DOI: https://doi.org/10.15446/ga.v23n1.83464

Profile of the Use of Microorganisms within Environmental Management: Systematic Review 2012-2017

Perfil de usos de los microorganismos en gestión ambiental: revisión sistemática 2012-2017

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ABSTRACT

The use of microorganisms as part of environmental management action, aimed at dealing with environmental issues, results in an interesting and more environmentally friendly alternative to the conventional physicochemical decontamination methods. In this sense, a profile of the use of microorganisms in environmental management would prove helpful for people and organizations to make their processes more sustainable. However, the publications that describe the use of microorganisms within environmental management tend to show their author's point of view, rather than the results of a systematic study in this field of knowledge. Consequently, descriptions of microorganisms, environmental issues and economic sectors involved do not necessarily reflect how developed research in microbiology and environmental management is. Therefore, the aim of this study was to describe the use given to microorganisms within environmental management, providing a profile related to the environmental issues tackled, natural resources affected, and economic sectors involved. A systematic review of scientific literature published between 2012 and 2017 led us to the description of three types of use given to microorganisms, six types of natural resources protected through such uses, ten types of environmental issues, and eight economic sectors in which the uses mentioned are applicable.

KEYWORDS: environmental management; microbiology; economic sectors; natural resources; sustainability.

RESUMEN

El uso de los microorganismos en acciones de gestión ambiental, con el propósito de resolver problemas ambientales, ha sido una alternativa interesante con respecto a los métodos fisicoquímicos convencionales de descontaminación porque suelen ser más amigables con el ambiente. En ese sentido, disponer de un perfil de usos de microorganismos en gestión ambiental sería de utilidad para quienes tienen responsabilidades de gestión ambiental en sus organizaciones o para quienes deben hacer más sostenibles los procesos en los que participan. No obstante, las publicaciones que caracterizan los usos de microorganismos en gestión ambiental suelen presentar la postura del autor y no el resultado de una lectura sistemática de un área de conocimiento, de tal modo que lo que se ha descrito sobre los usos de microorganismos, problemas ambientales y sectores económicos en los que dichos usos tienen aplicabilidad, no necesariamente reflejan el grado de desarrollo de los estudios en microbiología y gestión ambiental. Por esa razón, el objetivo de este estudio fue describir el perfil de usos de microorganismos en la gestión ambiental según los problemas ambientales, recursos naturales afectados y sectores económicos involucrados. Se llevó a cabo una revisión sistemática de literatura científica publicada entre el 2012 y 2017 y se encontraron tres tipos de usos de microorganismos, seis tipos de recursos naturales que son objeto de protección de esos usos, diez tipos de problemas ambientales, y ocho sectores económicos en los que tienen aplicabilidad estos usos.

PALABRAS CLAVE: gestión ambiental; microbiología; sectores económicos; recursos naturales; sostenibilidad.

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Received: November 12, 2019. Accepted: April 22, 2020

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Introduction

At present, environmental management focuses on diverse environmental issues that bear worldwide attention and importance. Ozone layer depletion, biodiversity loss and global warming, which is caused by the release of greenhouse gases such as carbon dioxide, methane, and nitrous oxide into the atmosphere, are examples of such challenges. In turn, these problems originate in human actions that include the use of fossil fuels; land use changes; the release into the atmosphere of organic substances that are used as cooling and solvent agents, aerosols or insecticides; economic activities such as agriculture and livestock; forest degradation and deforestation; illegal hunting and plant and animal extraction; and the introduction of alien species to certain ecosystems (Anand, 2013).

Other issues worth mentioning are wastewater discharge; solid waste generation; aquifer depletion; surface and groundwater pollution; inadequate management of solid waste in municipalities, such as its disposal in open-pit landfills; soil degradation, caused by deforestation, overgrazing, intensive agricultural and mining practices that result in erosion; and soils contaminated due to livestock and agricultural activities that entail the use of fertilizers and pesticides, while generating organic waste (UNEP, 2016).

Environmental management is the set of actions accepted by the society, or by part of it, aimed at preventing, mitigating, restoring and/or solving environmental problems. Given the anthropogenic character of its challenges, this field comprises different types of instruments such as environmental regulations and incentives for the development of environmentally- friendly production activities. Its planning instruments include environmental impact assessments, management plans, as well as environmental management, education, research, and technical support systems (Rodríguez-Becerra and Espinoza, 2002).

Microbiology has become particularly relevant when dealing with environmental damage caused by pollution. Most environmental management actions that have as an objective to solve pollution problems rely on technologies based on chemical and physical methods which are often expensive and can simultaneously generate contaminating residues. Conversely, alternatives based on microorganisms utilization tend to be friendlier with the environment and low-cost (Satyanarayana et al., 2012).

