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Review

Worldwide Research on Low Cost Technologies through Bibliometric Analysis

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Abstract: It is essential to address research into low-cost technologies, as those employed on a wide scale demand a great amount of resources. The main goal of this work was to analyze the research on low cost technologies worldwide by studying the scientific output recorded in the Scopus database. This analysis makes it possible to determine the evolution of research into low cost technologies. In particular, we analyzed the distribution of this research by the different scientific categories, the categories' evolution over time, the types of publications, the geographical distribution throughout different countries, the main institutions in each scientific category, and the areas of research identified through the main keywords indexed in the publications. A remarkable finding of this work has been that the universities that are most active in low-cost technologies are those in the most technologically advanced countries. There is only one exception to the above statement and it is in the field of medicine, where the most technologically developed countries are not always the most interested in this field. Given the trends observed in recent years, there is a need for a major change and for low-cost technologies to become an area of interest in countries with emerging economies.

Keywords: low-cost; technology; worldwide research; bibliometrics; data mining

1. Introduction

Low-cost technologies are expected to be easy to build, to have little or no energy consumption, and should be easy to maintain and operate [1]. The use of sustainable technologies is essential in order to move towards greater global coverage of technology, and therefore to improve human quality of life [2]. However, existing technologies often require the use of various kinds of resources and generate an associated cost that cannot be met by developing countries [3].

There is no general agreement on what low-cost technology is. It can be argued that it should be technology that offers a more economical solution than the one traditionally offered, i.e., the commercial solution. Usually, this low-cost solution gives lower returns in absolute terms, but the returns are good enough to be considered. It has been a widespread trend that major technological advances are achieved by leading research centers, but usually at prohibitive costs that are absorbed by the general consumer market. Once the technological advancement is achieved, it is necessary to make efforts to adapt or achieve similar results with more accessible technologies, which are known as low-cost technologies. Low-cost technologies are sometimes linked to open source solutions for hardware, software, and standards. Many articles in the literature are available and can help to better explain the meaning and uses of low-cost and unconventional technologies [4]. In short, low-cost technologies make technical or practical applications feasible.

For several decades now, the arguments that have justified the social usefulness of research and innovation in universities or research centers have focused on the contributions they make to economic and social growth [5]. Economic growth would benefit from the increase in productivity in existing activities, while social development would come together with research and innovation through new areas of activity or the development of new models of relationships between people based on technology or the lowering of basic services, including access to energy [6].

Therefore, the technology of the future is a focus in today's society, progressing some of the innovations that will spread in the next decades, which will not be as much a part of science fiction as one could imagine. At present, for instance, looking back only a few decades and imagining that the people of the time did not have something as basic as the smartphone makes one think of three very simple words: anything is possible. Another great example of technological advancement is the use of mobile phones that allow users to make phone calls from wherever and whenever they want, in almost any country in the world. In the future, it is very probable that another type of technology that now seems distant will be installed among the people in the most normal way. For this to be possible, technology must be accessible. In this respect, the key will be the development of low-cost technologies. Low-cost technology means resources that one can build oneself, or that one can obtain at a minimal cost, either because the technology has already been withdrawn or it is obtained free of charge for the user [7]. From a broader perspective, it would also include general market resources that can be used for another product or invention. These low-cost technologies (very close to do-it-yourself) require knowledge, which provides autonomy and self-sufficiency. One should be able to do much of the work on one's own.

Low-cost products always respond to a specific need, even if no in-depth analysis of the situation or possible solutions has been carried out [8]. For users and their families, this artisanal solution is often the only possible solution, either temporarily or permanently, especially in developing countries. From a global point of view, this knowledge allows us to decide whether to invest funds in an industrial solution or to invest time in building a hand-made solution. Although low-cost solutions require a lower economic investment for their acquisition, it is very possible that it is necessary to dedicate more time to construction and maintenance, and this may mean that its efficiency is lower. On the other hand, commercial solutions may offer greater performance, be better finished, or be more reliable, but the difference in price may not make up for this increased quality.

Having the skill to apply scientific knowledge to inventions improves the use of industrial techniques in all their dimensions. According to the concepts of engineering, this is a career or profession in which skills are used in a correct way and with good judgment. Knowledge of natural sciences and mathematics are acquired through study, practice, and experience in order to be able to use the materials and forces of nature in an effective way to the benefit of society. Engineering should then be focused on low-cost technologies.

Scientific literature is the result of worldwide research [9]. In most studies, these works have gone through a revision process and have given rise to scientific publications, including books, articles in journals, and communications in specialized publications. These works are indexed in the scientific databases in order to facilitate the search for these works and to allow science to advance from work that has already been carried out [10]. There are those who define science as studies that are published in scientific journals [11]. In short, a scientific article is one of the methods inherent to science, the essential purpose of which is to communicate the results of research, ideas, and debates in a clear, concise, and reliable manner.

Until now, bibliometric studies related to the application of low-cost technologies have been applied to particular subjects. This can be found especially in fields related to medicine. For example, there are issues related to medicine, such as crowdsourcing, which is a tool used for outsourcing tasks, thus reducing the workload of the members of a particular organization [12]. Other issues include studies related to the interventions of waste collection workers, as they are often exposed to significant occupational risks [13], studies related to the lack of improvement in scientific integrity [14], or the challenges and opportunities faced by low-income countries concerning orthopedic information [15]. In the engineering field, bibliometric studies related to low-cost technologies are mainly focused on wastewater treatment [16,17] or carbon capture and storage [18]. It should be noted that very few bibliometric works are dedicated to low-cost technological issues; only some were found about Radio Frequency Identification (RFID) and only for a short period of time, i.e., from 2006 to 2016 [19]. Other studies focused on very specific technologies such as electronic tongue sensing in environmental aqueous matrices to replace more expensive techniques such as chromatographic systems used for environmental monitoring [20]. Other studies point out the limitations of bibliometric research, firstly, that the number of publications does not indicate the quality of the work, and secondly, that not all technological advances are published [21].

In short, all bibliometric studies in relation to low cost to date focus on very specific issues and no study has been detected that provides a global perspective on low-cost research. Nowadays, bibliometric publications are a very useful tool, since they offer a global vision of all the research works that have been carried out in a specific field of knowledge [22]. The objective of this work is to show the current state of research in low-cost technologies around the world, showing which are the main research fields, the main countries and institutions involved in each of those research fields.

