Hydrocarbon-degrading bacteria in Colombia: systematic review

Diana Carolina Rache-Arce · Maryuris Machacado-Salas · Doris Rosero-García

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Abstract Petroleum industry activities worldwide have caused pollution and resulted in environmental degradation. Microorganisms with the potential to reduce pollutant levels by degradation processes have been reported, and bacteria are among such organisms. The first study on bacterial degradation in Colombia was published in 1996. The study isolated bacteria belonging to the *Pseudomonas* genus from hydrocarbon-polluted sediments. Since then, different reports on degrading bacteria have been published. The objective of this systematic review is to identify and analyze all the studies on hydrocarbon-degrading bacteria performed in Colombia. To accomplish this goal, a literature search was conducted. Inclusion and exclusion criteria were applied, and 37 relevant articles were obtained. We found that 2018 was the year with the largest number of publications in Colombia, and most frequently identified bacterial genera were *Pseudomonas* and *Bacillus*. Some studies showed that the degradation of hydrocarbons is more efficient when bacterial consortia are used rather than pure cultures. This study provides information about bacteria with the potential to degrade hydrocarbons in Colombia, which in turn will be a source of information for future studies in this field.

Keywords Bacteria · Colombia · Degradation · Hydrocarbons

Introduction

Petroleum hydrocarbons are fossil fuels formed from organic matter, which are distributed in the subsoil layers and used for industrial energy production worldwide (Velásquez-Arias 2017). Currently, the presence of various kind of automobiles, the use of cleaning solvents, and some cosmetics may contain large amounts of hydrocarbons, which has caused an increase in their use (Ahmed and Fakhruddin 2018). The petroleum industry has grown in Colombia in recent years. The reserves of this fossil fuel are estimated to be about 1.5 billion barrels, which represents 26% of the country’s exports (Hernández-Rodríguez 2020). The growth of this industry has provided many benefits to the national economy by actively contributing to exports and the production of goods. The sector has further stimulated the generation of jobs and royalties for the financing of public expenditure (Hernández-Rodríguez 2020). However, unfortunately, petroleum sources also contribute to pollution and changes in land use as well as surface and groundwater utilization owing to exploitation, refining, lack of maintenance, and fuel theft (Sales...
da Silva et al. 2020). Moreover, Colombia has been affected by terrorist attacks approximately 829 times between 2007 and 2015 caused spills of thousands of barrels of hydrocarbons (Mendizabala et al. 2021). These problems may affect terrestrial and aquatic biodiversity due to landscape alteration (Sales da Silva et al. 2020).

In the abovementioned context, microorganisms with the potential to reduce pollutant levels by degradation processes have gained attention (Garzón et al. 2017; Sales da Silva et al. 2020). Bacteria are among those microorganisms that are able to convert the pollutants to less toxic molecules, and hence, allow the reclamation of large expanses of polluted areas (Hernández Ruiz et al. 2017; Rentería and Rosero 2019). Bacteria are capable of tolerating and using certain pollutants as sources of carbon and energy, contributing to the remediation of affected ecosystems (Marquez-Rocha et al. 2001). The oxygen-dependent enzymes called monooxygenases provide a means to use hydrocarbons as substrates, which allows the survival of bacteria in hydrocarbon-polluted environments (Das and Chandran 2011). Certain bacteria isolates such as Escherichia coli, Alcaligenes sp. and Thiobacter subterraneus can contribute in the degradation process by combining several metabolic pathways in a consortium to increase the extent of degradation of polycyclic aromatics hydrocarbons—PAHs (Pandey and Dubey 2012). Another important aspect is the presence of indigenous bacterial populations, which are of interest in degradation studies as they can be directly isolated from polluted sites and be characterized for a better understanding of the mechanism of biodegradation (Das and Chandran 2011).

