) evaluated the socio-ecological system (SES) that characterizes the Brazil nut (*Bertholletia excelsa*), based on Ostrom's proposals for analysis of the conservation of the exploitation of this Amazonian forest resource. On this same research topic, Fleischman *et al.* (2010) developed an analytical framework for robustness analysis of socio-ecological systems (SES) over time. The authors have indicated through their empirical results some key variables that need to be at the center of theoretical work on the robustness of self-organized systems. In the study conducted by Vogt *et al.* (2015), the authors intend to “unpack” the ecology in the structure of the socio-ecological system proposed by Ostrom. They argue that the framework early proposed by Ostrom has limited capacity to deal with the ecological complexity. Alternatively, they suggest the development of an interdisciplinary structure for the study of SES.

Regarding the evaluation of the institutions, the IAD (Institutional Analysis and Development) framework proposed by Ostrom was approached by Wilkes-Allemann *et al.* (2017). The authors evaluated the forest recreation governance system using IAD framework and qualitative data based on cases and interviews. Bouriaud *et al.* (2015), in turn, studied institutional factors and opportunities for adapting European forest management to climate change through the Ostrom’s framework. The study presents the main factors that influence climate change adaptations when several levels of decision are being considered.

Sekher (2001) has studied organized resource management through insights from community forestry practices in India. The study explores how different local organizations affect the participatory management of common resources. The analysis was developed in accordance with Ostrom’s DP and IAD structure. The author provides some broad organizational guidelines for development initiatives that require community involvement. Milupi *et al.* (2017) have also been concerned with reviewing the initiatives of Community-Based Natural Resource Management (CBNRM) in different countries. They also used the Ostrom's design principles and objective measures to determine the success and failure cases of CBNRM. The challenges for community-based management in forest systems were also addressed by Urech *et al.* (2013), where the authors studied some cases of forest management success in Madagascar and pointed out issues that still need to be solved in this management system. Regarding the co-management of forest resources, Zhu *et al.* (2014) presented contradictory cases in China. The authors argue that the capacity of the co-management mechanisms depend, among other factors, on the interests of local power actors, which are considered key factors in deciding the success of the implementation of that kind of management system.

The institutional approach performed by Quinn *et al.* (2007) considered the evaluation of community management in Tanzania through Ostrom’s design principles. The authors emphasize the need for flexibility to deal with ecological uncertainty and support the view that these principles should not be used as a model to be imposed on resource management regimes. Bibili *et al.* (2015) have also studied institutional performance issues and argued that a structure of multiple institutional logics of action may be more capable of explaining change and institutional performance than institutionalism and Ostrom’s design principles. Following the same approach, Andersson *et al.* (2014) evaluated institutional diversity and local forest governance. The authors argue that the more governance functions to help communities to decide how to organize, the more likely local forests are to become sustainable. Premrl *et al.* (2015) used an up-to-date version of Ostrom’s design principles to assess the capacity of the legal framework to enable the robustness of historical institutions. The authors reveal that the rigid legal framework can affect efficiency in governance of common resources. Gatto and Bogataj (2015) also used design principles to analyze disturbances, robustness, and adaptation in common forest management. The authors argue that forest commons are robust and adaptive socio-ecological systems, and point out the need for more research to better understand them.

In relation to property rights, Roy *et al.* (2013) addressed community perceptions about state forest ownership and management. The theoretical framework of Schlager and Ostrom was adopted to examine the role of potential property variations. The same authors presented in Roy *et al.* (2012) a review of the role of property rights and forest policies in the management of common forests in Bangladesh. Dorji *et al.* (2006) studied forest property rights under nationalized forest management in Bhutan. Changes in forest property rights were also analyzed using Ostrom and Schlager's 'rights package' structure. As well as Roy *et al.* (2013), Dorji *et al.* (2006) argue that the successful management of forests requires a minimal difference between *de jure* policies and *de facto* practices.

Alló and Loureiro (2016), in turn, tested whether the Principles of Collective Action[9] (PCA) postulated by Ostrom (1990) were being followed in a sample of communal forests or not. The authors found a negative relation between the PCA compliance and the number of forest fires. The authors Loaiza *et al.* (2016) and Collen *et al.* (2016) addressed REDD+[10] efforts in different contexts. They used Ostrom's Principles (1990) to assess land configuration and institutional arrangements for decision-making on the use of shared resources and their implications for REDD+ implementation. Collen *et al.* (2016) adopted an approach on building local institutions to national conservation programs by highlighting lessons for the development of REDD+ programs. To date, payment schemes for environmental services (PES), aimed at preserving threatened tropical forests (often denoted as "reduced emissions from deforestation" and "forest degradation" - REDD+ schemes) have shown positive impacts on forestry net economy. Further information on this domain can be obtained in Chomitz (2007), Porras *et al.* (2013), and Strand (2018).

Non-case Studies

In the context of publications classified as non-case studies, the authors Lopez and Moran (2016) addressed in their work the legacy of Elinor Ostrom in the issues related to the conservation, management and analysis of institutional diversity. The authors presented a broad overview of Ostrom's contributions to governance of common-pool resources and reported the author's contributions as founder and co-founder of programs and seminars. Hinkel *et al.* (2014) sought to reinforce in their work the structure of the SES formulated by Ostrom through a formalization. They suggest that SES structures may include seven formal components: variables, concepts, assignment relationships, subsumption relationships, process relations,

[9] According to Ostrom (1990) collective action occurs when more than one individual is required to contribute to an effort in order to achieve a result. Often, however, it is difficult to exclude non-participants from benefiting from the collective action of others. In Allo and Loureiro (2016) it is possible to find the Principles of Collective Action (PCA) proposed by Ostrom (1990) in Appendix A.

[10] The landmark Paris Agreement on climate change has created a new context for international efforts to mitigate climate change and affirmed the existing framework for reducing emissions from deforestation and forest degradation and the role of sustainable management of forests, conservation and enhancement of forest carbon stocks, known as REDD+." (FAO, 2018)

aggregation relationships, and evaluation metrics. These components are identified as generic. The insights obtained through the study can be used for the development of other SES structures.

Cox *et al.* (2010) conducted a review of design principles for community-based natural resource management. The authors analyzed 91 studies that explicitly or implicitly approached Ostrom’s design principles to empirically evaluate which theoretical issues have arisen since its introduction. The authors argue that the principles are well supported empirically and propose a reformulation based on the common points found in the studies. Finally, Deegen (2013) presented the study about economics of the external and the extended orders of markets and politics and their application in forestry. At first, the author systematizes existing economic theories and forestry models, such as Faustmann’s approach and Ostrom’s precepts, and other references. In a second step, the interrelationships between these approaches were studied. From this point of view, the author identifies some unanalyzed or less analyzed areas, which allows some comments for future research in forestry economics.

General approach

As a general synthesis, it was possible to perceive that Ostrom's contributions were significant for issues related to management, forest conservation and understanding of institutional diversity. Ostrom has proven in her studies that self-governance is possible but that it is also influenced by several factors. In her work, the author emphasized the importance of multinational, multidisciplinary and comparative research between the social and natural sciences, and the inherent complexity of governance systems (Lopez and Moran, 2016). Much of this insight became evident through the analysis of publications retrieved by bibliometric analysis.