2. Materials and Methods

The two major global databases of bibliographic references and journal citations are Web of Science (WoS) formerly Web of Knowledge (WOK), which is owned by Clarivate Analytics, and Scopus, which is owned by Elsevier [23]. Scopus is a multidisciplinary database for scientific research. The total coverage of the Scopus database by areas of knowledge can be summarized as follows: 5400 publications in Chemistry, Physics, Mathematics, and Engineering; 6300 publications in Life and Health Sciences; 1975 publications in Social Sciences, Psychology, and Economics. In addition, it offers interdisciplinary access to more than 27 million abstracts and citations. Therefore, the use of this database, Scopus, to make a bibliometric study in a particular field gives a sample size equal to or greater than the other global database [24]. Therefore, the expected results offered are equivalent to using other scientific databases [25], and in this work Scopus database was used.

In order to carry out this work, a bibliometric study has been carried out by consulting the Scopus database with the following search string TITLE-ABS-KEY (“low cost”), and, as will be seen below for the analysis by subfields, the specific searches have been limited to the indexation categories of Scopus, as for example for the Computer Science field, the search term was: (TITLE-ABS-KEY(“low cost”) AND (LIMIT-TO (“SUBJAREA,”“COMP”))). Figure 1 shows the methodology applied in this research, the main search is done in the Scopus database and the data analysis in Excel. Note that it has also been tested with the term “low-cost”, and the results were not different. In mathematics, it draws attention because a priori it did not seem a term of scientific importance here, so that this discipline uses low cost at the same level as other categories such as the energy category, since this term is linked to the economy. Regarding the category of medicine, it is also noteworthy that low-cost solutions are sought from the point of view of research. The reasons for this will be discussed later.

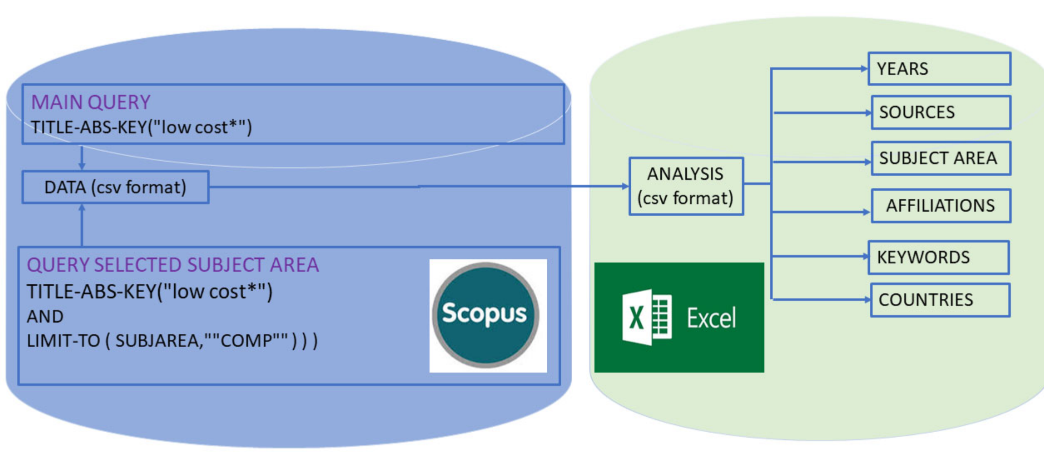

Figure 1. Methodology.

3. Results

The search found 292,335 documents from 1950 to 2018. Figure 2 presents these results as a percentage. It is observed that 10 categories are the most representative, these are: Engineering, Materials Science, Computer Science, Physics and Astronomy, Chemistry, Medicine, Chemical Engineering, Energy, Environmental Science, and Mathematics. It should be noted that in total there are 27 subject categories involved in these publications. As expected, the publications are led by Engineering, followed by Material Science. However, among this top 10, the categories of Medicine and Mathematics stand out, since they do not seem to be cost-related fields.

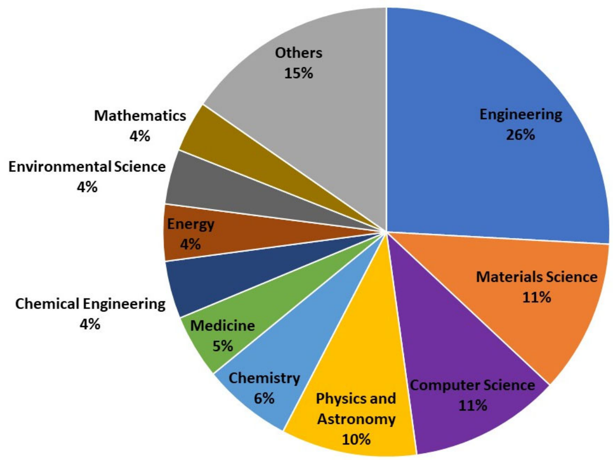

Figure 2. Distribution of low-cost publications by scientific categories indexed in Scopus.

Figure 3 shows the evolution trend of these publications. The engineering category has always led the way on this issue. Regarding the second post, until 2006 it was the Physics and Astronomy category, from then on it was the Computer Science category until 2014, where from then became the Mathematics category. These last three categories have always been in the positions of second to fourth. In fifth place has always been the Chemistry category.

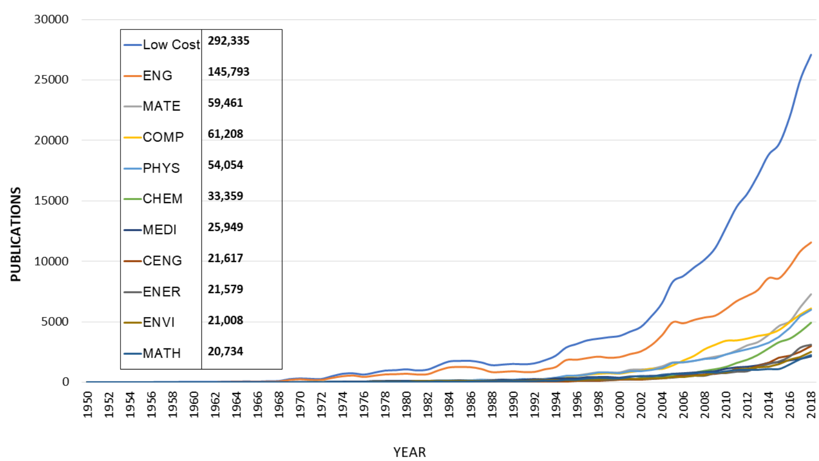

Figure 3. Temporal evolution of low-cost publications by scientific categories indexed in Scopus.