The first study on bacterial degradation in Colombia, published in 1996, isolated bacteria belonging to the Pseudomonas genus from sediments highly polluted by PAHs (Vargas et al. 1996). Since then, several studies have been published, including reviews that list hydrocarbon-degrading bacteria (HDB) and discuss the importance of their management in polluted environments (Lozano 2005; Benavides-López et al. 2006; Trujillo-Toro and Ramírez-Quirama 2012; Garzón et al. 2017; De La Rosa Martínez and Rabelo-Florez 2020). However, thus far, there is no known review gathering data from all the research on hydrocarbon-degrading bacteria, advantages, and applications in Colombia. Since the problem of hydrocarbon pollution is of global relevance (Zhang and Chen 2017; Sales da Silva et al. 2020) and Colombia also considers it a critical issue. Therefore, in this review the objective is to identify all the studies on HDB conducted in the country so far. This paper provides an analysis about bacterial hydrocarbon degradation capability, pinpoint the areas in which degradation studies have been performed, and identify the most evaluated hydrocarbon. This information towards the better understanding in bioremediation challenges and will allow researchers interested in this field to have adequate baseline information to plan future studies.

**Materials and methods**

Investigations were selected from the Scielo, Pub-Med, Redalyc, ScienceDirect, Scopus, and Dial-net databases. Google Scholar was also used for the search of gray literature, and for peer reviewed articles. The following keywords were defined in Spanish (degradación, Colombia, hidrocarburos, bacterias), and in English (degradation, Colombia, hydrocarbon, bacteria). Different combinations of last keywords were employed to obtain a high number of publications in the exhaustive search. For the selection of publications suitable for analysis, the following inclusion criteria were established: type of study (original articles and theses), place (Colombia), degraded pollutant (petroleum, diesel, gasoline, motor oil), degrading microorganism (bacteria), publication date (between 1996 and 2021), and language (Spanish and English). During the literature search, those articles that did not meet the established criteria were excluded: articles about studies performed outside Colombia, degrading organisms other than bacteria, such as fungi, microalgae, and plants, and degraded pollutants other than hydrocarbons, such as heavy metals and pesticides.

The results of the analysis of the collected studies were recorded in a table using Microsoft® Excel 2019 according to author’s name, year of publication,
source in which the study was conducted, type of study, and identified bacterium (genus and/or species). Additionally, an analysis to determine the behavior and the interest in studying HDB between 1996 and 2021 was performed. The impact and the interest in research on this topic in Colombia were assessed and compared with some reviews performed for other regions of the world.

**Results**

The exhaustive search yielded 1288 articles, 410 of which were published in Spanish and 878 in English (Table 1).

After removal of the duplicate articles and application of the inclusion criteria, 37 articles were obtained (Fig. 1).

From the analysis of the 37 selected publications, it was observed that a high number of studies on bacterial hydrocarbon degradation were published mainly in 2018 (Fig. 2). This study was done in Colombia’s subnational territories, which comprise Bogotá as Capital District (C.D.), and 32 political-administrative entities called departments. Moreover, the country is divided into six natural regions constituted by differences in topography, weather, vegetation, types of soil and oil production. The Andean Region, covering the three branches of the Andes mountains; the Caribbean Region, covering the area adjacent to the

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**Table 1** General statistical information for the articles of hydrocarbon-degrading bacteria (until May 2021)

| Database        | Spanish | English |
|-----------------|---------|---------|
| Scielo          | 59      | 154     |
| PubMed          | 0       | 82      |
| Redalyc         | 0       | 137     |
| ScienceDirect   | 1       | 302     |
| Scopus          | 0       | 0       |
| Dialnet         | 0       | 1       |
| Google Scholar  | 350     | 202     |
| **Total number of articles** | **410** | **878** |

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**Fig. 1 PRISMA flowchart showing the selection of the research articles of hydrocarbon-degrading bacteria in Colombia**

Caribbean Sea; the Pacific Region adjacent to the Pacific Ocean; the Orinoquía Region, part of the Llanos plains mainly in the Orinoco River basin along the border with Venezuela; the Amazon Region, part of the Amazon rainforest; and finally the Insular Region, comprising islands in both the Atlantic and Pacific oceans (Fig. 3). Among the departments in which a high number of studies on HDB have been conducted are Antioquia and Cundinamarca with eight and seven publications respectively, located at Andean Region with a oil production of 319 Million barrels per day in 2020 (Minenergía 2021).
Remarkably, the Orinoquía Region had the highest oil production, but two studies have been conducted only (Fig. 3).