With regard to common resources units, norms, social and even emotional relationships were listed as important factors to promote sustainable management (Alló and Loureiro, 2016). Some types of resource units have been portrayed as being strongly influenced by the type and level of intervention to which they are subjected. In this sense, promoting dialogue among different stakeholders in the management of common resources – which also includes buyers at the end of the value chain – can be instrumental in improving the equity and benefits of resource sharing (Guariguata *et al.*, 2017). It has also been argued that the structure of Ostrom’s SES is based on a solid empirical basis (Hinkel *et al.*, 2014). However, as it was initially constructed, this structure was portrayed as limited in its ability to understand joint socio-ecological outcomes and human-environmental problems. Fortunately, it is possible to include ecology in the structure of SES, as demonstrated by Vogt *et al.* (2015).

Ostrom's design principles have also been characterized in the literature as robust to the empirical test, but this does not mean that they are complete (Cox *et al.*, 2010). The design principles failed to fully explain some cases of management success, as demonstrated by Babili *et al.* (2015). The incompleteness is the most relevant empirical critique of the Ostrom's Design Principles (Cox *et al.*, 2010). In addition, variables such as the size of user groups, the different types of heterogeneity within or between user groups, and the type of government regime are also important issues that should be better addressed and discussed in this context (Agrawal, 2002).

The discussion on institutions and governance regimes was one of the main research topics that generated a number of conclusions by the authors. Ostrom's IAD framework, for example, proved to be effective in identifying and characterizing the planning and management of CPR, as in the case of forest recreation addressed by Wilkes-Allemann *et al.* (2017). Other authors, however, argue that robust institutions, strongly suggested by Ostrom in the management of common resources, may in some cases be influenced by factors such as institutional and operational changes (Babili *et al.*, 2015). Even institutions considered to be strong may weaken over time in the face of changes. The weakness of management regimes seems to be involved in the inability of these institutions to deal with changes (Quinn *et al.*, 2007). Bouriaud *et al.* (2015) argue that adaptation to change is clearly institutionally directed through the ownership structure and the level of forest policy formation. In this context, location, ethnicity and ecology were listed as important drivers of institutional arrangements (Quinn *et al.*, 2007). Regulatory and sanctioning systems also represent important ingredients of effective forest governance arrangements (Andersson *et al.*, 2014). Communities that exhibit successful cases of CPR management present a virtuous cycle in which group investment produces persistent and robust communities that are better suited to institutional disruptions (Fleischman *et al.*, 2010). Engaging diverse stakeholders in governance increases public commitment and robustness and fosters consensus to reduce conflicts (Sekher, 2001; Wilkes-Allemann *et al.*, 2017).

A community-based natural resource management program is possible when users of these resources are motivated to care for common resources (Milupi *et al.*, 2017). On the other hand, limited capacity for community-level concessions and exploration decisions may threaten sustainable governance of forest resources (Loaiza *et al.*, 2016). When there are contradictions and conflicts of interest between the different actors and the system of co-management institutions, the implementation of co-management may be terminated. A strictly top-down approach may also encounter land-user challenges and weaken this type of regime (Zhu *et al.*, 2014; Collen *et al.*, 2016). There is therefore a need for flexible and continuous support for local communities in the development of robust local institutions (Collen *et al.*, 2016). Different stakeholder groups should always be involved in the decision-making process (Urech *et al.*, 2013), and the incompatibility between *de jure* policies and *de facto* practices should be minimal if forests are to be managed successfully (Dorji *et al.*, 2006).

Roy *et al.* (2012) argued that the effectiveness of the community management regime should be fostered through partnerships between state forest communities with a clearly implemented property rights regime. The provision of management incentives involves community participation through the allocation of appropriate property rights (Roy *et al.*, 2013). Rules that attribute property rights and how they are enforced among stakeholders are important elements of sustainable management (Dorji *et al.*, 2006). When community property rights over the common resource and its users are not recognized it can easily lead to legal anticommons (Premrl *et al.*, 2015). It is only through effective changes in the regime of property rights and policies that the sustainability of the common resource can be achieved (Roy *et al.*, 2012).

Finally, one of the most frequent topics of insight on common forest management concerns the role of state management in mediating access to common forest resources and subsidizing self-governance regimes (Dorji *et al.*, 2006; Roy *et al.*, 2012; Urech *et al.*, 2013; Gatto and Bogataj, 2015; Premrl *et al.*, 2015; Guariguata *et al.*, 2017). As a political implication of this specific theme, it is important to consider the political objectives with local community practices (Babili *et al.*, 2015) from an integrated approach, implying a collaborative strategy among all involved, not only within the community of users, but also between the community and the government (Sekher, 2001).

4. Conclusions

The objective of this work was to retrieve and analyze the scientific publications indexed in the *Web of Science* database that addressed the common forests research under the bias of the systemic concepts of Ostrom (Governing the Commons), through a bibliometric analysis. From the presented results, it was possible to understand how studies have been approached (case-studies and non-case studies), the trends and the most relevant research topics of the body of literature (author's keywords analysis), the most influential journals and authors, and countries (or regions) where researches have been conducted. This information can help to direct new research perspectives as they demonstrate the breadth of the topic in various parts of the world and provide a synthesis of the experience of several authors in different contexts. The bibliometric indicators presented in this study demonstrate the visibility of academic results concerning a specific database (WoS) and not of the entire scientific community. At the moment of the searches, the use of Boolean Operators (AND; OR), quotation marks (*) and asterisks (*) - search tips - was essential to limit and retrieve the bibliometric sample used in this study.

Based on the analysis of the publications, it is suggested that future studies should contemplate the following aspects: (1) the possibility that there are certain types of rules that are more important than others when it comes to governance outcomes; (2) in the context of self-governance, to consider finding new ways for national governments to support forest user communities in their local efforts to manage forest resources efficiently (Andersson *et al.*, 2014); (3) it is recommended that studies on community-based natural resource management be carried out with larger samples using different techniques to increase the understanding of the multiple factors that are necessary to reach these initiatives effectively and sustainably (Milupi *et al.*, 2017); (4) to stimulate studies that seek to adopt the ecological thinking to the SES structure (Vogt *et al.*, 2015). In addition, it is argued in the governance literature that it is not so much the rule per se that it matters, but how it fits into specific local biophysical, socioeconomic, and cultural circumstances (Basurto and Coleman, 2010; Andersson *et al.*, 2014). Cox *et al.* (2010) reinforce that much work still needs to be done to increase the sophistication of case studies on common-pool resource to understand how institutional variables interact with such biophysical variables to produce results. Finally, in order to be able to propose more general considerations about the management of common forests, more empirical research is necessary, considering different spatial and temporal scales (Sekher, 2001; Vogt *et al.*, 2015; Wilkes-Allemann *et al.*, 2017).

Supplemental Data

Table S1. Retrieved publications by the *second search* ranked by years; followed by title, authors, journal and number of citations.

References

Agrawal, A. (1996). The Community versus the Market and the State. Journal of Agricultural and Environmental Ethics 9(1):1-15.