For those in charge of environmental management in their organizations, a document describing the diverse possible uses of microorganisms in environmental management actions could represent a valuable decision-making tool regarding the application or development of alternative solutions and research routes. However, environmental management manuals usually focus on its instruments, rather than on the types of uses of microorganisms. For their part, microbiology books tend to focus on the types of microorganisms and their processes, neglecting their alternative uses and the economic sectors which could benefit from them.

There are no reports of studies synthetizing the diversity of uses of microorganism in environmental management. The publications related to the use of microorganisms within environmental management by Satyanarayana et al. (2012), Kuhad (2012) and Mosttafiz et al. (2012) present the point of view of the authors and do not necessarily reflect the state of art of the knowledge area. As their conclusions are not the result of an extensive review of studies that relate microbiology and environmental management, these works emphasize on the alternatives the authors know and do not provide information about the diverse options offered by research in microbiology. Moreover, the works mentioned do not provide a profile of the economic sectors which may support and benefit from the use of microorganisms for environmental management actions.

The lack of a systematic approach to the elaboration of such works, together with the economic sectors involved not being mentioned, affect both the technological transfer and social appropriation of knowledge that research should generate. In this sense, the elaboration of a profile of the use of microorganisms within environmental management, the environmental issues tackled, and the economic sectors involved, requires a systematic review to be carried out. This method is appropriate since 1) it demands a strict protocol for the studies of the same type to be identified among research works on microbiology related to environmental management;

2) it allows to gather, evaluate and synthesize several studies, which specifically in the present case, would enable the construction of a global profile of environmental issues, economic sectors and uses of microorganism; 3) it allows to identify research trends; and 4) the protocol applied ensures completeness and reproducibility (Cardona-Arias et al., 2016). Therefore, the aim of this study was to describe the use given to microorganisms within environmental management, as well as environmental issues and economic sectors.

Materials and methods

A systematic review of scientific literature. Search and study selection protocol in accordance with PRISMA (*Preferred Reporting Items for Systematic Reviews and Meta-Analyses*) guidelines (Moher et al., 2010).

Search and identification of studies

Selection of search terms and databases

A preliminary search was conducted in the *Scopus* database in order to identify the search terms. The search strategy Microbiology AND "Environmental management" was entered in the title, abstract and keywords fields. After using the *"Keyword"* filter, two groups of terms were obtained from the list of keywords registered in the database. One group related to microorganisms - *microbiology, microorganism, microbial, bacteria, bacterium, fungi, microalgae, fungus, alga,* and *biofilm* –; and another with the terms related to environmental management - *environmental management, environmental protection, pollution control, environmental control, environmental impact assessment, waste management,* and *environmental planning*.

Search for articles was conducted in *ScienceDirect, Scielo,* and *Springer* databases, given their multidisciplinary character, the availability of the title and abstract fields, and the possibility to perform combined searches. These last two features guaranteed search reproducibility. To make the search more exhaustive, *Google Scholar* was also considered.

Search strategies

Seven searching strategies were used to get the information. These strategies were obtained by combining the set of terms related to microorganisms with each of the terms related to environmental management: (Microbiology OR microorganism OR microbial OR bacteria OR bacterium OR fungi OR microalgae OR fungus OR alga OR biofilm) AND ("Environmental management" OR "Environmental protection" OR "Pollution control" OR "Environmental control" OR "Environmental impact assessment" OR "Waste management" OR "Environmental planning") (Table 1).

Table 1. Search strategy in each database

Database	Search strategy examples
Science Direct	Both sets of terms in title/abstract/keywords. • Syntax: TITLE-ABSTR-KEY (Microbiology OR microorganism OR microbial OR bacteria OR bacterium OR fungi OR microalgae OR fungus OR alga OR biofilm) and TITLE-ABSTR-KEY ("environmental management")
Scielo	Both sets of terms, in abstract. • Syntax: (ab:(Microbiology OR microorganism OR microbial OR bacteria OR bacterium OR fungi OR microalgae OR fungus OR alga OR biofilm)) AND (ab:("environmental management"))
Springer	Terms related to microorganisms were entered in the field "*With at least one of the words"*, and the terms related to environmental management, in the field "*Where the title contains".* • Syntax: (Microbiology OR microorganism OR microbial OR bacteria OR bacterium OR fungi OR microalgae OR fungus OR alga OR biofilm)
Google Scholar	Terms related to microorganisms were entered in the field "*Con al menos una de las siguientes palabras"*, and the terms related to environmental management, in the field "*Con la frase exacta".* • Syntax: Microbiology OR microorganism OR microbial OR bacteria OR bacteria OR fungi OR microalgae OR fungus OR alga OR biofilm "environmental management"

Sources: this study.