*Pseudomonas* sp. was the most representative genus of HDB on the papers in Colombia (Table 2). In the present study, 19 publications describing the isolation of bacteria belonging to this genus with *Pseudomonas aeruginosa* and *Pseudomonas putida* being the most frequently isolated species (Fig. 4). Furthermore, 7 publications reported bacteria belonging to the *Bacillus* genus (Table 2). Some studies did not report the bacterial genus and/or species because unidentified strains from bacterial consortia were used (Table 2). Among the analyzed studies, 16 on petroleum, 12 on diesel, 4 on gasoline, 1 on oil motor, 1 on kerosene, and 1 on tar. Three studies did not report the evaluated hydrocarbon (Table 2). In addition, an analysis of the universities, companies, and research groups that participated in the publications was performed (Table 3). The bacterial strains able to degrade hydrocarbons were isolated and identified, from soils samples mainly (Table 2).
### Table 2  Studies of hydrocarbon degrading bacteria conducted in Colombia

| Authors and year of publication | Source of the environmental samples | Hydrocarbon-degrading bacteria (HDB) isolated/identified | Methodology for hydrocarbon-degrading bacteria isolation/identification | Evaluated hydrocarbon |
|---------------------------------|------------------------------------|---------------------------------------------------------|---------------------------------------------------------------------|-----------------------|
| Vargas et al. (1996)             | Bucaramanga Santander             | Pseudomonas stutzeri, Pseudomonas aeruginosa, Pseudomonas resinovarans, Pseudomonas nitroreducens | Two selection systems called fast route and slow route                | Petroleum             |
| Suárez-Medellin and Vives (2004) | Bogotá D.C Cundinamarca            | Pseudomonas luteola, Pseudomonas putida, Micrococcus sp., Alcalines denitrificans, Pseudomonas sp., Pseudomonas aeruginosa | Direct isolation/traditional microbiology                           | Gasoline              |
| Perdomo-Rojas and Pardo-Castro (2004) | Zipaquirá Cundinamarca        | Stenotrophomonas maltophilia, Acinetobacter iwoffii, Burkholderia cepacia, Pseudomonas putida, Chomobacterium violaceum, Flavimonas oryzihabitants | Direct isolation/BBL™ Crystal™ Identification Systems               | Petroleum             |
| Vallejo et al. (2005)            | Bogotá D.C Cundinamarca           |                                          | Direct isolation/biochemical test                                   | Petroleum             |
| Authors and year of publication | Source of the environmental samples | Methodology for hydrocarbon-degrading bacteria isolation/identification | Evaluated hydrocarbon |
|---------------------------------|-----------------------------------|--------------------------------|-----------------|
| Gomez et al. (2006)              | Colombian Caribbean                | Strains were identified by 16S rRNA | Petroleum       |
| Duran-Rincon and Contreras (2006)| Pereira                            | Inoculation with Pseudomonas aeruginosa bacteria | Diesel          |
| Camargo-Millán and Acero-Pérez (2007) | Tunja                             | Inoculation with Pseudomonas aeruginosa bacteria | Petroleum       |
| Narváez-Flórez et al. (2008)     | Colombian Caribbean                | Direct isolation/ BBL crystal and API 50 CHB/E | Diesel, petroleum |
| Authors and year of publication | Source of the environmental samples | Methodology for hydrocarbon-degrading bacteria isolation/identification | Hydrocarbon-degrading bacteria (HDB) isolated/identified | Evaluated hydrocarbon |
|-------------------------------|-------------------------------------|-------------------------------------------------|-----------------------------------------------|----------------------|