Agrawal, A. (2007). Forests, Governance, and Sustainability: Common Property Theory and its Contributions. International Journal of the Commons, 1(1), pp.111–136. DOI: http://doi.org/10.18352/ijc.10

Agrawal, A., & Ribot, J. (1999). Accountability in decentralization: A framework with South Asian and West African cases. The Journal of Developing Areas, 33, 433–502.

Aleixandre-Benavent, R., Aleixandre-Tudó, J., Castelló-Cogollos, L. and Aleixandre, J. (2018) Trends in global research in deforestation. A bibliometric analysis. Land Use Policy, 72, 293-302.

Alló, M. and Loureiro, M. (2016). Evaluating the fulfillment of the principles of collective action in practice: A case study from Galicia (NW Spain). Forest Policy and Economics 73, 1-9.

Andersson, K., Benavides, J. and León, R. (2014). Institutional diversity and local forest governance. Environmental Science & Policy, 36, 61-72.

Antinori, C. and D. B. Bray. (2005). Community Forest Enteprises as Entreprenuerial Firms: Economic and Institutional Perspectives from Mexico. World Development 33(9): 1529-43.

Arnold, J. E. M. (1998). Managing Forests as Common Property. FAO Forestry Paper 136. Rome: FAO.

Azevedo, P.G., Mesquita, F.O., Young, R.J. (2005). Fishing for gaps in science: a bibliographic analysis of Brazilian freshwater ichthyology from 1986 to 2005. J. Fish Biol. 76, 2177–2193.

Aznar-Sánchez, J., Belmonte-Ureña, L., López-Serrano, M. and Velasco-Muñoz, J. (2018) Forest Ecosystem Services: An Analysis of Worldwide Research. Forests, 9, 453.

Babili, I., Mtalo, E., Kajembe, G. and van der Wal, H. (2015). Institutional Change and Institutional Performance Under Decentralized Forest Management in Babati District, Tanzania. Small-scale Forestry, 14, 381-400.

Barton, D., Benavides, K., Chacon-Cascante, A., Le Coq, J., Quiros, M., Porras, I., Primmer, E. and Ring, I. (2017) Payments for Ecosystem Services as a Policy Mix: Demonstrating the institutional analysis and development framework on conservation policy instruments. Environmental Policy and Governance, 27, 404-421.

Basurto, X., Coleman, E., (2010). Institutional and ecological interplay for successful self-governance of community-based fisheries. Ecological Economics 69 (5) 1094–1103.

Becker, C. and Ostrom, E. (1995) Human Ecology and Resource Sustainability: The Importance of Institutional Diversity. Annual Review of Ecology and Systematics, 26, 113-133.

Bennett, N. J., Dearden, P. (2014). Why local people do not support conservation: Community perceptions of marine protected area livelihood impacts, governance and management in Thailand. – Marine Policy 44: 107-116.

Benson, D., Jordan, A., Cook, H., Smith, L. (2013). Collaborative environmental governance: are watershed partnerships swimming or are they sinking? Land Use Policy 30, 748–757

Blank, L., Vasl, A., Levy, S., Grant, G., Kadas, G., Dafni, A., Blaustein, L. (2013). Directions in green roof research: a bibliometric study. Build. Environ. 66, 23–28.

Boanares, D., Azevedo, C.S. (2014). The use of nucleation techniques to restore the environment: a bibliometric analysis. Nat. Conserv. 12, 93–98. http://dx.doi.org/10.1016/j.ncon.2014.09.002.

Bonnell, B. (2012). Trends in research and collaboration in the Canadian Model Forest Network, 1993–2010. For. Chron. 88 (3), 274–282.

Bouriaud, L., Marzano, M., Lexer, M., Nichiforel, L., Reyer, C., Temperli, C., Peltola, H., Elkin, C., Duduman, G., Taylor, P., Bathgate, S., Borges, J., Clerkx, S., Garcia-Gonzalo, J., Gracia, C., Hengeveld, G., Kellomäki, S., Kostov, G., Maroschek, M., Muys, B., Nabuurs, G., Nicoll, B., Palahí, M., Rammer, W., Ray, D., Schelhaas, M., Sing, L., Tomé, M., Zell, J. and Hanewinkel, M. (2015). Institutional factors and opportunities for adapting European forest management to climate change. Regional Environmental Change, 15, 1595-1609.

Bowen, M., McAlpine, C., House, A. and Smith, G. (2007). Regrowth forests on abandoned agricultural land: A review of their habitat values for recovering forest fauna. Biological Conservation, 140, 273-296. https://doi.org/10.1016/j.biocon.2007.08.012.

Bray, D.B., C. Antinori, and J.M. Torres-Rojo. (2006). The Mexican model of community forest management: The role of. agrarian policy, forest policy and entrepreneurial organization. Forest Policy and Economics 8(4): 470-84.

Bromley, D. (1992). Making the commons work: Theory, practice and policy. San Francisco: Institute for Contemporary Studies Press.

Brooks, J., Waylen K. A., Mulder, M. B. (2013): Assessing community-based conservation projects: A systematic review and multilevel analysis of attitudinal, behavioural, ecological, and economic outcomes. – Environmental Evidence 2:2

Castro e Silva, M.C., Teixeira, A.A.C. (2011). A bibliometric account of the evolution of EE in the last two decades. Is ecological economics (becoming) a post-normal science? Ecol. Econ. 70, 849–862.

Chhatre, A. and Agrawal, A. (2008). Forest commons and local enforcement. Proceedings of the National Academy of Sciences, 105, 13286-13291.

Chomitz, K.M. (2007). At loggerheads? Agricultural expansion, poverty reduction, and environment in the tropical forests. In: World Bank Research Report.

Chuang, K.Y., Huang, Y.L., Ho, Y.S. (2007). A bibliometric and citation analysis of strokerelated research in Taiwan. Scientometrics 72, 201–212. https://http://dx.doi.org/10.1007/s11192-007-1721-0.

Clement, F., Amezaga, J. (2013). Conceptualising context in institutional reforms of land and natural resource management: the case of Vietnam. Int. J. Commons 7, 140–163.

Collen, W., Krause, T., Mundaca, L. and Nicholas, K. (2016). Building local institutions for national conservation programs: lessons for developing Reducing Emissions from Deforestation and Forest Degradation (REDD+) programs. Ecology and Society, 21.

Cox, M., Arnold, G., and Tomás, S.V. (2010). A review of design principles for community-based natural resource management. Ecology and Society 15(4): 38.

Crawford, S. E. S. and Ostrom, E. (1995). “A Grammar of Institutions.” American Political Science Review 89(3): 582–600.

Cronkleton P, Larson AM, Feintrenie L, García C, Levang P. (2013). Reframing community forestry to manage the forest-farm interface. Small Scale For 12:5–13

Cronkleton P, Pulhin JM and Saigal S. (2012). Co-management in community forestry: how the partial devolution of management rights creates challenges for forest communities. Conserv Soc 10:91–102

Deegen, P. (2013). Economics of the external and the extended orders of markets and politics and their application in forestry. Forest Policy and Economics, 35, 21-30.