Screening

Studies were screened using two inclusion criteria: 1) only articles published between 2012 and 2017 were considered, due to that the most recent background research was published in 2012; and 2) original research articles. Therefore, it was verified that the articles included were not reviews and were written in an introduction-methods-results structure. After applying the inclusion criteria and obtaining the total of articles for each database, duplicates were eliminated in Excel.

Eligibility

The following exclusion criteria were applied to the resulting articles: articles that were not related to environmental management and microbiology. Considering such criterion, it was verified if the study reported the use of a microorganism and if it had a purpose based on environmental management.

Inclusion

The resulting studies after applying the exclusion criteria were included in the review.

Data collection

A data collection guide was designed to extract the information from the articles. A pilot test was accomplished with 30 articles (≈10% of the total articles), to adjust the guide and for criteria unification among the reviewers. Resources-ecosystems, environmental issues, use of microorganisms, and economic sectors were classified by following an inductive categorization that eased the establishing of several response options which were later coded. Such codes were also included in the data collection guide.

Data was recorded in an Excel database after being collected using the variables: author, year, institution, country, name of the journal, natural resource or ecosystem subject to damage or protection, environmental issue, given use to the microorganism in the research, and economic sector or activity in which the use of the microorganism has applicability. The Abstract, Introduction, Materials and methods, and Results sections of each article were reviewed.

Data analysis

Data were analyzed using the IBM SPSS Statistics 2 Software. Absolute and relative frequencies were employed to describe the variables.

Evaluation of reproducibility

A guide for gathering data and a protocol for the identification, screening, election, and inclusion of the articles were designed to avoid bias during the data collection. Such process was carried out by two reviewers independently to ensure the reproducibility of this review. The databases designed by each reviewer were compared and when discrepancies could not be solved by consensus, the participation of a third party was necessary.

Results and discussion

In general, 240 studies, published over the five continents, were found during this review. These led to the identification of ten environmental issues linked to six natural resources (or ecosystems depending on the case), and three types of microorganisms use, applied in eight economic sectors.

Selection algorithm

A total of 435,888 publications were initially obtained (Figure 1) after following the article search and identification protocol. The number of resulting publications after applying the inclusion criteria was 373. Seven duplicates were identified, leaving a total of 366 articles to be reviewed entirely. Of these publications, 126 were excluded because they did not address issues related to environmental management and microorganisms. Finally, a total of 240 articles were included in the review.

General characteristics of the studies

No clear trend emerged from the evaluation of the author, institution, and journal variables in the 240 studies. The diversity of authors, institutions, and journals did not allow the identification of any high frequency, which may indicate that the field of research in microbiology related with environmental management is not dominated by any institution, journal, or author. However, with respect to