3.1. Types of Publications

Analyzing the type of publication according to the indexation category, the following can be found: Abstract Report, Article, Book, Book Chapter, Business Article, Conference Paper, Conference

Review, Editorial, Erratum, Letter, Note, Report, Retracted, Review, and Short Survey. Figure 4 shows the distribution of the type of publication for the top 10 scientific categories.

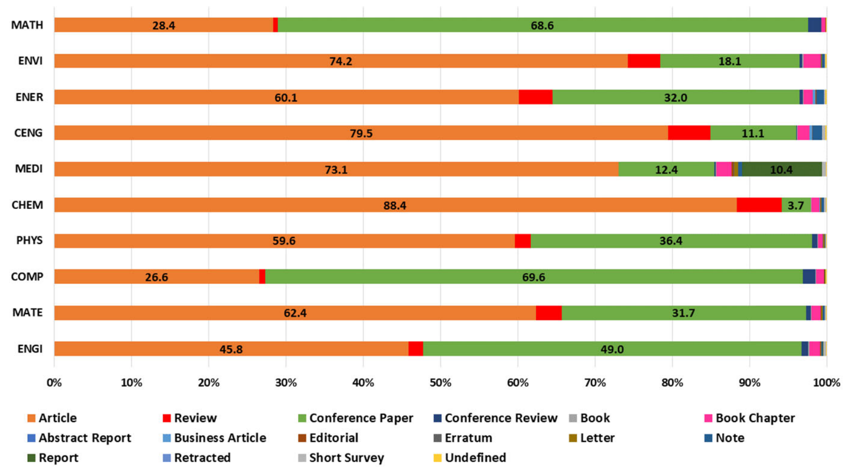

Figure 4. Distribution by publication type according to the scientific category.

The chemical category has the highest percentage of articles with 88.4%, followed by chemical engineering with 79.5%. Regarding conference papers, they lead the Computer Science categories with 69.6% followed by Mathematics with 68.6%. Regarding the book chapters, the representation is very low, only 2% notable in the category of Medicine. In this same category the high percentage of report stands out with 10.4%. In broad terms, science is more established in a particular field [26], if the percentage of books is significant, which is not the case in this field. For example, the most cited article in the low cost subject, "A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO2 films" [27] with 22,465 cites, was compared with the most cited conference paper, "Cricket location-support system" [28] cited 2703 times; it was observed that the articles were cited approximately 10 times more than conference papers.

3.2. Distribution of Publications by Countries

Figure 5 shows a world map with the scientific production of countries on the topic of low cost. It is observed that the great development of this field is in industrialized countries and that they are technological strengths, such is the case of USA (20%), China (16%), India (5%), and European countries. Table 1 shows the publications in the 30 main countries and the percentage of the total that they represent. It should be clarified that the Scopus database, when counting the documents by country, indexes a document as many times as there are different affiliations, then the sum of publications by country could be greater than the total sum of works; generally this does not happen as there are many publications with undefined country.

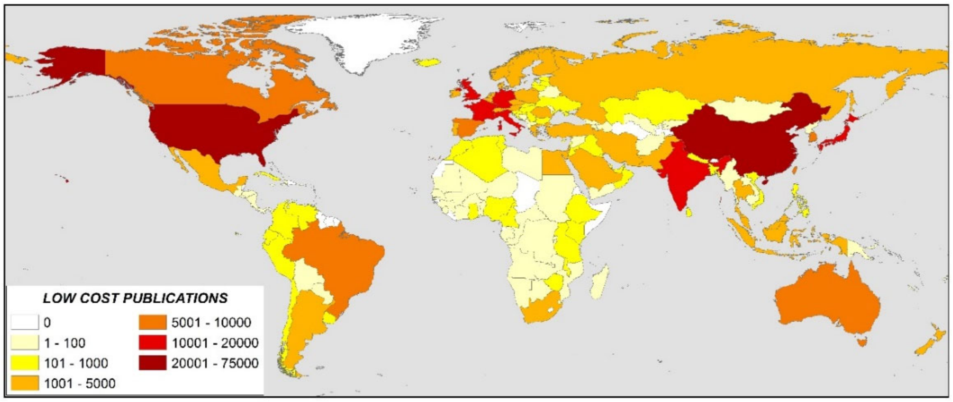

Figure 5. Worldwide research on low cost.

Table 1. Top 30 countries publications (N) their population (P) in millions of inhabitants and their Gross domestic expenditure on R&D (GERD) in billions of dollars.

Country/Territory	Publications (N)	N (%)	P	N/P	GERD	N/GERD
Australia	7966	2.28	24.99	319	21.20	376
Belgium	2754	0.79	11.42	241	14.18	194
Brazil	9035	2.58	209.47	43	39.90	226
Canada	9683	2.77	37.06	261	27.18	356
China	56,182	16.05	1392.73	40	495.98	113
Egypt	2068	0.59	98.42	21	6.85	302
France	10,159	2.90	66.99	152	62.95	161
Germany	13,561	3.87	82.93	164	127.11	107
Greece	2470	0.71	10.73	230	3.40	727
Hong Kong	3083	0.88	7.45	414	-	-
India	17,922	5.12	1352.62	13	49.75	360
Iran	4510	1.29	81.8	55	3.32	1360
Italy	12,780	3.65	60.43	212	32.47	394
Japan	12,288	3.51	126.53	97	175.84	70
Malaysia	4549	1.30	31.53	144	12.41	366
Mexico	2433	0.69	126.19	19	11.03	221
Netherlands	4033	1.15	17.23	234	18.01	224
Poland	2299	0.66	37.98	61	11.44	201
Portugal	2886	0.82	10.28	281	4.33	667
Saudi Arabia	1933	0.55	33.7	57	12.51	154
Singapore	3325	0.95	5.64	590	11.11	299
South Africa	1919	0.55	57.78	33	6.09	315
South Korea	8883	2.54	51.64	172	89.83	99
Spain	9342	2.67	46.72	200	21.37	437
Sweden	2845	0.81	10.18	279	16.74	170
Switzerland	3431	0.98	8.52	403	17.79	193
Taiwan	7247	2.07	23.11	314	-	-
Turkey	3265	0.54	82.32	40	20.58	159
United Kingdom	17,456	0.93	66.49	263	47.81	365
United States	70,588	4.99	327.17	216	543.25	130

Tables 2 and 3 show the top 20 countries in scientific production with respect to the low-cost topic. United States leads the categories of: Engineering, Computer Science, Physics and Astronomy, Medicine, Environmental Science, and Mathematics. China leads the categories of: Materials Science, Chemistry, Chemical Engineering, and Energy.