| Kopytko and Ibarra-Mojica (2009) | Bucaramanga Santander | Original article Soils | Direct isolation | Serratia sp. Petroleum |
| Gómez et al. (2009) | Medellín Antioquia | Original article Soils | Direct isolation | Bacillus sp. Diesel, gasoline |
| Nisperuza-Vidal and Montiel-Aroca (2010) | San Sebastián Córdoba | Undergraduate thesis Crude oil well | Direct isolation/Api20E®, Api20NE® and the software Api-Web® | Burkholderia cepacia, Pseudomonas putida, Pseudomonas fluorescens, Pseudomonas aeruginosa |
| Vásquez et al. (2010) | Río Frio Santander | Original article Sludge | Direct isolation/Biochemical test and BBL CRYSTAL-NF | Pseudomonas spp., Acinetobacter spp., Enterobacter cloacae, Citrobacter spp., Bacillus brevis, Micrococcus spp., Nocardia spp. Diesel |
| Yanine (2010) | Complejo Ecorregional Andes del Norte (CEAN), Pereira | Master’s thesis Soils | Direct isolation/Strains were identified by 16S rRNA 49 degrading bacteria species (See reference for list) | Diesel |
| Vallejo et al. (2010) | Ecoregión cafetera Valle, Risaralda, Quindío | Original article Soils | Direct isolation/Inoculation with Acinetobacter sp. bacteria | Degrading bacteria: gram-positive No data available |
| Echeverri Jaramillo et al. (2011) | Cartagena Bolívar | Original article Biofilms, sediment, or sludge, neuston and water subsurface | Direct isolation/Biochemical test | Pseudomonas aeruginosa Petroleum |
| García et al. (2011) | Bogotá D.C Cundinamarca | Original article Contaminated soils | Direct isolation | Degrading bacteria Petroleum |
| Authors and year of publication | Source of the environmental samples | Methodology for hydrocarbon-degrading bacteria isolation/identification | Evaluated hydrocarbon | Type of study | Environmental sample | Hydrocarbon-degrading bacteria (HDB) isolated/identified |
|---------------------------------|------------------------------------|---------------------------------------------------------------|----------------------|---------------|----------------------|--------------------------------------------------|
| Arrieta-Ramírez et al. (2012)   | Medellín                           | Direct isolation/Strains were identified by 16S rRNA          | Diesel               | Original article | Soils               | Enterobacter sp., Bacillus sp., Staphylococcus aureus, Sanguibacter soli, Arthrobacter sp., Flavobacterium sp. |
| Pino et al. (2012)              | Apartadó                           | Direct isolation                                             | Diesel               | Original article | Soils               | Degrading bacteria Diesel, gasoline               |
| Quintana-Saavedra et al. (2012) | Cartagena                          | Direct isolation/Biochemical test                            | Diesel, gasoline     | Original article | Water               | Pseudomonas spp., Bacillus subtilis, Staphylococcus sp. |
| Gómez-Rivera and Kopitko (2012) | Puerto Boyacá                     | Direct isolation                                             | Petroleum            | Undergraduate thesis | Soils               | Pseudomonas spp.                                  |
| Ñuste-Cuartas et al. (2014)     | Dosquebradas                       | Direct isolation                                             | Diesel, gasoline     | Original article | Sewage water        | Degrading bacteria                                |
| Pérez-Robles et al. (2015)      | Medellín                           | No data available                                            | Diesel, gasoline     | Original article | Soils               | Degrading bacteria                                |