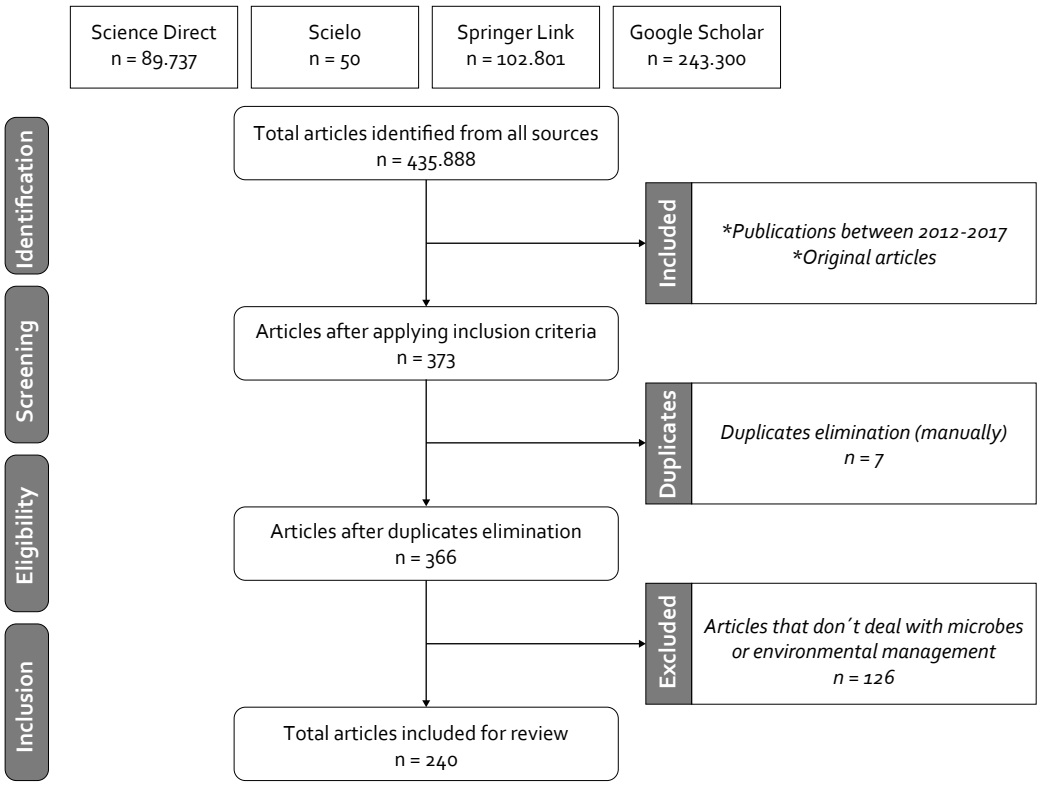

Figure 1. Article selection algorithm. Sources: this study

geographic distribution and number of publications over time, some trends were observable.

Geographic distribution and number of publications over time

The number of publications increased over time (Table 2). Such trend has also emerged in works by other authors, who have found that the publication of studies related to sustainability and sustainable development only has increased in recent years (Kajikawa et al., 2014; Olawumi and Chan, 2018).

Table 2. Publication year of the articles included in the review

Publication year	Frequency	Percentage (%)
2012	30	12.50
2013	31	12.92
2014	37	15.42
2015	38	15.83
2016	52	21.67
2017	52	21.67
Total	240	100.00

Sources: this study.

Regarding geographical distribution, the studies were found all over the world, although the lowest frequency was observed in Africa (Figure 2). The highest number of publications was observed in four countries worth highlighting: The United States with 18.1%, India 13%, China 8.4%, and Spain 7.6%. Such results are consistent with those reported by Kajikawa et al. (2014), who found that India, China, and certain nations from Western Europe stand out. Olawumi and Chan (2018) identified the United States and China as the countries with the greatest contribution to the field of research in sustainability and sustainable development. In turn, the report on sustainability science presented by Elsevier, together with SciDev.Net, states that the United States and China are among the countries with the greatest production of research in sustainability science, with a 31.6% and 9.3% of the total of publications between 2009 and 2013, respectively. Spain is also worth mentioning, as it is ranked ninth among the countries that contribute the most to research in sustainability in the world (Elsevier, 2013).

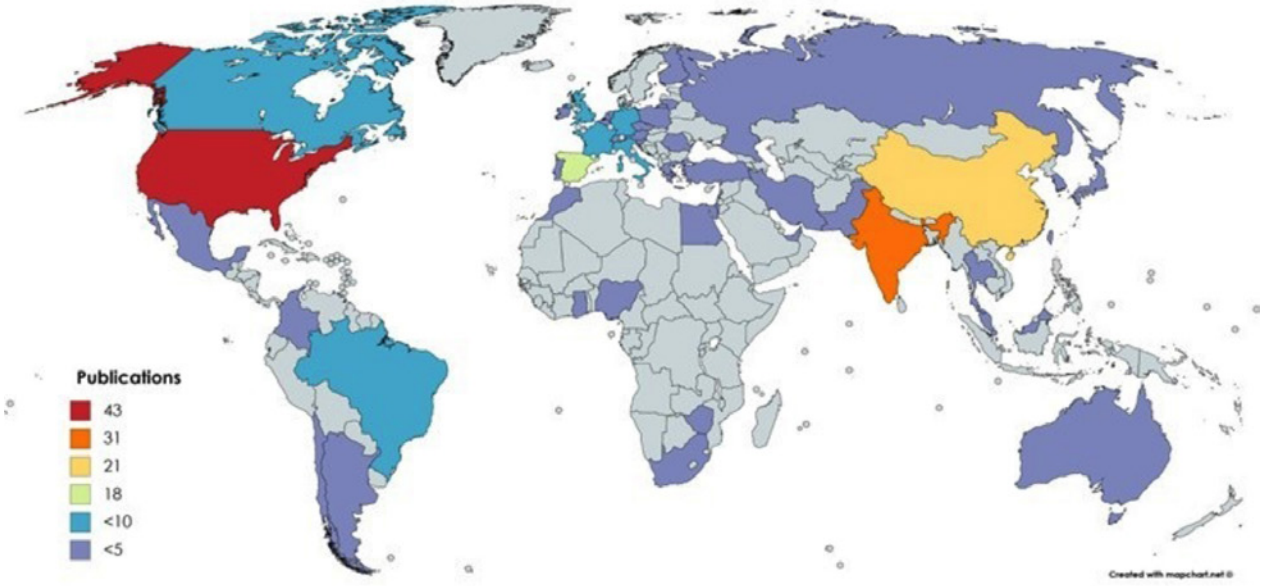

Figure 2. Geographical distribution of the studies included in the review. Sources: this study