Table 2. Worldwide publications by country on low cost for the top five categories.

	Engineering	Materials Science	Computer Science	Physics and Astronomy	Chemistry
1	United States	China	United States	United States	China
2	China	United States	China	China	United States
3	United Kingdom	India	India	Germany	India
4	India	Japan	United Kingdom	United Kingdom	South Korea
5	Japan	Germany	Germany	Japan	United Kingdom
6	Germany	United Kingdom	Italy	India	Spain
7	Italy	South Korea	Japan	Italy	Brazil
8	France	France	France	France	Germany
9	South Korea	Taiwan	Canada	South Korea	Japan
10	Canada	Italy	Spain	Spain	Italy
11	Taiwan	Spain	Taiwan	Canada	Iran
12	Spain	Canada	South Korea	Taiwan	France
13	Australia	Australia	Australia	Brazil	Australia
14	Brazil	Brazil	Brazil	Australia	Canada
15	Malaysia	Singapore	Malaysia	Malaysia	Taiwan
16	Netherlands	Hong Kong	Singapore	Switzerland	Singapore
17	Singapore	Malaysia	Portugal	Iran	Hong Kong
18	Iran	Iran	Netherlands	Netherlands	Turkey
19	Hong Kong	Switzerland	Greece	Singapore	Saudi Arabia
20	Switzerland	Netherlands	Hong Kong	Hong Kong	Malaysia

Table 3. Worldwide publications by country on low cost por the categories from 6 to 10.

Title	Medicine	Chemical Engineering	Energy	Environmental Science	Mathematics
1	United States	China	China	United States	United States
2	United Kingdom	United States	United States	China	China
3	Italy	India	India	India	Germany
4	China	South Korea	United Kingdom	United Kingdom	United Kingdom
5	India	United Kingdom	Japan	Brazil	India
6	Brazil	Brazil	Germany	Australia	Italy
7	Germany	Germany	South Korea	Spain	France
8	Canada	Spain	Australia	Italy	Japan
9	Australia	Japan	Italy	Germany	Spain
10	France	Italy	Canada	Canada	Canada
11	Spain	Canada	Spain	Japan	South Korea
12	Japan	Iran	Brazil	Malaysia	Taiwan
13	Netherlands	Australia	France	France	Australia
14	Switzerland	France	Taiwan	Iran	Brazil
15	Iran	Taiwan	Malaysia	South Korea	Netherlands
16	Turkey	Malaysia	Iran	Turkey	Belgium
17	Belgium	Singapore	Turkey	Netherlands	Poland
18	Mexico	Turkey	Singapore	Taiwan	Malaysia
19	Sweden	Saudi Arabia	Hong Kong	Sweden	Switzerland
20	South Korea	Portugal	Sweden	Greece	Singapore

India has a very prominent role occupying relevant positions in these categories: Engineering (4), Materials Science (3), Computer Science (3), Physics and Astronomy (6), Chemistry (3), Medicine (5), Chemical Engineering (3), Energy (3), Environmental Science (3), and Mathematics (5).

United Kingdom also stands out by occupying relevant positions in these categories: Engineering (3), Materials Science (6), Computer Science (3), Physics and Astronomy (3), Chemistry (4), Medicine (2), Chemical Engineering (5), Energy (4), Environmental Science (4), and Mathematics (4).

Broadly speaking, these are the same countries that make the effort to research low-cost technologies independently of the scientific area. Perhaps the scientific category less like the others is Medicine, where countries such as Belgium or Mexico appear in this top 20.

Therefore, it can be concluded that the distribution with scientific areas shows that in general the countries have a similar percentage distribution in all areas, see Figure 6. The efforts are not polarized in function of the scientific field, but it is a constant and transversal bet in all the areas of knowledge affected.

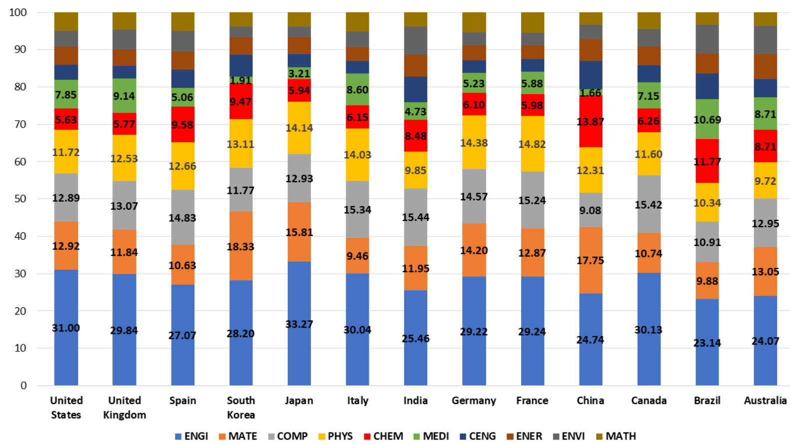

Figure 6. Distribution by scientific categories according to countries.

3.3. Distribution of Publications by Affiliation

The distribution of the scientific effort by affiliations shows those institutions that are more specialized in each scientific field in the subject of low cost. In the case of the Engineering category, Table 4, it is observed the large number of institutions in China, because about half of the top 20 institutions are from this country, and leading the category with two of these affiliations: Chinese Academy of Sciences, and Ministry of Education China.

For the categories of Materials Science and Computer Science, it is the same as for Engineering, which are categories dominated by Chinese institutions. The first institution from another country is the Georgia Institute of Technology in Atlanta, USA, which is in third or fourth place for the three categories cited. This institution has an endowment of $2.091 billion (2018) for 32,718 students.

In the third and fourth categories, Table 5, Physics and Astronomy, and Chemistry, it happens as in the previous categories that are led in the first two places by Chinese institutions: Chinese Academy of Sciences, and Ministry of Education China. It is striking that the third place is for the Centre National de la Recherche Scientifique (CNRS) in the category of Physics and Astronomy. The CNRS is the most important research institution in France and has a multidisciplinary character. This institution also ranks sixth in the Chemistry category.