Dorji, L., Webb, E. And Shivakoti, G. (2006). Forest property rights under nationalized forest management in Bhutan. Environmental Conservation, 33, 141-147.

Drack, M. (2009). Ludwig von Bertalanffy's early system approach. Systems Research and Behavioral Science, 26, 563-572.

Drack, M. and Wolkenhauer, O. (2011). System approaches of Weiss and Bertalanffy and their relevance for systems biology today. Seminars in Cancer Biology, 21, 150-155.

Durieux, V.; Gevenois, P.A. (2010). Bibliometric Indicators: Quality Measurements of Scientific Publication. Radiology 255, 342–351.

FAO. (2018). From reference levels to results reporting: REDD+ under the UNFCCC. 2018 update. Rome, Food and Agriculture Organization of the United Nations (FAO).

Fleischman, F. (2015). Understanding India's forest bureaucracy: a review. Regional Environmental Change, 16, 153-165.

Fleischman, F. D., K. Boenning, G. A. Garcia-Lopez, S. Mincey, M. Schmitt-Harsh, K. Daedlow, M. Lopez, X. Basurto, B. Fischer, and E. Ostrom. (2010). Disturbance, response, and persistence in selforganized forested communities: analysis of robustness and resilience in five communities in southern Indiana. Ecology and Society 15(4): 9.

Fu, H., Fang, K. and Fang, C. (2018). Characteristics of scientific impact of Resources Conservation and Recycling in the past 30 years. Resources, Conservation and Recycling, 137, 251-259.

Fu, H.Z., Wang, M.H., Ho, Y.S. (2013). Mapping of drinking water research: a bibliometric analysis of research output during 1992–2011. Sci. Total Environ. 443, 757–765. http://dx.doi.org/10.1016/j.scitotenv.2012.11.061.

Gardner, R., Ostrom, E. And Walker, J. (1990). The Nature of Common-Pool Resource Problems. Rationality and Society, 2, 335-358.

Garfield, E. (1990). Keywords Plus: ISI's breakthrough retrieval method. Part 1. Expanding your searching power on current contents on diskette. Curr. Contents 32, 5–9.

Gatto, P. and Bogataj, N. (2015). Disturbances, robustness and adaptation in forest commons: Comparative insights from two cases in the Southeastern Alps. Forest Policy and Economics, 58, 56-64.

Gautam, A.P., Shivakoti, G.P. & Webb, E.L. (2004). A review of forest policies, institutions, and change in the resource condition in Nepal. International Forestry Review 6: 136–148.

Gordon, H.S. (1954). The Economic Theory of a Common Property Resource: The Fisheryî, journal of Political Economy 62, 124-142.

Grafton, R. Quentin. (2000). Governance of the Commons: A Role for the State? Land Economics 76(4): 504-17.

Guariguata, M., Cronkleton, P., Duchelle, A. and Zuidema, P. (2017). Revisiting the 'cornerstone of Amazonian conservation': a socioecological assessment of Brazil nut exploitation. *Biodiversity and Conservation* 26: 2007-2027.

Guo, L., Xu, F., Feng, Z., Zhang, G. (2016). A bibliometric analysis of oyster research from 1991 to 2014. Aquacult. Int. 24, 327–344. http://dx.doi.org/10.1007/s10499-015-9928-1.

Gurneya, G. G., Cinnera, J. E., Sartinb, J., Presseya, R. L., Banc, N. C., Marshalld, N. A., Prabuning, D. (2016). Participation in devolved commons management: Multistage socioeconomic factors related to individuals' participation in community-based management of marine protected areas in Indonesia. – Environmental Science and Policy 61: 212-220.

Hardin, G. (1968). The tragedy of the commons. Science,162:1243-1248.

Hinkel, J., Bots, P. and Schlüter, M. (2014). Enhancing the Ostrom social-ecological system framework through formalization. Ecology and Society, 19.

Hlaing, E., Inoue, M. and Pulhin, J. (2013). A Property-Rights Approach to Understanding Regulations and Practices in Community-Based Forest Management: Comparison of Three Systems in the Philippines. Small-scale Forestry, 12, 579-596.

Holden, S. and Tilahun, M. (2018). The importance of Ostrom's Design Principles: Youth group performance in northern Ethiopia. World Development, 104, 10-30.

Hu, J., Yuwei, M., Zhang, L., Gan, F., Ho, Y. (2010). A historical review and bibliometric analysis of research on lead in drinking water field from 1991 to 2007. Sci. Total Environ. 408, 1738–1744.

Huang, L.; Zhang, Y.; Guo, Y.; Zhu, D.; Porter, A.L. (2014). Four dimensional science and technology planning: A new approach based on bibliometrics and technology roadmapping. Technol. Forecast. Soc. Chang. 81, 39–48.

Janssen, M., Holahan, R., Lee, A. and Ostrom, E. (2010). Lab Experiments for the Study of Social-Ecological Systems. Science, 328, 613-617.

Klenk, N.L., Dabros, A., Hickey, G.M. (2010). Quantifying the research impact of the sustainable forest management network in the social sciences: a bibliometric study. Can. J. For. Res. 40, 2248–2255.

Łapniewska, Z. (2016). Reading Elinor Ostrom through a Gender Perspective. Feminist Economics, 22, 129-151.

Leipold, S. (2014). Creating forests with words — a review of forest-related discourse studies. For. Policy Econ. 40, 12–20.

Lise W (2007). An econometric and game theoretic model of common pool resource management: people’s participation in forest management in India. Nova Science, New York.

Liu, X., Zhang, L., Hong, S. (2011). Global biodiversity research during 1900–2009: a bibliometric analysis. Biodivers. Conserv. 20, 807–826.

Liu, X., Zhang, L., Hong, S. (2011). Global biodiversity research during 1900–2009: a bibliometric analysis. Biodivers. Conserv. 20, 807–826.

Loaiza, T., Nehren, U. and Gerold, G. (2016). REDD+ implementation in the Ecuadorian Amazon: Why land configuration and common-pool resources management matter. Forest Policy and Economics 70, 67-79.

Lopez, M. and Moran, E. (2016). The legacy of Elinor Ostrom and its relevance to issues of forest conservation. Current Opinion in Environmental Sustainability 19, 47-56.

Malesios, C.; Arabatzis, G. (2012). An evaluation of forestry journals using bibliometric indices. Ann. For. Res. 55, 147–164.

Martín-López, B.; Oteros-Rozas, E.; Cohen-Shacham, E.; Santos-Martín, F.; Nieto-Romero, M.; Carvalho-Santos, C.; González, J.A.; García-Llorente, M.; Klass, K.; Geijzendorffer, I.; et al. Ecosystem Services Supplied by Mediterranean Basin Ecosystems. (2016). In Handbook of Ecosystem Services; Potschin, M., Haines-Young, R., Fish, R., Turner, K., Eds.; Routledge: New York, NY, USA, pp. 405–414.

Millennnium Ecosystem Assessment (MA). (2005). Ecosystems and Human Well-Being; Biodiversity SynthesisWorld Resources Institute: Washington, DC, USA.

Milupi, I., Somers, M. and Ferguson, W. (2017). A Review of Community-Based Natural Resource Management: Applied Ecology and Environmental Research, V. 15, No. 4, P. 1121-1143.