Certain characteristic aspects of these countries could explain such results. Firstly, a thorough environmental legislation. Countries such as the United States and India have high-quality environmental regulations, based on three fundamental pillars: justice, transparency, and participation, where the latter is linked to the promotion of research in environmental management (World Resources Institute, 2015). Secondly, the level of environmental degradation. A study based on seven indicators of environmental degradation locates the United States, China, and India in a ranking of the most affected countries by the environmental impact of anthropogenic origin (Bradshaw et al., 2010). These countries are major natural resources consumers, have an elevated GDP and a high population density (Bradshaw et al., 2010; WorldoMeter, 2018).

Characterization of environmental issues, resources or ecosystems involved, use of microorganisms and economic sectors

Ecosystems, natural resources, and environmental issues

This study reviewed the ecosystems or natural resources that, according to the publications, have been damaged and need to be protected (Table 3). Almost 40% of the articles are related to water and a high number of studies, 19.1% of the total, does not describe or specify any resource or ecosystem.

The number of studies about food, water, air, and energy tends to increase over time (Figure 3). However, it should be considered that no studies related to food were found to have been published in 2015, and neither related to air in 2017. The studies are mainly related to ten environmental issues (Table 4): fecal or enteric pathogen contamination (15%), solid waste pollution (14.6%), industrial and agro-industrial wastewater discharges (11.7%), microbiological infection or contamination (8.3%), energy depletion (7.5%), and soil loss or erosion (5.8%). The 17.5% of the studies did not mention the environmental problem that motivated the research. Such data seems to reveal how intricately linked natural resources and/or ecosystems are, the environmental challenges that affect them and reduce their availability, and the research trends in microbiology related to said resources.

The results reveal an increasing trend of studies in water, air, energy, and food, which may be related to the growing challenges that the loss and contamination of these resources have. Both water quality and quantity are continuously affected by demographic growth and unsustainable and irresponsible economic practices, worsened by climatic change

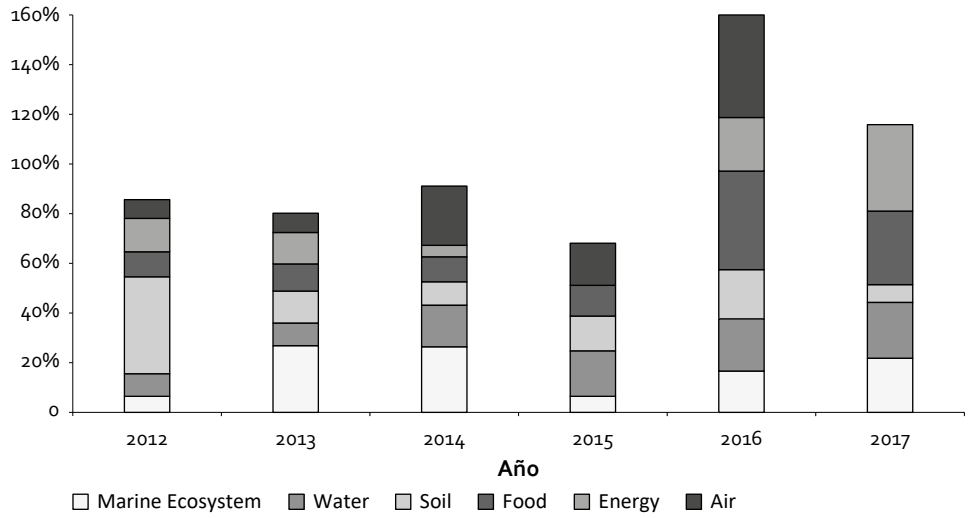

Figure 3. Behavior of the publications over time in relation with resources or ecosystems involved [Each resource is equivalent to 100%]. Sources: this study

Table 4. Environmental issues mentioned in the articles

Environmental issue	Frequency	Percentage (%)
Fecal or enteric pathogen contamination • issues related to water or food contaminated with pathogens	36	15.00
Solid waste pollution • mainly agricultural, such as manure, hulls, or feathers; plastic waste	35	14.58
Industrial and agro-industrial discharges • dyes, food, herbicides, and oil industry	28	11.67
Microbiological infection or contamination • in surfaces at intra-hospital environments, vegetable crops and vineyards	20	8.33
Energy depletion • energy overdemand and fossil fuels scarcity	18	7.50
Soil loss or erosion • pollution by heavy metals, petroleum by-products, pesticides; organic matter loss due to anthropogenic activities and drought related to fire	14	5.83
Eutrophication	13	5.42
Air pollution by volatile organic compounds • volatile organic compounds, greenhouse gases, and odor-causing gases	11	4.58
Domestic wastewater discharges	7	2.92
Leachate effluents • from landfill sites	7	2.92
Not described/not specified	42	17.50
Others	9	3.75
Total	240	100.00