In the Medicine category, Table 6, a different dynamic is observed from the rest of the categories, clearly dominated by USA institutions, since of the first 20 institutions, 14 are from the USA, including the first one, Harvard Medical School. It is noteworthy that the second institution is from Brazil, the Universidade de Sao Paulo (USP), the sixth from the UK (London School of Hygiene & Tropical Medicine), the seventh from Canada (University of Toronto), and the eighth from France (Inserm).

In the Chemical Engineering and Energy categories, the general dynamic is dominated by Chinese institutions, but even more accentuated, where the first five institutions are from this country, see Table 6. In the Energy category, the first two US institutions occupy the 7th and 9th places, Georgia Institute of Technology National and Renewable Energy Laboratory (NREL).

The last two categories studied are those of Environmental Science and Mathematics, see table 7, which follow the general dynamic of being led by Chinese institutions in at least the first three places. From the fifth place in the category of Environmental Science appears a Brazilian institution, Universidade de Sao Paulo (USP). Moreover, in the Mathematics category in fourth place is an institution from France, Centre National de la Recherche Scientifique (CNRS).

Table 4. Worldwide publications by affiliation/university on low cost for the top three categories.

	Engineering	Materials Science	Computer Science
1	Chinese Academy of Sciences	Chinese Academy of Sciences	Chinese Academy of Sciences
2	Ministry of Education China	Ministry of Education China	Tsinghua University
3	Georgia Institute of Technology	Tsinghua University	Georgia Institute of Technology
4	Tsinghua University	University of Chinese Academy of Sciences	Ministry of Education China
5	IEEE	Georgia Institute of Technology	CNRS Centre National de la Recherche Scientifique
6	CNRS Centre National de la Recherche Scientifique	Huazhong University of Science and Technology	Nanyang Technological University
7	Zhejiang University	CNRS Centre National de la Recherche Scientifique	Massachusetts Institute of Technology
8	Nanyang Technological University	Nanyang Technological University	Huazhong University of Science and Technology
9	Massachusetts Institute of Technology	Zhejiang University	Carnegie Mellon University
10	Harbin Institute of Technology	University of Science and Technology of China	IEEE
11	Huazhong University of Science and Technology	Harbin Institute of Technology	Zhejiang University
12	Southeast University	Shanghai Jiao Tong University	University of Michigan, Ann Arbor
13	Shanghai Jiao Tong University	Peking University	Beihang University
14	University of Chinese Academy of Sciences	South China University of Technology	Shanghai Jiao Tong University
15	Beihang University	Consiglio Nazionale delle Ricerche	Beijing University of Posts and Telecommunications
16	National Taiwan University	Soochow University	Politecnico di Torino
17	University of California, Berkeley	National University of Singapore	Harbin Institute of Technology
18	National Cheng Kung University	Jilin University	Consiglio Nazionale delle Ricerche
19	Politecnico di Torino	Tianjin University	Stanford University
20	University of Michigan, Ann Arbor	Central South University China	ETH Zürich

Table 5. Worldwide publications by affiliation/university on low cost for the categories from 4 to 5.

	Physics and Astronomy	Chemistry
1	Chinese Academy of Sciences	Chinese Academy of Sciences
2	Ministry of Education China	Ministry of Education China
3	CNRS Centre National de la Recherche Scientifique	University of Chinese Academy of Sciences
4	Tsinghua University	Tsinghua University
5	University of Chinese Academy of Sciences	Zhejiang University
6	Consiglio Nazionale delle Ricerche	CNRS Centre National de la Recherche Scientifique
7	Huazhong University of Science and Technology	University of Science and Technology of China
8	Georgia Institute of Technology	Jilin University
9	Nanyang Technological University	South China University of Technology
10	Zhejiang University	Nanyang Technological University
11	Massachusetts Institute of Technology	Nanjing University
12	Shanghai Jiao Tong University	Peking University
13	Harbin Institute of Technology	Wuhan University
14	University of Electronic Science and Technology of China	Huazhong University of Science and Technology
15	Beihang University	Harbin Institute of Technology
16	IEEE	Universidade de Sao Paulo - USP
17	University of Science and Technology of China	Sichuan University
18	University of Cambridge	Soochow University
19	Tianjin University	Consiglio Nazionale delle Ricerche
20	University of California, Berkeley	Shanghai Jiao Tong University

Table 6. Worldwide publications by affiliation/university on low cost for the categories from 6 to 8.

	Medicine	Chemical Engineering	Energy
1	Harvard Medical School	Chinese Academy of Sciences	Chinese Academy of Sciences
2	Universidade de Sao Paulo - USP	Ministry of Education China	Ministry of Education China
3	University of Washington, Seattle	University of Chinese Academy of Sciences	Tsinghua University
4	University of California, San Francisco	Tsinghua University	University of Chinese Academy of Sciences
5	UCL	South China University of Technology	Huazhong University of Science and Technology
6	London School of Hygiene & Tropical Medicine	CNRS Centre National de la Recherche Scientifique	Zhejiang University
7	University of Toronto	Zhejiang University	Georgia Institute of Technology
8	Inserm	Beijing University of Chemical Technology	University of Science and Technology of China
9	University of Michigan, Ann Arbor	University of Science and Technology of China	National Renewable Energy Laboratory
10	Johns Hopkins University	Nanyang Technological University	Nanyang Technological University
11	University of California, Los Angeles	Jilin University	South China University of Technology

12	VA Medical Center	Harbin Institute of Technology	Shanghai Jiao Tong University
13	Johns Hopkins Bloomberg School of Public Health	Dalian University of Technology	Massachusetts Institute of Technology
14	Brigham and Women's Hospital	Tianjin University	University of New South Wales UNSW Australia
15	Massachusetts General Hospital	Shanghai Jiao Tong University	CNRS Centre National de la Recherche Scientifique
16	University of Oxford	National University of Singapore	University of Texas at Austin
17	Centers for Disease Control and Prevention	Sichuan University	Xi'an Jiaotong University
18	University of Pennsylvania	Central South University China	Harbin Institute of Technology
19	Stanford University	Peking University	Oak Ridge National Laboratory
20	The University of North Carolina at Chapel Hill	Nanjing University	Dalian University of Technology

Table 7. Worldwide publications by affiliation/university on low cost for the categories from 9 to 10.