Nabane, N., Matzke, G. (1997). A gender-sensitive analysis of a community-based wildlife utilization initiative in Zimbabwe's Zambezi Valley. – Society and Natural Resources 10 (6): 519- 535

Nagendra, H. (2002). Tenure and forest conditions: community forestry in the Nepal Terai. Environment Conservation 29(4): 530–539.

Nagendra, H., and E. Ostrom. (2011). The challenge of forest diagnostics. Ecology and Society16(2):20.

Nagendra, H., Karmacharya, M. & Karna, B. (2005). Evaluating forest management in Nepal: views across space and time. Ecology and Society 10(1): 24.

Nagendra, H., Karmacharya, M. & Karna, B. (2005). Evaluating forest management in Nepal: views across space and time. Ecology and Society 10(1): 24.

Nigussie, Z., Tsunekawa, A., Haregeweyn, N., Adgo, E., Cochrane, L., Floquet, A. and Abele, S. (2018). Applying Ostrom’s institutional analysis and development framework to soil and water conservation activities in north-western Ethiopia. Land Use Policy, 71, 1-10.

Nigussie, Z., Tsunekawa, A., Haregeweyn, N., Adgo, E., Cochrane, L., Floquet, A. and Abele, S. (2018). Applying Ostrom's institutional analysis and development framework to soil and water conservation activities in north-western Ethiopia. Land Use Policy, 71, 1-10.

Olson, Mancur. (1965). The Logic of Collective Action. Cambridge: Harvard University Press.

Ostrom, E. (1986). An agenda for the study of institutions. Public Choice 48(1):3–25.

Ostrom, E. (1990). Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge University Press.

Ostrom, E. (2002). Chapter 24 Common-pool resources and institutions: Toward a revised theory. Agriculture and its External Linkages, 1315-1339.

Ostrom, E. (2007). A diagnostic approach for going beyond panaceas. Proceedings of the National Academy of Sciences, 104, 15181-15187.

Ostrom, E. (2008) The Challenge of Common-Pool Resources. Environment: Science and Policy for Sustainable Development, 50, 8-21.

Ostrom, E. (2010). Beyond markets and states: Polycentric governance of complex economic systems. American Economic Review, 100(3), 641–672.

Ostrom, E. And Cox, M. (2010). Moving beyond panaceas: a multi-tiered diagnostic approach for social-ecological analysis. Environmental Conservation, 37, 451-463.

Ostrom, E. and Nagendra, H. (2006). Insights on linking forests, trees, and people from the air, on the ground, and in the laboratory. Proceedings of the National Academy of Sciences, 103, 19224-19231.

Ostrom, E., Gardner, R., Walker, J. (1994). Rules, Games, and Common-pool Resources. University of Michigan Press, Ann Arbor, MI.3

Pennisi, E. (2003). SYSTEMS BIOLOGY: Tracing Life's Circuitry. Science, 302(5651), 1646–1649.

Pohjanmies, T.; Triviño, M.; Le Tortorec, E.; Mazziotta, A.; Snäll, T.; Mönkkönen, M. (2017). Impacts of forestry on boreal forests: An ecosystem services perspective. Ambio 46, 743–755.

Porras, I., Barton, D.N., Canon-Cascante, A., Miranda, M. (2013). Learning From 20 Years of Payments for Ecosystem Services in Costa Rica. International Institute for Environment and Development, London.

Poteete, A. and Ostrom, E. (2004). In pursuit of comparable concepts and data about collective action. Agricultural Systems, 82, 215-232.

Premrl, T., Udovč, A., Bogataj, N. and Krč, J. (2015). From restitution to revival: A case of commons re-establishment and restitution in Slovenia. Forest Policy and Economics, 59, 19-26.

Quinn, C., Huby, M., Kiwasila, H. and Lovett, J. (2007). Design principles and common pool resource management: An institutional approach to evaluating community management in semi-arid Tanzania. Journal of Environmental Management, 84, 100-113.

Rafols, I.; Porter, A.L.; Leydesdorff, L. (2010). Science overlay maps: A new tool for research policy and library management. J. Am. Soc. Inf. Sci. Technol., 61, 1871–1887.

Robinson, D.K.; Huang, L.; Guo, Y.; Porter, A.L. (2013). Forecasting Innovation Pathways (FIP) for new and emerging science and technologies. Technol. Forecast. Soc. Chang. 80, 267–285.

Romanelli, J., Fujimoto, J., Ferreira, M. and Milanez, D. (2018). Assessing ecological restoration as a research topic using bibliometric indicators. Ecological Engineering, 120, 311-320.

Rostaing, H., Barts, N., & Le´veille´, V. (200)7. Bibliometrics: Representation instrument of the multidisciplinar positioning of a scientific area. Implementation for an advisory scientific committee. pp. 341–50 In Proc.8th Int.conf.of the ISKO Spanish Chapter. University of Leon.

Roy, A., Alam, K. and Gow, J. (2012). A review of the role of property rights and forest policies in the management of the Sundarbans Mangrove Forest in Bangladesh. Forest Policy and Economics, 15, 46-53.

Roy, A., Alam, K. and Gow, J. (2013). Community perceptions of state forest ownership and management: A case study of the Sundarbans Mangrove Forest in Bangladesh. Journal of Environmental Management, 117, 141-149.

Saunders, F.P. (2014). The promise of common pool resource theory and the reality of commons projects. International Journal of the Commons, 8 (2), 636–656. doi:10.18352/ijc.477

Schlager, E.&Ostrom, E. (1992) Property rights regimes and natural resources: a conceptual analysis. Land Economics 68: 249–62.

Schlager, E., & Ostrom, E. (1992). Property-rights regimes and natural resources: A conceptual analysis. Land Economics, 68(3), 249–262.

Sekher, M. (2001). Organized participatory resource management: insights from community forestry practices in India. Forest Policy and Economics, 3, 137-154.

Şenel, E. and Demir, E. (2018). Bibliometric and Scientometric Analysis of the Articles Published in the Journal of Religion and Health Between 1975 and 2016. Journal of Religion and Health, 57, 1473-1482.

Şenel, E., Demir, E., & Alkan, R. M. (2017). Bibliometric analysis on global behc¸et disease publications during 1980–2014: Is there a silk road in the literature? Journal of the European Academy of Dermatology and Venereology, 31(3), 518–522.

Sharitz, R., Boring, L., Lear, D. and Pinder, J. (1992). Integrating Ecological Concepts with Natural Resource Management of Southern Forests. Ecological Applications, 2, 226-237. https://doi.org/10.2307/1941857

Sikor, T., He, J. and Lestrelin, G. (2017). Property Rights Regimes and Natural Resources: A Conceptual Analysis Revisited. World Development, 93, 337-349.

Singleton, B. (2017). What's missing from Ostrom? Combining design principles with the theory of sociocultural viability. Environmental Politics, 26, 994-1014.

Somanathan, E., Prabhakar, R., and Mehta, B. S. (2005). Does decentralization work? Forest conservation in the Indian Himalayas. Discussion Paper 05-04. New Delhi: Indian Statistical Institute.