Sources: this study

(USAID, 2017). Besides, petroleum consumption — therefore, the amount of its emissions — is expected to triple over the next 15 years driven mainly by emerging economies such as China, India, and Brazil (International Energy Agency, 2013). Energy production usually requires water, and in turn, energy is necessary to guarantee water availability for human use and consumption (Rodríguez et al, 2012). In the same way, food production depends directly on water and energy availability (Rodríguez

et al., 2012). Just as petroleum consumption, the demand for such resources is expected to increase given worldwide human population growth (UNEP, 2016).

There were no studies related to issues such as forest overexploitation, intensive mining or fishing or biodiversity loss. This may be due to the accurate role that microbiology plays in consumption and overexploitation issues since microorganisms are frequently employed in solving their effects than the problem itself. Regarding biodiversity loss, studies in microbiology about the issue may be more oriented towards ecology than to environmental management, hence their absence in this review. If so, this may indicate that research in microbial diversity with sustainable development is quite scarce.

Use of microorganisms reported in the studies

Three types of use of microorganisms are found in this review. In the first type, the microorganism is employed as a resource quality indicator or as part of monitoring processes; in the second type, it is used for biodegrading pollutants or reducing their toxicity; and, in the third type, it is employed to make waste useful and generate added-value products. A special group consists of those studies in which the microorganism does not have a specific purpose, but it makes part of the environmental issue under study (Table 5).

According to this review, microorganisms were most frequently used for water, soil, air, or food quality monitoring (43.7%), followed by waste utilization to generate products (21.7%), and pollutant biodegradation and toxicity reduction (21.2%). A lower proportion of studies reported the analysis of microorganisms as part of an environmental issue, instead of giving them any specific use.

These types represent different levels of complexity within the uses given to microorganisms. The lowest level of complexity contains studies which conceive the microorganism as part of an environmental issue. It requires the researcher to identify the former. The next level includes the utilization of microorganisms as indicators of natural resources quality, or to evaluate method efficiency (monitoring). This demands the researcher to identify the relation between the microorganism and certain parameters of interest. Finally, the most complex uses are contaminant biodegradation and waste utilization. These are considered the most complex because they may require the implementation of processes and/or technology to ensure optimal conditions for microorganisms to be degraded; they may even require microorganisms to be transformed genetically to enhance their metabolic potential and improve their efficiency.

It was observed that the most complex uses have continuously increased (Figure 4), while the use of microorganisms as resource indicators or to evaluate methods has been kept at the same level over time. This may point at microbiology developing towards pollutant biodegradation and waste utilization, which demand more knowledge about

Table 5. Uses of microorganisms in the studies

Use of the microorganism	Frequency	Percentage (%)
Contaminant / Part of the environmental issue • affecting air and surfaces	26	10.83
Indicator / Monitoring • used to evaluate water, soil, air, and food quality	105	43.76
Pollutant biodegradation or toxicity reduction • used to reduce organic matter, N, P; denitrification and nitrification; heavy metals bioremediation, petroleum by-products, dyes and emerging pollutants in aquatic ecosystems, wastewaters, and soils	53	22.08
Waste utilization / By-products generation • used to produce biofuels, compost, and hydrolytic enzymes	50	20.83
Not described / not specified	6	2.5
Total	240	100.00

Sources: this study.