	Environmental Science	**Mathematics**
1	Ministry of Education China	Chinese Academy of Sciences
2	Chinese Academy of Sciences	Tsinghua University
3	Tsinghua University	Ministry of Education China
4	University of Chinese Academy of Sciences	CNRS Centre National de la Recherche Scientifique
5	Universidade de Sao Paulo - USP	Zhejiang University
6	CNRS Centre National de la Recherche Scientifique	Consiglio Nazionale delle Ricerche
7	Harbin Institute of Technology	Huazhong University of Science and Technology
8	Universiti Sains Malaysia	Beihang University
9	United States Environmental Protection Agency	Massachusetts Institute of Technology
10	Zhejiang University	Harbin Institute of Technology
11	South China University of Technology	Georgia Institute of Technology
12	Universiti Putra Malaysia	University of Michigan, Ann Arbor
13	University of Florida	Nanyang Technological University
14	Nanjing University	California Institute of Technology
15	University of California, Berkeley	University of Chinese Academy of Sciences
16	Consiglio Nazionale delle Ricerche	Shanghai Jiao Tong University
17	Hunan University	Beijing Institute of Technology
18	Shandong University	Jet Propulsion Laboratory, California Institute of Technology
19	Stanford University	Peking University
20	The University of North Carolina at Chapel Hill	Nanjing University

3.4. Analisys of Keywords by Categories

Keyword analysis shows the major lines of research in a field. Table 8 shows the top 20 keywords for the first three categories analyzed. Thus, for the category of Engineering it is observed that it is dominated by two great subfields of engineering as they are the electronics and the computer science, and at the same time supported by the mathematics. Since in the first place of the keywords of this category appears Sensors, and Computer Simulation in fourth place. On the other hand, Algorithms and Optimization, are mathematical tools widely used in engineering, through computer science. The most cited work in this category is "A survey on sensor networks" [29]. Other examples are those related to relatively recent technologies such as GPS, "GPS-less low-cost outdoor localization for very small devices" [30], or the synthesis of biodiesel, "Synthesis of biodiesel via acid catalysis" [31]

Table 8. Worldwide publications by affiliation/university on low cost for the categories from 1 to 3.

Engineering	Materials Science	Computer Science
Sensors	Solar Cells	Algorithms
Cost Effectiveness	Electrodes	Sensors
Algorithms	Substrates	Wireless Telecommunication Systems
Computer Simulation	Scanning Electron Microscopy	Signal Processing
Substrates	Thin Films	Wireless Sensor Networks
Optimization	Cost Effectiveness	Robotics
Wireless Telecommunication Systems	Nanoparticles	Cost Effectiveness
Signal Processing	Fabrication	Cameras
Design	X Ray Diffraction	Computer Simulation
Electrodes	Polymers	Image Processing
CMOS Integrated Circuits	Graphene	Optimization
Solar Cells	Sensors	Embedded Systems
Bandwidth	Silicon	Design
Antennas	Carbon	Hardware
Fabrication	Mechanical Properties	Global Positioning System
Manufacture	Synthesis (chemical)	Internet Of Things
Scanning Electron Microscopy	Efficiency	Antennas
Thin Films	Temperature	Computer Vision
Robotics	Nanostructured Materials	Artificial Intelligence
Mathematical Models	Fibers	Virtual Reality

In the Materials Science category, research is led by Solar Cells, followed by Electrodes and Substrates. It is striking that the fourth place is for an analysis technique such as Scanning Electron Microscopy, as it has proven to be an indispensable technique for the analysis of materials. The most cited work in Materials Science category is "Processable aqueous dispersions of graphene nanosheets" [32]. Other examples are related to batteries, "Challenges for rechargeable Li batteries" [33], "Sodium-ion batteries" [34].

In the Computer Science category, the situation is very similar in the first keywords to the Engineering category, dominated by Algorithms and Sensors. In third position appears Wireless Telecommunication Systems; without a doubt it is in this field where a great research effort is being made in the topic of the low cost. The most cited work in Computer Science [29] category is the same as for Engineering category, this is possible because some works can be indexed in several categories. Concerning the algorithms, works such as the following stand out, "Optimizing search engines using clickthrough data" [35].

Table 9 shows the main keywords in categories 4 to 6, Physics and Astronomy, Chemistry, and Medicine. Then, for the Physics and Astronomy category, it was found again that the subject of sensors is the main keyword. Followed in second and third place by Substrates, and Thin Films. In fourth place appears the Scanning Electron Microscopy. One could say that it is very similar to the category of materials, changing very little the order of the main keywords. Then, it can be concluded that there is a high degree of research in the field of physics oriented to the science of materials. The most cited work in the category of Physics and Astronomy is "A consistent and accurate ab initio parametrization of density functional dispersion correction (DFT-D) for the 94 elements H-Pu" [36].

Related to cost effectiveness, following manuscript is worth highlighting "TiO 2 photocatalysis: A historical overview and future prospects" [37].

Table 9. Keywords on low cost research for the categories from 4 to 6.

Physics and Astronomy	Chemistry	Medicine
Sensors	Electrodes	Female
Substrates	Adsorption	Male
Thin Films	Scanning Electron Microscopy	Adult
Scanning Electron Microscopy	Carbon	Health Care Cost
Solar Cells	Nanoparticles	Major Clinical Study
Cost Effectiveness	Controlled Study	Aged
Electrodes	Graphene	Middle Aged
Optical Fibers	Unclassified Drug	Procedures
Fabrication	Solar Cells	Nonhuman
Silicon	X Ray Diffraction	Methodology
Nanoparticles	Limit Of Detection	Adolescent
X Ray Diffraction	Procedures	Economics
Fibers	Catalysts	Health Care Cost
Polymers	Ions	Clinical Article
Refractive Index	Synthesis (chemical	Child
Signal Processing	Electrolytes	Treatment Outcome
Light Emitting Diodes	Catalyst Activity	Sensitivity And Specificity
Optical Communication	Electrocatalysts	Cost Effectiveness Analysis
Bandwidth	Catalysis	Cost Benefit Analysis
Efficiency	Temperature	Clinical Trial

In the category of Chemistry, Electrodes is found as the main keyword, which was also the first in the category of materials. The second keyword is Adsorption, followed by the aforementioned Scanning Electron Microscopy technique. As main materials studied in chemistry related to low cost, there are carbon, nanoparticles, and Graphene. The most cited work in the category of Chemistry is the same as for the category of Physics and Astronomy [36]; some journals are indexed in several categories as is the case of Journal of Chemical Physics. The works related to the batteries are very outstanding in this category, they are the ones related to the keyword electrodes, as "Challenges for rechargeable Li batteries" [38], or "Lithium batteries and cathode materials" [39].