Song, Y.; Zhao, T. (2013). A bibliometric analysis of global forest ecology research during 2002–2011. SpringerPlus, 2, 204.

Stolte, K. (2001). Forest Health Monitoring and Forest Inventory Analysis Programs Monitor Climate Change Effects in Forest Ecosystems. Human and Ecological Risk Assessment: An International Journal, 7, 1297-1316. https://doi.org/10.1080/20018091095014.

Strand, J. (2018). Forest Preservation Under REDD+ Schemes With Incentives Distortions. Ecological Economics, 154, 343-348.

Suominen, A.; Toivanen, H. (2016). Map of science with topic modeling: Comparison of unsupervised learning and human-assigned subject classification. J. Assoc. Inf. Sci. Technol. 67, 2464–2476.

The Drama of the Commons. (2002). National Academies Press, Washington, DC.

Urech, Z., Sorg, J. and Felber, H. (2013). Challenges for Community-Based Forest Management in the KoloAla Site Manompana. Environmental Management, 51, 602-615.

Vain, P. (2007). Trends in GM crop, food and feed safety literature. Nat. Biotechnol. 25, 624–626.

van Eck NJ, Waltman L, Dekker R, van den Berg J (2010). A comparison of two techniques for bibliometric mapping: Multidimensional scaling and VOS. J Am Soc Inf Sci Technol 61(12):2405–2416.

van Raan AFJ (2006). Comparison of the Hirsch-index with standard bibliometric indicators and with peer judgment for 147 chemistry research groups. Scientometrics 67(3):491.

Vespa, N., Zurita, G., Gatti, M. and Bellocq, M. (2018). Seed movement between the native forest and monoculture tree plantations in the southern Atlantic forest: A functional approach. Forest Ecology and Management, 430, 126-133. https://http://dx.doi.org/10.1016/j.foreco.2018.07.051.

Vogt, J., Epstein, G., Mincey, S., Fischer, B. and McCord, P. (2015). Putting the "E" in SES: unpacking the ecology in the Ostrom social-ecological system framework. Ecology and Society, 20.

von Benda-Beckmann, F., & von Benda-Beckmann, K. (1999). A functional analysis of property rights, with special reference to Indonesia. In T. van Meijl, & F. von Benda-Beckmann (Eds.), Property rights and economic development: Land and natural resources in Southeast Asia and Oceania (pp. 15–56). Kegan Paul International: London and New York.

von Bertalanffy L. (1969). General System Theory: Foundations, Development, Applications. Braziller: New York.

Wilkes-Allemann, J., Hanewinkel, M. and Pütz, M. (2017). Forest recreation as a governance problem: four case studies from Switzerland. European Journal of Forest Research 136: 511-526.

World Commission on Environment and Development (WCED). (1987). Our Common Future (New York: Oxford University Press), 8.

Young, O.R. (2012). On Environmental Governance. Sustainability, Efficiency, and Equity. Paradigm Publishers, Boulder, CO.

Zhang, J., Yu, Q., Zheng, F., Long, C., Lu, Z., Duan, Z. (2016). Comparing KeyWords Plus of WOS and author keywords: a case study of patient adherence research. J. Assoc. Inf. Sci. Technol. 67, 967–972.

Zhang, Y.; Zhang, Y.; Shi, K.; Yao, X. (2017). Research development, current hotspots and future directions of water research based on MODIS images: A critical review with a bibliometric analysis. Environ. Sci. Pollut. Res. Int. 24, 15226–15239.

Zhu, T., Krott, M. and Chen, H. (2014). Co-management implementation in forested national reserves: Contradicting cases from China. Forest Policy and Economics, 38, 72-80.

CONCLUSÃO GERAL

Abordagem geral

A análise bibliométrica é precursora do desenvolvimento de indicadores bibliométricos, que por meio de métricas específicas, pode revelar informações importantes sobre o dimensionamento da literatura, o alcance e o direcionamento da pesquisa e a contribuição de pesquisadores em suas redes de colaborações. É evidente que esse tipo de informação representa diversas vantagens científicas e intelectuais, e desempenha um papel importante na avaliação da ciência. A abordagem teórica e prática da bibliometria apresenta focos de estudo relativamente distintos entre a comunidade LIS (*Library Information Science*) e a comunidade não-LIS. Assuntos como "as tendências e os resultados das pesquisas" são frequentemente abordados pela literatura não-LIS. Já a literatura LIS domina os assuntos mais tradicionais relacionados ao aprimoramento dos métodos bibliométricos (Ellegaard, 2018).

Nas Ciências Ambientais, os recursos bibliométricos têm sido empregados por pesquisadores de diversas formas para avaliar os *outputs* da pesquisa, figurando entre os estudos da comunidade não-LIS. Todavia, o processo de buscar, manipular, delimitar e analisar os metadados ainda é relativamente obscuro nesse domínio da ciência, o que pôde ser evidenciado através dos indicadores bibliométricos obtidos pela *Web of Science*, apontada como a principal fonte de citações nessa área do conhecimento. Nesse sentido, muitos autores vêm sinalizando a importância de se compreender melhor a dinâmica das disciplinas que envolvem o campo interdisciplinar das Ciências Ambientais, o que justificou, dentre outros aspectos, o desenvolvimento desse estudo.

Em geral, apresentamos nos capítulos dessa tese diferentes metodologias de análise bibliométrica para abordar tópicos de pesquisa que envolvem as Ciências Ambientais e seus subcampos. Nessa conclusão geral, apresentamos uma síntese da experiência interdisciplinar aprendida nesses cinco capítulos, principalmente no tocante à utilização dos indicadores bibliométricos para avaliar os *outputs* da ciência, gerar novos conhecimentos e discutir as estruturas de carreiras de pesquisadores individuais e seus grupos de pesquisa (Tabela 1).

Tabela 1. Síntese das configurações iniciais de buscas realizadas na *Web of Science;* e indicadores bibliométricos utilizados nos estudos.

	Science Citation Index Expanded (SCI-EXPANDED)					
	Research	***Chapter 1***	***Chapter 2***	***Chapter 3***	***Chapter 4***	***Chapter 5***
Initial settings	***Timespan***	Arbitrary (21 years)	Systematic (27, 10 e 5 years)	Arbitrary (20 years)	All years (1945 - 2018)	Systematic (28 years)
	Basic Search	Topic	Topic	Topic	Topic	Topic and Author
	Searched term(s)	One single term	Multiple terms	Multiple terms	One single; Multiple terms	Multiple terms
	Final database	3,297 records	9,636 records	2,776 records	662 records	24 records
Bibliometric indicators	***Network Collaboration***	Countries, authors and organization	Countries, authors and organization	-	-	-
	Geographic Distribution	-	20 most productive countries	10 most productive countries	-	-
	Rankings	NP, NC, NO	NP, NC, NO, IF, h-index	NP, NC, IF, h-index	NP	-
	WoS Categories	Top 5	Top 6	Top 5	Top 2	-
	Journals	Top 20	Top 40	Top 10	Top 10	Top 3
	Keywords	Keywords-Plus and Author's Keywords (40 words)	Keywords-Plus and Author's Keywords (50 words)	Author's Keywords (50 words)	Author's Keywords (5 occurences)	Author's Keywords (2 occurences)
	Most cited papers	Top 12 (20 years)	Top 40 (27, 10 and 5 years)	Top 10 (20 years); top 10 (5 years)	Presented as supplemental material	-

Abbreviation: NP= number of publications; NC=number of citations; NO=number of occurrences; IF=impact factor.