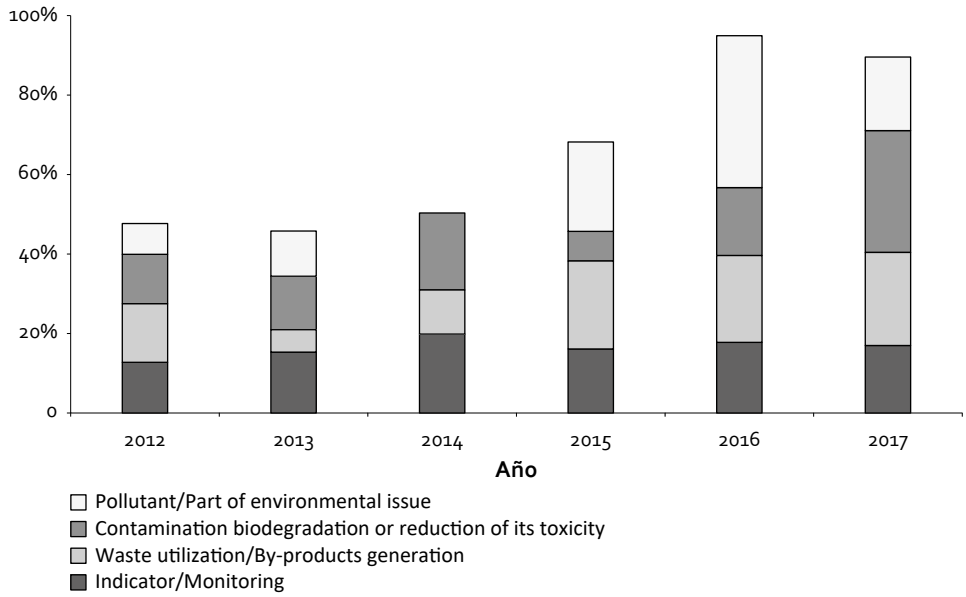

Figure 4. Behavior of publications over time in relation to the use given to microorganisms in the studies. Sources: this study

potential microorganisms, their metabolic pathways to degrade pollutants, optimal conditions, and technologies required to carry out decontamination processes.

These findings are consistent with descriptions made by other authors of the microorganisms applications (Satyanarayana et al., 2012; Steffan et al., 2015). Regarding their use for monitoring processes, microorganisms could be employed as a variable to gather information about air, water, or soil quality, depending on the type of impact. In addition, microorganisms can be employed as indicators of ecotoxicity in compounds released into the ecosystems since microbes are often the basis or an essential part of food webs (Steffan et al., 2015). They can also function as indicators of fertility in soil recovery processes (Satyanarayana et al., 2012).

Considering pollutant biodegradation and reduction, microorganisms have been employed in contexts as diverse as industrial effluents treatment, water disinfection, eutrophication reduction based on microbial denitrification, bioremediation of soils polluted by heavy metals, radionuclides and organic compounds as hydrocarbons derived from petroleum and pesticides (Satyanarayana et al., 2012). In respect of solid waste utilization, microorganisms have been employed to produce rich compost [in microorganisms], manage solid waste derived from agriculture, produce seafood, added-value products from waste, and biofuels (Satyanarayana et al., 2012).

Economic sector or activity

The most frequently identified sectors were agriculture, agroindustry and livestock (22.9%), followed by municipal wastewater treatment (11.7%), ecosystem surveillance and monitoring programs (10.4%) and others such as energy production, municipal solid waste management, and chemical industry sectors (Table 6). In 18.1% of the articles, the sector or economic activity was not made explicit. Regarding the agriculture, agroindustry and livestock sectors, this result is consistent with the reports on the applicability of biotechnology in agriculture for food security and sustainable food production (Mosttafiz et al., 2012).

According to the United Nations report on the environmental state of the planet, agriculture, livestock, mining, energy production, and the pharmaceutical and chemical industry sectors cause the greatest environmental impacts worldwide (UNEP, 2016). Except for mining, all of these were identified as sectors where microbiology is applicable.

The sectors with the highest potential are those where microorganisms present a variety of uses. A clear example is agriculture, where different types

Table 6. Economic sectors or activities identified in the study

Economic sector / activity	Frequency	Percentage (%)
Agriculture/agroindustry/livestock • seafood, vegetables, fruits, cereals, meat, and milk production	55	22.92
Wastewater management and treatment • United States Environmental Protection Agency (USEPA), Center of Documentation, Research and Experimentation on Accidental Water Pollution (CEDRE), International Water Association (IWA)	28	11.67
Ecosystem surveillance and monitoring programs • Ministry of Environmental Protection of China, Department of Water and Forest Affairs (DWAF), Committee for Environmental Protection (CEP) of the Antarctic Treaty Consultative Meeting (ATCM), Environmental Protection Agency (EPA)	25	10.42
Energy production • Coal-fired power plants, International Energy Agency (IEA), National Renewable Energy Laboratory (NREL)	23	9.58
Surveillance of public health/ healthcare services • Center for Disease Control and Prevention (CDC), Environmental Protection Agency of the United States (EPA), The National Epidemiological and Environmental Assessment of Recreational Water (NEEAR), Florida Department of Health: Florida Healthy Beaches Program (FHBP)	22	9.17
Municipal solid waste management • Plastic industries, hospital waste treatment plants, landfill sites, solid waste transfer, and optical sorting plants	16	6.67
Chemical industry • Distilleries, dyes, plastic, pharmaceutical, and oil industries	16	6.67
Textile and leather industry	7	2.92
Not described / not specified	43	17.92
Others • Economic activities such as mining and maritime transport	5	2.08
Total	240	100.00

Sources: this study.

of waste can be converted, by microbial action, in valuable products for other economic activities. Microorganisms can also help to increase crop productivity through beneficial interactions with plants or function as indicators of soil health. In other sectors such as energy production, microorganisms can be used as tools to generate alternative clean energies from circular economies. This represents the intersection of various economic sectors that have found diverse uses for microorganisms.