In the category of medicine, it is focused on studies by gender or by age, as they are led by: Female, Male, and Adult. In general, medical research on low cost is focused on the cost of trials: Major Clinical Study, Procedures, Methodology, Clinical Article, or Clinical Trial. It is noteworthy that Treatment Outcome is only ranked 16th on the list. The most cited manuscript in this category is "Brain-computer interfaces for communication and control" [40], with 4593 cites. Much of this highly cited work is also related to genetics, as "Single cell gel/comet assay: Guidelines for in vitro and in vivo genetic toxicology testing" [41], or "MEGAN analysis of metagenomic data" [42].

Table 10 shows the top 20 keywords in the categories Chemical Engineering, and Energy. In the Chemical Engineering category, one finds the same as in the Chemistry category, which does not attract attention as in essence the research results are published in the same journals. The most cited work in Chemical Engineering category is the same as for Material Science [32]. Related to the most cited keyword in this category, adsorption, highlight in the work "Biosorbents for heavy metals removal and their future" [43].

Table 10. Keywords on low cost research for the categories 7 and 8.

Chemical Engineering	Energy
Adsorption	Solar Cells
Scanning Electron Microscopy	Electrodes
Electrodes	Carbon
Carbon	Cost Effectiveness
Nonhuman	Energy Efficiency
Controlled Study	Solar Energy
Chemistry	Efficiency
Nanoparticles	Carbon Dioxide
Catalysts	Electrolytes
X Ray Diffraction	Energy Conversion
Unclassified Drug	Cathodes
Catalyst Activity	Catalysts
Graphene	Secondary Batteries
Temperature	Solar Power Generation
Catalysis	Electric Batteries
Oxygen	Biomass
Particle Size	Optimization
Synthesis (chemical)	Fuel Cells
Human	Electrocatalysts
Synthesis	Power Electronics

The energy category has its first two keywords just like the materials category with Solar Cells and Electrodes. It is observed that this category is dominated by solar energy, energy conservation especially in the subject of batteries: Secondary Batteries, Electric Batteries, or Fuel Cells. As a remarkable result there is the issue of biomass, which is undoubtedly an alternative to generating energy cheaply especially if it is agricultural waste or industry. The most cited work in this category is "Non-conventional low-cost adsorbents for dye removal: A review" [44]. Additionally, related to energy storage, the following paper stands out: "Room-temperature stationary sodium-ion batteries for large-scale electric energy storage" [45].

In Table 11, the main keywords of the Environmental Science and Mathematics categories are shown. The Environmental Science category is dominated by: Adsorption and PH. The most cited work is "Single cell gel/comet assay: Guidelines for in vitro and in vivo genetic toxicology testing" [41]. It is striking that in this category focused on low cost is the recovery and treatment of water: Wastewater Treatment, Water Treatment, Aqueous Solution, Wastewater, Water Pollutants (Chemical), and Waste Water Management. One of the most innovative research topics in water treatment is advanced oxidation [46]. The treatment of water and its pollutants does not need any further explanation as it is a major problem worldwide [47], and for all types of industries and even agriculture, for example, nitrate pollution of aquifers [48].

Table 11. Keywords on low cost research for the categories 9 and 10.

Environmental Science	Mathematics
Adsorption	Sensors
PH	Algorithms
Wastewater Treatment	Computer Simulation
Chemistry	Cost Effectiveness
Pollutant Removal	Optimization
Controlled Study	Cameras
Water Treatment	Design
Aqueous Solution	Robotics
Wastewater	Image Processing

Kinetics	Signal Processing
Biomass	Optical Fibers
Carbon	Wireless Telecommunication Systems
Water Pollutants, Chemical	Computer Vision
Isotherm	Artificial Intelligence
Reaction Kinetics	Wireless Sensor Networks
Temperature	Hardware
Concentration (composition)	Mirrors
Procedures	Embedded Systems
Scanning Electron Microscopy	Mathematical Models
Waste Water Management	Bandwidth

The low-cost mathematics category is quite similar to Engineering, which is natural because engineering problems are solved with advanced mathematical tools. What is striking is that there are many terms for robotics and artificial vision, given that image processing has a high computational cost and making it more efficient saves time and really reach the concept of real time decision making. In this sense the key words related to this subject are: Cameras, Robotics, Image Processing, Signal Processing, Computer Vision, or Artificial Intelligence. The most cited manuscript is this category is "Scalable molecular dynamics with NAMD" [49], which as observed is a work of Computational Chemistry. This field of research has a strong link to bioinformatics, e.g., "The metagenomics RAST server—A public resource for the automatic phylogenetic and functional analysis of metagenomes" [50]. Note that metagenomics is the technique, that uses the techniques of massive sequencing of DNA to transfer all the microorganisms present in a given environment to the laboratory [51]; this is largely possible due to the evolution of lower cost DNA sequencing techniques [9].

4. Discussions

The results show that the global trend towards research into low-cost technologies is increasing exponentially, especially since 2000. As expected, the engineering category is the one that has always led the way in the number of scientific publications. With respect to the other scientific categories, there was a period, between 2006 and 2014, that the computer science category was undoubtedly the second. In the last year with full data, 2018, however, the categories of Mathematics, computer science, and Physics and Astronomy are very close.

In the later analysis of the main keywords it has been observed that Engineering and Computer science share the same subjects. The same occurs on the one hand between the categories of Materials Science, Physics and Astronomy, and Energy, and on the other hand with the categories of Chemistry and Chemical Engineering. Medicine is the only one that does not seem like any other and should be studied separately as a case study.

These documents are published mainly in the form of articles, apart from computer science and mathematics, which dominated by conference papers. This is usually the case in these fields of research where the congresses have great recognition among researchers.