| Barrios-Ziolo et al. (2015)     | Medellín                           | Direct isolation/Traditional microbiology                    | Oil motor            | Original article | Soil contaminated with used motor oils            | Coccus and bacilli-gram-negatives                   |
| Authors and year of publication | Source of the environmental samples | Environmental sample | Methodology for hydrocarbon-degrading bacteria isolation/identification | Hydrocarbon (HDB) isolated/identified | Evaluated hydrocarbon |
|---------------------------------|------------------------------------|----------------------|-------------------------------------------------|----------------------------------------|----------------------|
| Mezquida et al. (2015)          | Lorica                             | Soil                 | Direct isolation/macroscopic and microscopic observations, biochemical tests, Commercial kits Api20E® and Api20NE® | Achromobacter denitrificans, Sphingomonas paucimobilis, Pseudomonas putida, Brevundimonas vesicularis, Acinetobacter baumanii, Rhizobium radiobacter, Comamonas testosteroni, Chryseobacterium indologenes | Diesel               |
| Vallejo-Quintero et al. (2016)  | Soacha                             | Soils                | Direct isolation | Not data reported | Petroluem |
| Álvarez et al. (2016)           | Medellín                           | Water                | Direct isolation/Biochemical test, VITEK® | Pseudomonas sp., Serratia sp., Bacillus sp. | Tar |
| Pardo-Díaz et al. (2017)        | Castilla la Nueva y Apiay          | Soils                | Direct isolation/Strains were identified by 16S rRNA | Pseudomonas sp., Pseudomonas putida, Achromobacter sp. | Petroleum |
| Delgado-Vallejo (2017)          | Medellín                           | Soils                | No data available | Degrading bacteria | Petroleum |
| Ondoñez-Burbano et al. (2018)   | Cali                               | Soils                | Direct isolation/BBL CRYSTAL™ | Burkholderia cepacia | Kerosene |
| Doria-Argumedo (2018)           | Rioacha                            | Soils                | Direct isolation | Pseudomonas spp., Acinetobacter spp., Bacillus spp. | Diesel |
| Authors and year of publication | Source of the environmental samples | Methodology for hydrocarbon-degrading bacteria isolation/identification | Evaluated hydrocarbon |
|-------------------------------|-------------------------------------|---------------------------------------------------------------|---------------------|
| **Martínez-Rivera (2018)**    | Medellín Antioquia Master’s thesis Soils  | Direct isolation/ Metagenomic V3-V4 region/ 16S rRNA | 21 degrading bacteria Phyla (See reference for list) Petroleum |
| **Malaver and Muñoz (2018)**  | Cajibio Cauca Undergraduate thesis Soils  | No data available | Degrading bacteria Petroleum |
| **Reyes-Reyes et al. (2018)** | Región centro-oriental Campo petrolero Original article Sludges | Direct isolation/ Strains were identified by 16S rRNA | Bacillus sp., Pseudomonas sp., Serratia sp., Raoultella sp., Enterobacter sp. Petroleum |
| **Pinto-Varón and Sánchez-Vargas (2018)** | Bogotá D.C Cundinamarca Undergraduate thesis Soils | Inoculation with two bacteria | Pseudomonas putida, Acinetobacter baumannii Diesel, gasoline |
| **Galvis-Ibarra (2019)**      | San Carlos de Guaroa Meta Undergraduate thesis Oily sludge (Oil residue) | Inoculation with consortium bacteria | Degradation bacteria Petroleum |
| **Garcés-Ordoñez and Espinoza-Díaz (2019)** | Mira river, Tumaco Nariño Original article Mangrove sediments | No data available | Degradation bacteria Not data reported |
| **Arenas-Soler (2020)**       | Bogotá, D.C Cundinamarca Undergraduate thesis Bioassays | Inoculation with bacteria | Chromobacterium violaceum, Pseudomonas aeruginosa Diesel |
Discussion