All things considered, this review managed to outline a broader profile of the economic sectors where microbiology has applicability, in contrast with its background publications (Kuhad, 2012; Mosttafiz et al., 2012; Satyanarayana et al., 2012). Perhaps these authors were focused on the sectors that generate pollution rather than on the role of microorganisms in the management of environmental issues.

Use of microorganisms according to environmental issues and economic sectors

When the use is observed according to the environmental issue, the economic sector, and the type of microorganism, three types of microorganisms can be highlighted. Except for fungi in the monitoring case, bacteria, fungi, and microalgae, at large, can be used in the three ways described in this study (Table 7).

Bacteria can use a variety of pollutants as carbon and energy sources, given the number of enzymes capable of transforming diverse organic and inorganic compounds. They have several mechanisms for absorption, transformation, immobilization, and mobilization of pollutants. They can also adapt to adverse environments, not only because of

Table 7. Main environmental issues and economic sectors found in relation to the use given to the microorganism

Use	Environmental issue	Economic sector	Microorganism
Issue or pollutant	• Microbiological infection or contamination (*n*=11) • Fecal or enteric pathogen contamination (*n*=5)	• Surveillance of public health and services (*n*=8) • Agriculture, agroindustry, and livestock (*n*=8)	*E. coli*, fungi and phytopathogenic bacteria, *Salmonella* spp., microalgae
Indicator or monitoring	• Fecal or enteric pathogen contamination (*n*=30) • Industrial and agro-industrial effluents (*n*=12) • Soil loss or erosion (*n*=9) • Eutrophication (*n*=9)	• Ecosystem surveillance and monitoring programs (*n*=25) • Agriculture, agroindustry, and livestock (*n*=16) • Surveillance of public health and services (*n*=13)	*E. coli*, total coliforms, microalgae, cyanobacteria, *Cryptosporidium* spp.
Biodegradation and toxicity reduction	• Solid waste pollution (*n*=13) • Industrial and agro-industrial landfills (*n*=12)	• Agriculture, agroindustry, and livestock (*n*=10) • Municipal wastewater management and treatment (*n*=9)	*Bacillus* spp., *Pseudomonas* spp., microalgae, fungi, denitrifying bacteria
Waste utilization	• Energy depletion (*n*=15) • Solid waste pollution (*n*=13)	• Agriculture, agroindustry, and livestock (*n*=17) • Energy production (*n*=13)	*Bacillus* spp., microalgae, filamentous fungi, yeasts

Sources: this study

their metabolic versatility but also because of their high replication rate and the presence of physical and biochemical barriers that protect themselves from toxic compounds. In addition, they can be subject to genetic modifications aimed at enhancing degradation capacities to cover a wide range of pollutants and facilitate generation of value-added products from organic waste (Karigar and Rao, 2011).

Fungi stand out for their ability to survive in a variety of complex matrix habitats (soils, fresh and marine waters) under different environmental and extreme conditions such as elevated salinity and pHs. The most relevant characteristic of these microorganisms is their large amount of intracellular and extracellular enzymes capable of transforming a wide range of pollutants, even recalcitrant toxic compounds, and of hydrolyzing polymeric substances such as cellulose, starch, proteins and lipids present in solid waste to generate added-value products (Deshmukh et al., 2016).

Microalgae can lower the high levels of CO_2 emissions that acidify water bodies. Their capacity to obtain energy by fixing nitrates and phosphates reduces the probability of water eutrophication. Besides, they can integrate their metabolism with residual chemical pollutants. The main attribute of this microbial group is that, through the transformation of solar energy into carbon compounds, they can generate a large amount of biomass and hence, alternative sources of energy such as bioethanol, biomethanol and biodiesel (Abdel-Raouf et al., 2012).

Conclusions

Based on the studies reviewed, it can be stated that microorganisms have at least three uses within environmental management: monitoring/indicator, biodegradation and toxicity reduction, and waste utilization. Over time, the use of microorganisms for biodegradation/reduction of toxicity and waste utilization have become more frequent and complex. Both uses seem to be progressively giving more depth to the role of microbiology within environmental management, which is consistent with the current position of making processes more environmentally responsible.

The profile presented in this review also shows that microorganisms have their greatest potential for application inside the agroindustry, agriculture, and livestock sectors. Highly polluting activities take place in these areas and microorganisms are already being employed in the three ways mentioned above. Finally, microbiology research related to environmental management actions tends to focus on the most contaminated resources such as water and air, and on the search for energy alternatives.

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