The distribution by countries shows that the countries with the most technological development also do so in research into low-cost technologies. Above all, the role of USA, China, India, the UK, and Germany stands out, these five countries being always in the first positions of all the studied scientific categories. However, if the distribution of the efforts of each country by the different scientific disciplines is analyzed, there are practically no differences between them. That is to say that the industrialized countries are investing efforts in a similar way in the main branches of the science studied, and that they are the most important in low-cost subjects. Research centers, which are really where research is taking place, are dominated by Chinese institutions across the board in all scientific categories. Only the exception is found in the category of medicine, where there is no Chinese institution in the top 20.

Table 1 shows the top 30 countries with the most low-cost publications and calculates the ratio per million inhabitants. It shows how the Asian countries, Singapore and Hong Kong, occupy the top positions together with Switzerland in third position and Australia in fourth position. Regarding the countries with more than 200 million people, the USA leads the ranking with a ratio above 200, while Brazil and China are around 43 and 40, respectively, and finally China with a ratio around 13.

About publications in terms of total investment in research, Gross domestic expenditure on R&D (GERD), Iran stands out in the first position, perhaps because of its current particular commercial relationship with the rest of the world. This rank is followed by European Union countries in this order: Greece, Portugal, Spain, and Italy. These are countries with a high level of technological education and expertise but with more limited research resources, and their researchers are proportionally paying attention to low-cost technologies. Regarding the countries with more than 200 million people, India leads the ranking with a ratio above 360, while Brazil and Mexico are around 226 and 221, respectively, and finally, the USA and China are around 130 and 113, respectively.

In this research it has been shown that the effort in low-cost technologies, except for special circumstances such as those of Iran, is being made by countries of the European Union that have great access to technology, but their investment in it does not reach that of the great economies of the world. All G8 countries, except Italy and Canada, are at the end of the list of low-cost publications in respect of their investment in R&D, see Figure 7. The implications of several studies suggest that investment in R&D is very important for long-term productivity [53]. It should be noted that the leading economies had already addressed the issue of low cost and its relationship to productivity, to what was called "low-cost producer" strategy [54]. They concluded to reduce costs, which had an immediate negative effect on quality, delivery, and market share. However, low-cost solutions are being used in various sectors with very good results, for example in the field of construction, where energy efficiencies in buildings are obtained simply by adopting bioclimatic architectural measures [55,56]. In agricultural topics several low-cost solutions can be found that make agricultural systems more sustainable from an economic [57], environmental [58], and social point of view [59]. This report aims to record the strong interconnections between low-cost technologies and the economic and environmental dimensions of sustainability from the perspective of being advantageous to strategies promoting national and regional economic growth. In broad terms, these solutions make production more sustainable, and therefore, the benefits are for the user but also for society, as the interdependencies and trade-offs between these aspects are important, and economic sustainability should not be seen in isolation as the sole driver.

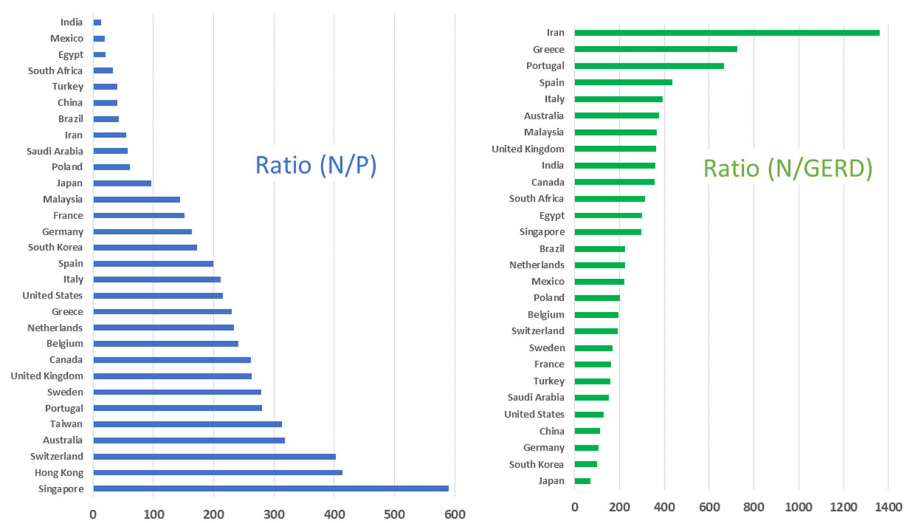

Figure 7. Distribution of country publications by population (P) and gross domestic expenditure on R&D (GERD).

5. Conclusions

The construction of a system of research and innovation by universities or research institutions for technological development should also be promoted with a view to low-cost technology, as this will certainly contribute to the well-being of society and the popularization of technology. To this end, it is essential that the various social agents have a systemic vision of how to approach the problems to be solved in the technological field in order to make them more sustainable. This research shows that low-cost technologies are being developed by the most technologically advanced countries, and by the most advanced research institutions in the technological world. With respect to the scientific categories that work more in low cost can be summarized or grouped into five, the first would be the one that groups: Engineering, Computer Science, and Mathematics, focused on lower costs and especially in communications and sensors, which include the mathematical algorithms of optimization that solve engineering problems. The second category also includes: Materials, Physics and astronomy and energy, especially in the study of solar cells from different points of view and in many cases using electronic microscopy (Scanning Electron Microscopy) as a fundamental tool in research in these fields. The third category includes Chemistry and Chemical Engineering with a great focus on the study of Graphene, and with the most cited technique X-Ray Diffraction. The fourth category would be Environmental Science with a strong focus on Water Treatment. Finally, category five is the most singular of all, and the one that we can consider with little relation to the others: the category of medicine, which is not only different by the subjects treated as expected, but by the institutions and countries that lead it, especially from the USA (Harvard Medical School or the University of Washington, Seattle, WA) and UK (London School of Hygiene & Tropical Medicine). However, there are also institutions from France (Inserm), Brazil (Universidade de Sao Paulo-USP), and Canada (University of Toronto, ON).

This work highlights that the main lines of research in low-cost technologies are carried out by highly technological countries and by those institutions with greater research potential. It therefore seems complicated to transfer this so-called modern technology, although low-cost, to the countries of the developing world. The inadequate adaptation of low-cost technologies to the economic, social and cultural context of the countries that should use them has been proven in practice. A technological change is therefore required that, by applying the principles of sustainable development, adapts and improves the systems of capture, treatment, and reuse, until they become fully sustainable systems. The paper concludes that low-cost technology research is clearly important for economic development at various scales.

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