Configurações de busca

As configurações iniciais de buscas na *Web of Science – Timespan*, *Basic Search* e os termos de busca – influenciaram diretamente a quantidade de publicações recuperadas nas pesquisas, e consequentemente determinaram os tipos de indicadores praticáveis na análise bibliométrica. Nessa perspectiva, foi possível observar que as bases de dados relativamente maiores (capítulos 1, 2 e 3) possibilitaram análises mais robustas em termos da geração e utilização dos indicadores bibliométricos, mas também expressaram resultados de forma mais generalistas. A menor base de dados, por outro lado (capítulo 5), possibilitou a síntese de resultados mais específicos, mas não justificou a utilização de alguns tipos de indicadores bibliométricos. Os *rankings* de citações e de publicações acumuladas, por exemplo, não forneceriam informações tão relevantes nesse caso.

Quanto à definição dos períodos de análise (*timespans*), foram consideradas diferentes estratégias. Nos capítulos 1 e 3, por exemplo, foram utilizados intervalos arbitrários (duas décadas). Já nos capítulos 2 e 4, os períodos de análise foram determinados após uma avaliação prévia do corpo de literatura, na seguinte ordem: primeiramente, foi considerado todo o período de busca disponível na *WoS* (1945 – ano atual*)*, em seguida, foi realizado um refinamento da base de dados a partir dos marcos relevantes do corpo de literatura em relação ao número publicações por ano. Uma outra forma de atribuir um marco no corpo de literatura e estipular um período específico de análise foi apresentado no capítulo 5. Nesse estudo, os anos pós-publicação do livro seminal de Ostrom foram utilizados como "*timespan"* para recuperar as publicações e conduzir a análise bibliométrica nesse tópico de pesquisa.

A configuração de busca básica (*Basic Search)*, por sua vez, também levou em consideração diferentes táticas de análise. Na maior parte dos estudos foi utilizada a busca por tópicos (*topic*), por ser uma forma abrangente de recuperar as publicações na *WoS*. No entanto, esse tipo de busca pode recuperar publicações indesejadas (ruídos), por contemplar a busca por *Keywords-Plus* – que utiliza os termos contidos nos títulos das referências utilizadas pelos autores. As publicações recuperadas pelas *Keywords-Plus* nem sempre estão diretamente associadas ao tema investigado, por isso, a busca por "*topic*" deve ser sempre condizida com precaução. Já a busca por autores (*authors*) foi utilizada no capítulo 5 com forma de complementar a discussão do trabalho e recuperar as publicações da própria autora do tema analisado, o que foi especialmente interessante para esse escopo de estudo.

Um último aspecto a ser discutido sobre a configuração inicial das buscas refere-se à quantidade de termos que são utilizados na recuperação das publicações. Em alguns casos, um único termo de busca pode ser suficientemente abrangente para recuperar a maioria das publicações de um tópico de pesquisa, como foi apresentado no capítulo 1 e 4. Todavia, não existiam nesses casos termos ambíguos ou sinônimos que pudessem comprometer a análise e favorecer a recuperação de ruídos, já que se tratam de tópicos de pesquisa bastante específicos. Vale ressaltar também como um único termo que contém várias palavras pode influenciar a busca por publicações. Por exemplo, *"Laser-induced breakdown spectroscopy"* (capítulo 4). Quando várias palavras ou termos são acompanhados por aspas – *search tips* – a busca é definida por um único termo. Isso configura uma estratégia de busca relativamente restritiva, onde as chances de recuperação de ruídos são baixas. Por outro lado, termos que contêm várias palavras podem comprometer a recuperação das publicações, por poder caracterizar uma tática de busca excessivamente conservadora.

Aprendemos com a experiência dos trabalhos que uma análise prévia de palavras-chave através do *software* VOSviewer pode ser especialmente interessante para a prática da definição dos termos de busca. É recomendável partir de um termo abrangente que caracteriza determinado tópico de pesquisa e posteriormente analisar as suas possíveis variações. Essa etapa é crucial para qualquer estudo bibliométrico, visto que, a ausência de determinados termos pode tornar a análise incompleta, e a robustez metodológica do trabalho pode ficar comprometida. Devemos destacar também que a utilização de siglas e abreviações como termos de busca podem recuperar ruídos, já que diferentes termos poder ser abreviados da mesma forma. Uma solução para tentar contornar esse tipo de problema pode advir da utilização do operador booleano (*NOT*), o que não foi testado nesse estudo.

Indicadores bibliométricos

Conforme foi discutido anteriormente, diferentes configurações iniciais de buscas determinam as estratégias de recuperação das bases de dados, que por sua vez, tornam praticáveis (ou não) a utilização de certos tipos de indicadores bibliométricos. De uma forma geral, os indicadores bibliométricos apresentados nos capítulos dessa tese (Tabela 1) contemplaram os seguintes aspectos: i) análise de redes, ii) distribuição geográfica da informação e, iii) elaboração de *rankings* – com base no número de publicações acumuladas, número de citações, número de ocorrências e índice-h.

A análise de redes, especificamente, tem sido amplamente utilizada nos últimos anos para medir as raízes sociais e intelectuais das disciplinas (Koseoglu,2016). Essa análise tem sido conduzida, principalmente, por meio dos critérios de co-ocorrência, co-citação, co-autoria ou análises conjuntas (Leydesdorff e Vaughan 2006; Abbasi et al. 2011; Zupic e Cair ater 2014). Quase todos os aspectos da colaboração científica podem ser rastreados de forma confiável através desse recurso (Glanzel e Schubert 2004). As análises de redes nesse estudo foram conduzidas através do *software* VOSviewer, considerando os critérios de: co-autoria – para avaliar as redes de colaborações entre autores, organizações e países (capítulos 1 e 2); e co-ocorrência – para avaliar as redes de palavras-chave dos autores em todos os capítulos. Esse tipo de análise permitiu a síntese da informação por meio de gráficos, e tornou possível a visualização e a avaliação da origem da pesquisa, os focos de estudo de cada país, as interações entre os diferentes grupos de pesquisa e o intercâmbio de colaborações.