This systematic review was designed to provide the most complete, up-to-date list of studies about hydrocarbon-degrading bacteria (HDB) in Colombia, with a total of 37 investigations. Selecting the HDB is of profound significance in evaluating, developing, and designing strategies for bioremediation studies owing to their potential to adapt to polluted environments and convert the pollutants such as hydrocarbons to innocuous substances by degradation (Das and Chandran 2011). Moreover, it is important to perform studies to identify bacteria with degradation capability like an important step toward successful bioremediation (Reyes-Reyes et al. 2018). In the present review, we found that authors from different universities, companies, and research groups have conducted studies in Colombia to isolate HDB on environmental samples since 1996 (Vargas et al. 1996). For Colombia, 2003 was a year of substantial advances with regard to petroleum exploration given that reforms attracted foreign investment (Trujillo-Quintero et al. 2017). Probably, this is the reason for an increase in publications after 2003. Most of the publications were from 2018, it is likely that the above issue might have aroused the interest of different researchers to study microbial degradation and provide possible solutions for the pollution problem using bioremediation (Rentería and Rosero 2019). Moreover, the increasing available grants to investigations and doctoral formation in last year’s support the results obtained here (Minciencias 2019).

In the Andean Region, the departments of Antioquia and Cundinamarca, there are research groups in microbiology, chemical engineering, and biotechnology, among others. This observation emphasizes the fact that this region is very much interested in and at the cutting edge of studies in HDB. Concerning the research groups, the ones belonging to Universidad Nacional de Colombia, particularly in Medellín at Antioquia department, and Pontificia Universidad Javeriana in Bogotá, D.C. at Cundinamarca department reported the highest number of publications on HDB in Colombia. This establishes the need to continue the search for HDB in all the departments of the country, mainly in those located in regions with high oil production where can provide hydrocarbon residues.

The occurrence of some species belonging to the Pseudomonas and Bacillus genera and others mentioned here, constitutes valuable information for HDB present in Colombia. According to the analyzed publications, Pseudomonas and Bacillus species are the most frequently isolated in hydrocarbon degradation studies in the country. Probably, this result could be attributed to the much higher cultivability of both genera by direct isolation of contaminated samples with hydrocarbons (Gómez et al. 2006; Quintanasavedra et al. 2012; Álvares et al. 2016; Doria-Argumedo 2018). However, Pseudomonas and Bacillus are genera truly important and have been found to play vital roles in petroleum hydrocarbon degradation (Vásquez et al. 2010; Yanine 2010; Das and Chandran 2011; Xu et al. 2018). For example, P. aeruginosa has been identified as a HDB capable of degrading aromatic and polyaromatic hydrocarbons because it produces biosurfactants during its stationary growth phase, which facilitates the solubilization and therefore the degradation (Silva et al. 2018). Inoculation with P. aeruginosa bacteria had the highest rates of hydrocarbon removal, in ground contaminated samples with the Castilla’s crude, coming from 10 fields (Camargo-Millán and Acero-Pérez 2007). Pseudomonas putida is part of the soil microbiota and possesses enzymes called dioxygenases that are involved in hydrocarbon degradation (Truskewycz et al. 2019). On the other hand, species belonging to the Bacillus genus present high adaptability and can grow in extreme and hostile environments such as hydrocarbon-contaminated soil and water (de Mesa et al. 2006; Valdivia-Anistro et al. 2018). Furthermore, the Bacillus genus is another bacterium reported as petroleum hydrocarbon degrader, and could be useful in reducing the levels of these hydrocarbons (Kolsal et al. 2017; Lima et al. 2020).

Another important result is taxonomic information for some HDB is unknown (Perdomo-Rojas and Pardo-Castro 2004; Vallejo et al. 2010; Yanine 2010; García et al. 2011). Additional investigations using molecular and other tools to identify all HDB is highly desirable in these cases. Overall, the taxonomy of environmental bacteria in Colombia is relatively
The bar chart shows the number of times different bacteria were isolated from environmental samples. The bacteria are listed in alphabetical order, and the bars indicate the frequency of isolation:

- Acinetobacter baumannii (1)
- Achromobacter denitrificans (1)
- Acinetobacter iwoffii (1)
- Acinetobacter sp. (1)
- Actinobacteria sp. (1)
- Afipia sp. (1)
- Agrobacterium sp. (1)
- Alcaligenes sp. (1)
- Alcalines denitrificans (1)
- Arthrobacter sp. (1)
- Bartonella sp. (1)
- Brevibacillus agri (1)
- Burkholdelia cepacia (1)
- Chromobacterium sp. (1)
- Chromobacterium violaceum (1)
- CORYNEBACTERIUM SP. (1)
- Corynebacterium sp. (1)
- Citrobacter sp. (1)
- Chromobacterium violaceum (1)
- Chrobacterium sp. (1)
- Burkholdelia cepacia (1)
- Brevisbacillus agri (1)
- Bartonella sp. (1)
- Degradating bacteria (1)
- Bacillus subtilis (1)
- Bacillus sp. (1)
- Bacillus brevis (1)
- Bacillus aquimarinus (1)
- Arthrobacter sp. (1)
- Alcalines denitrificans (1)
- Alcaligenes sp. (1)
- Agrobacterium sp. (1)
- Arficia sp. (1)
- Actinobacteria sp. (1)
- Acinetobacter sp. (1)
- Acinetobacter iwoffii (1)
- Achromobacter denitrificans (1)
- Acinetobacter baumannii (1)