No geral, pudemos perceber que as bases de dados com números relativamente grandes de publicações tornaram mais perceptíveis as redes de colaborações, como consequência da grande quantidade de informações disponíveis e da possível relação entre o número de publicações recuperadas com a abrangência do assunto em âmbito global. As bases de dados que contemplaram poucas publicações não justificaram ou tornaram praticáveis o desenvolvimento desse tipo de análise (capítulos 4 e 5). Por outro lado, a análise de redes intermediada pelo critério de co-ocorrência de palavras-chave mostrou ser exequível em bases de dados de diferentes tamanhos, e pôde revelar informações importantes em cada contexto onde foi empregada. Todavia, diferentes estratégias de análise tiveram de ser empregadas para viabilizar a utilização desse recurso em cada caso. Nos capítulos 1, 2 e 3, por exemplo, foi empregada a tática da contagem mínima de palavras/termos para gerar o mapeamento de redes, limitados para apresentar 40, 50 e 50 palavras, respectivamente. Nesse processo, as palavras sem sentido (*meaningless words /stopwords*) e/ou sinônimas foram eliminadas da análise para não comprometer a sua robustez. Já nos capítulos 4 e 5 foi empregada a estratégia de contagem mínima de "ocorrências de palavras" ao invés do "número de palavras". Essa tática foi utilizada nesses estudos devido ao fato de as bases de dados serem relativamente pequenas e apresentarem baixa ocorrência de palavras-chave.

A discussão sobre as redes de colaborações foi complementada nos capítulos 2 e 3 pelos recursos das geociências. A dinâmica da distribuição do número de publicações acumuladas por países foi apresentada nesses trabalhos através de mapas. Esse recurso de análise espacial permitiu uma visualização mais abrangente da dinâmica científica entre os países, e gerou uma série de questionamentos que poderão ser utilizados por outros pesquisadores em estudos futuros no campo das Ciências Ambientais, como: a proximidade entre os países pode favorecer as redes de colaborações? Ou: pode existir um foco de pesquisa característico em uma determinada região ou continente?

Assim como a análise de redes, os *rankings* e outras medidas de produtividade são importantes na avaliação da literatura (Harvey 2008; Abbott et al. 2010). A construção de *rankings* pode representar uma forma valiosa de apresentar os resultados da bibliometria, tornando visível o trabalho de pesquisadores individuais e os seus grupos de pesquisa. Nesse estudo, foram empregados diferentes tipos de informações na construção dos *rankings*: i) valores primários (como o número de citações e o número de publicações acumuladas); e ii) valores de índices e coeficientes científicos – como o fator de impacto (utilizado para avaliar periódicos) e o índice-h (utilizados para avaliar peródicos e autores). Contudo, os *rankings* fundamentados no número de publicações e no número de citações foram os mais utilizados.

A análise temporal dos *rankings* pôde revelar que: i) pode haver alterações de posicionamento significativas nos *rankings* de periódicos mais influentes considerando diferentes *timespans* – esse fato pode estar associado, entre outros fatores, às mudanças de preferências por parte dos autores por outras fontes de divulgação de pesquisas com o tempo. Vale ressaltar que o número de citações dos periódicos e o índice-h também tendem a acompanhar essa tendência, mostrando alterações significativas entre diferentes períodos de análise. Além disso, periódicos com diferentes escopos de apreciação de trabalhos podem ocorrer simultaneamente em um mesmo *ranking*; ii) *os rankings* de autores mais produtivos podem apresentar (ou não) alterações significativas com o tempo, contudo, é provável que novos autores se destaquem em *rankings* que consideram períodos mais curtos e recentes, quando comparados com os *rankings* de períodos mais extensos; iii) os *rankings* de publicações mais citadas podem se manter mais ou menos estáveis na análise temporal, principalmente, devido ao fato do número de citações dos trabalhos tender a aumentar com o passar do tempo, e as publicações com maior tempo de indexação tenderem a ser mais citadas. No entanto, trabalhos que foram publicados recentemente e que possuem um alto número de citações podem indicar novas perspectivas de pesquisa (Okubo, 1997). O conhecimento do tipo de publicação e da metodologia dos trabalhos mais citados pode ser de especial interesse para os pesquisadores e editores dos periódicos que visam a seleção e a avaliação dos trabalhos de uma área. Além disso, possibilitam a conscientização sobre os tipos de estudos que estão sendo ou não publicados (Shuaib et al. 2015; Martín-Del-Río et al., 2018); iv) por fim, os *rankings* de categorias de assuntos, representados pelas *WoS Categories* - SCI-EXPANDED, permitiram a visualização dos subcampos de pesquisa dentro de um determinado domínio científico que têm recebido maior (ou menor) atenção por parte dos pesquisadores, e quais focos de pesquisa tem apresentado ascensão ou declínio. Esse tipo de análise é uma forma eficaz de mapear os campos do conhecimento e o inferir sobre o direcionamento da pesquisa através dos indicadores bibliométricos.

REFERÊNCIAS

Abbasi, A., Altmann, J., & Hossain, L. (2011). Identifying the effects of co-authorship networks on the performance of scholars: A correlation and regression analysis of performance measures and social network analysis measures. Journal of Informetrics, 5, 594–607.

Abbott, A., Cyranoski, D., Jones, N., Maher, B., Schiermeier, Q., Van Noorden, R. (2010). Do metrics matter? Many researchers believe that quantitative metrics determine who gets hired and who gets promoted at their institutions. With an exclusive poll and interviews, nature probes to what extent metrics are really used that way. Nature, 465(7300), 860–863.

Bar-Ilan, J. (2008). Which h-index? Comparison of WoS. Scopus and Google Scholar. Scientometrics, 74(2), 257–271.

Ellegaard, O. (2018). The application of bibliometric analysis: disciplinary and user aspects. Scientometrics, 116(1), 181–202. doi:10.1007/s11192-018-2765-z.

Glanzel, W., & Schubert, A. (2004). Analyzing scientific networks through co-authorship. In H. F. Moed, et al. (Eds.), Handbook of quantitative science and technology research (pp. 257–276). Dordrecht: Kluwer Academic Publishers.

Harvey, L. (2008). Rankings of higher education institutions: A critical review. Routledge: Taylor & Francis.

Koseoglu, M. A. (2016). Mapping the institutional collaboration network of strategic management research: 1980–2014. Scientometrics, 109(1), 203–226. doi:10.1007/s11192-016-1894-5.

Leydesdorff, L.; Vaughan, L. (2006). Co-occurrence matrices and their applications in information science: Extending ACA to the Web environment. Journal of the American Society for Information Science and Technology, 57(12), 1616–1628.

Martín-Del-Río, B., Solanes-Puchol, Á., Martínez-Zaragoza, F., & Benavides-Gil, G. (2018). Stress in nurses: The 100 top-cited papers published in nursing journals. Journal of Advanced Nursing, 74(7), 1488–1504. doi:10.1111/jan.13566.

Okubo, Y., (1997). Bibliometric Indicators and Analysis of Research Systems: Methods and Examples. OECD, Paris.

Shuaib, W., Khan, M. S., Shahid, H., Valdes, E. A., & Alweis, R. (2015). Bibliometric Analysis of the Top 100 Cited Cardiovascular Articles. The American Journal of Cardiology, 115(7), 972–981. doi:10.1016/j.amjcard.2015.01.029.

Wildgaard, L. (2015). A comparison of 17 author-level bibliometric indicators for researchers in Astronomy, Environmental Science, Philosophy and Public Health in Web of Science and Google Scholar. Scientometrics, 104(3), 873–906. doi:10.1007/s11192-015-1608-4.

Zupic, I.; Čater, T. (2014). Bibliometric Methods in Management and Organization. Organizational Research Methods, 18(3), 429–472. doi:10.1177/1094428114562.