The chart indicates that some bacteria, such as Acinetobacter baumannii and Pseudomonas aeruginosa, were isolated more frequently than others.
poorly known. The taxonomic category of HDB is important for planning and interpreting future biodegradation studies (Ławniczak et al. 2020). In addition, the degradation of hydrocarbons is more effective when bacteria work together in a consortium. For example, Arrieta et al. showed the efficiency of a bacterial consortium that included the genera Arthrobacter, Bacillus, Flavobacterium, Sanguibacter, and Staphylococcus in the degradation of diesel (Arrieta-Ramírez et al. 2012). Vásquez et al. used a bacterial consortium composed of Acinetobacter, Bacillus brevis, Citrobacter, Enterobacter cloacae, Micrococcus, Nocardia, and Pseudomonas to study the degradation of oil sludge from a car wash (Vásquez et al. 2010). The hydrocarbons evaluated in the 37 selected publications; petroleum was the most studied one. In general, the authors suggest that short-chain aliphatic hydrocarbons such as those found in gasoline are more likely to volatilize and also tend to be toxic for bacteria (Suárez-Medellín and Vives 2004; Narváez-Flórez et al. 2008). This fact could explain why there are not as many studies on gasoline degradation as on petroleum.

This systematic review addresses studies specifically performed in Colombia with Columbian environmental samples. A more thorough investigation of knowledge about HDBs in different regions and their role in bioremediation of contaminated sites is useful. There are few similar studies that have systematically reviewed HDBs identified from specific regions or countries around the world. A review of remediation approaches for petroleum hydrocarbon contamination in the Arctic and Antarctic regions included bioremediation and identified bacteria isolated from these regions (Camenzuli and Freidman 2015). A recent review of PAH contamination in China, a country where rapid industrialization and urbanization have created fast economic growth, focused more on sources of PAHs in soils, but not on biodegradation (Zhang and Chen 2017). Other recent reviews examined more generally petroleum hydrocarbon biodegradation in aquifers (Logeshwaran et al. 2018) and provided an overview of enhanced hydrocarbon biodegradation strategies (Ławniczak et al. 2020). Notably, in Colombia a review article provided information regarding the most representative bacterium in biodegrading hydrocarbons Pseudomonas sp., Bacillus sp., Bacillus subtilis and Burkholderia sp. (De La Rosa Martinez and Rabelo-Florez 2020). A compilation of investigations conducted inside a specific country is important for establishing a baseline and needs for future research. This is especially pertinent in countries such as Colombia due to the presence of hydrocarbons as substantial contaminants in different ecosystems throughout the country, and where much research is still needed. We considering that it is also important that similar systematic reviews be conducted by researchers in the different countries to know the HDB and the studies that may be required to control hydrocarbons contamination.

**Conclusions**

A literature search yielded 1288 articles on HDB. After applying the inclusion criteria, 37 published studies were identified in Colombia between 1996 and 2020. However, among these, no doctoral theses were found. Most of the publications were from 2018, and Bacillus sp. and Pseudomonas sp. are the most studied genera in Colombia. Particularly, *P. aeruginosa* and *P. putida* are the most assessed species owing to the metabolic variation and enzymatic production that allow them to adapt to environments polluted with hydrocarbons. It was observed in several studies that hydrocarbon degradation is more efficient when bacterial consortia are used rather than pure cultures. The most studied hydrocarbon in Colombia is petroleum, while the least reported ones are oil motor, kerosene, and tar. Finally, this study is important because it provides useful information about bacteria that exhibit the potential to degrade hydrocarbons in Colombia.
Table 3 Universities, companies, and research groups that have published on Hydrocarbon Degrading Bacteria (HDB) in Colombia

| Universities and companies | Research groups or laboratories | # Authors and year of publication |
|----------------------------|---------------------------------|----------------------------------|
| Universidad Nacional de Colombia | Biorremediación y Desarrollo Tecnológico | 2 Delgado-Vallejo (2017); Martínez-Rivera (2018) |
|                            | Grupo de investigación en Ciencias de los Alimentos | 1 Arrieta-Ramírez et al. (2012) |
|                            | PARH-Pos grado de Aprovechamiento de Recursos Hidráulicos | 1 Pérez-Robles et al. (2015) |
|                            | Laboratorios de Química de Suelos, Análisis Instrumental, Microbiología Molecular y Microbiología Industrial / Laboratorio de Hidráulica/Laboratorio de Microbiología Ambiental y Aplicada | 3 Gómez et al. (2009); Barrios-Ziolo et al. (2015); Pardo-Díaz et al. (2017) |
|                            | CIEBREG-Centro de Investigaciones y Estudios en Biodiversidad y Recursos Genéticos | 1 Yanine (2010) |
| Universidad Pedagógica y Tecnológica de Colombia | GIGA-Grupo de Investigación en Geomática y Ambiente | 1 Camargo-Millán and Acero-Pérez (2007) |
| Universidad de La Guajira | Grupo de Investigación Territorios Semiáridos del Caribe | 1 Doria-Arguedo (2018) |
| Universidad de los Andes | CIMIC-Centro de Investigaciones Microbiológicas | 2 Suárez-Medellin and Vives (2004); Gomez et al. (2006) |
| Universidad de San Buenaventura | GIMA-Grupo de Microbiología y Ambiente | 1 Echeverri Jaramillo et al. (2011) |
|                            | CIOH-Centro de Investigaciones Oceanográficas e Hidrográficas del Caribe | 1 Quintana-Saavedra et al. (2012) |
| Universidad de Antioquia | GDCON-Diagnostic and Pollution Control Group | 1 Pino et al. (2012) |
| Universidad de La Salle | Laboratorios de Microbiología de la Universidad de La Salle | 2 Perdomo-Rojas and Pardo-Castro (2004); Arenas-Soler (2020) |
| Universidad Tecnológica de Pereira | Agua y Saneamiento | 1 Ñuste-Cuartas et al. (2014) |
|                            | Laboratorio de Oleoquímica de la escuela de Química | 2 Duran-Rincon and Contreras (2006) |
| Pontificia Universidad Javeriana | USBA-Unidad de Saneamiento y Biotecnología Ambiental | 5 Vallejo et al. (2005); García et al. (2011); Vallejo-Quintero et al. (2016); Pardo-Díaz et al. (2017); Galvis-Ibarra (2019) |
| Universidad Pontificia Bolivariana | A.T.P Ingeniería S.A.S | 1 Galvis-Ibarra (2019) |
|                            | Centro de Investigación en Biotecnología, Biotécnica y Ambiente | 1 Kopytko and Ibarra-Mojica (2009) |
| Universidad de Córdoba | GRUBIODEQ-Grupo de Investigación en Biotecnología | 2 Nisperuza-Vidal and Montiel-Aroca (2010); Mezquida et al. (2015) |
| Universidad del Valle | Laboratorio de Docencia de Microbiología de la Universidad del Valle | 1 Ordoñez-Burbano et al. (2018) |
| Universidad Libre | Laboratorios de Ingeniería Ambiental de la Universidad Libre | 1 Pinto-Varón and Sánchez-Vargas (2018) |
| Universidad de Santander | Laboratorio Clínico de la Universidad de Santander (UDES) | 1 Vásquez et al. (2010) |
| Fundación Universidad de America | Not information available | 1 Arenas-Piza (2018) |
| Universidad Industrial de Santander | Corporación para la Investigación de la Corrosión | 1 Reyes-Reyes et al. (2018) |
| Universidad central de Colombia | Agua y Desarrollo Sostenible | 1 Gamba and Pedraza (2017) |
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