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Microorganisms and spatial distribution of the sinkholes of the Yucatan Peninsula, underestimated biotechnological potential?

Pablo Antonio Moreno-Pérez [1], Marivel Hernández-Téllez[2], Ninfa Ramirez-Durán[1], Marcela Gamboa-Angulo[3] & Keila Isaac-Olivé[1]

[1]Faculty of Medicine, Autonomous University of the State of Mexico, Toluca, Mexico; [2]Inter-American Institute of Technology and Water Sciences, Autonomous University of the State of Mexico, Toluca, Mexico; and [3]Biotechnology Unit, Scientific Research Center of Yucatan, A.C., Merida, Mexico

Keywords

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Correspondence
P. A. Moreno-Pérez, Faculty of Medicine, Universidad Autónoma del Estado de México, Toluca, Mexico. Email: saieto@hotmail.com

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Abstract

Objective: To detect the spatial distribution of the sinkholes of the Peninsula of Yucatan (SPY) and identify those cenotes where microorganisms have been registered. **Methods:** The geographic coordinates of the SPYs were obtained from various databases, as well as from scientific publications relating to the terminology 'sinkholes', 'karst systems' and 'cenotes'. All coordinates were transformed into the Universal Transverse Mercator reference system (UTM) with datum WGS84. An infrared composite image was created with 432 RGB bands from the Landsat 8 satellite. The points with the location of the cenotes were imported into the Software TerrSet. **Results:** Total 1026 coordinates of sinkholes were recorded in the Yucatan Peninsula. In 18 sinkholes (<2%), microorganisms have been recovered and identified in various taxonomic levels, and only 6 sinkholes (<0.6%) has their biotechnological potential been evaluated. **Conclusions:** The microorganisms that inhabit the sinkholes of the Yucatan Peninsula are a reservoir with practically unexplored biotechnological potential.

Introduction

The Yucatan Peninsula (YP), is located in the Gulf of Mexico, it is a large platform consisting mainly of limestone, constituted by several hundred metres of subhorizontal thickness (Šafanda *et al.*, 2005; Mejia-Ortiz *et al.*, 2007). The limestone soil is highly permeable due to the combination of the dissolution mechanisms of calcium carbonate and collapse of the rock, this allows the fluvial waters to filter quickly into the aquifer, thus the absence of rivers on the surface (Polanco Rodríguez *et al.*, 2017; Rosiles-González *et al.*, 2017). The high permeability and porosity of the limestone soil of the YP has formed underground water reservoirs that flow slowly in a complex system of caverns (Kambesis and Coke, 2016). These are occasionally open to the surface forming large circular pools (Rubio *et al.*, 2016), known in Mexico as 'cenotes', a word derived from the Mayan language, d'zonot. Their depth varies, reaching more than 100 m (Šafanda *et al.*, 2005), and they are geographically distributed in almost all of the YP. The cenotes are classified in the lotics, which have a continuous water flow with transparent waters due to the low availability of nitrogen and phosphorus sources, limiting photosynthesis; lentics, which have less water exchange with the aquifer, are rich in nutrients and phytoplankton; they have four characteristic shapes: (A) pitchers, the connection with the surface is narrower than the diameter of the body of water, (B) cylindrical, vertical walls and the opening equals the diameter of the body of water, (C) watery, water deposits stagnant surface, (D) caves, which have a horizontal entrance and dry section (Schmitter-Soto *et al.*, 2002; Mejia-Ortiz *et al.*, 2007). There is a particularly remarkable pattern of semicircular distribution, 165 km in diameter, formed by a depression of 3–5 m deep and almost 5000 m wide; this characteristic is associated with the basin of the Chicxulub crater formed by the impact of a meteorite, Mexico (Hildebrand *et al.*, 1995; Jet Propulsion Laboratory, 2003). The underground aquifer of the YP and its associated sinkholes which emerge to the surface, is one of the most extensive on the planet, on which diverse ecosystems depend (Bauer-Gottwein *et al.*, 2011). The geomorphological characteristics of the sinkholes of the Yucatan Peninsula (SYP) and their underground connection to the cave systems condition the presence of particularly fragile ecosystems which provide habitat for numerous species (MacSwiney *et al.*, 2007), some of which are endemic. Though the SYP are very abundant, very little knowledge of the microorganisms that inhabit it and of its biotechnological potential has been generated. The objective of this research was to detect the spatial distribution of the SYP, and identify those cenotes where microorganic taxa have been recovered and registered, as well as those that have been evaluated with biotechnological potential.

Methods

The study area was the Yucatan peninsula, comprising the states of Campeche, Yucatan and Quintana Roo, located in the Gulf of Mexico and the Caribbean Sea with an approximate area of 125 000 km^2. To determine the location of the SYPs, the geographic coordinates of the database of the (Quintana Roo Speleological Survey [QRSS], 2018; Secretariat of Human Development and the Environment [SEDUMA], 2018), and scientific publications related to the terminology 'cenotes', 'karst systems' and 'sinkholes' of the Yucatan Peninsula were consulted. All the coordinates were transformed to the Universal Transverse Mercator Reference System (UTM) with datum WGS84, a colour image was created in Infrared with bands 432 RGB of the Landsat 8 satellite, subsequently the points with the location of the cenotes were imported Software TerrSet Geospatial Monitoring and Modeling (Ronald, 2016), version 18.3.

Results

A total of 1026 coordinates of sinkholes were recorded in the states of Campeche, Yucatan and Quintana Roo, located in the Yucatan Peninsula, Mexico, of which 782 coordinates were recovered from SEDUMA, 205 from scientific publications and 39 from the QRSS (Fig. 1). Of the total number of sinkholes registered, in only 18 SYPs (Fig. 2) have microorganisms been recovered and identified at various taxonomic levels and only in 6 sinkholes of the total recorded (<0.6%) have microorganisms been recovered in order to evaluate them biotechnologically.

In total, in the last 10 years, 104 taxa of microorganisms such as fungi, bacteria, cyanobacteria, microalgae, diatoms, as well as various taxonomic groups have been recovered and identified, of which 26 microorganisms have demonstrated a promising biotechnological potential (Table 1).

Discussion

According to the SEDUMA in the State of Yucatan, alone 2241 sinkholes have been identified, of which only 782 coordinates have been registered. In the State of Quintana Roo, only 39 sinkholes were georeferenced, though the location of more than 700 sinkholes has been recorded within more than a hundred cave systems, common in the state, such as the systems: Sac Actun, Dos Ojos, K'Oox Baal, Ox Bel Ha, Xunaan Ha, Ponderosa and Murena-Aak Kimin, among others (Quintana Roo Speleological Survey, 2018). In the State of Campeche, only one register was found, despite the numerous reports of their presence in the state (Villalobos-Zapata *et al.*, 2010; Vidal *et al.*, 2015). The estimate of close to 10,000 SYP (Lara-Lara *et al.*, 2008), may be based on the lack of knowledge of their

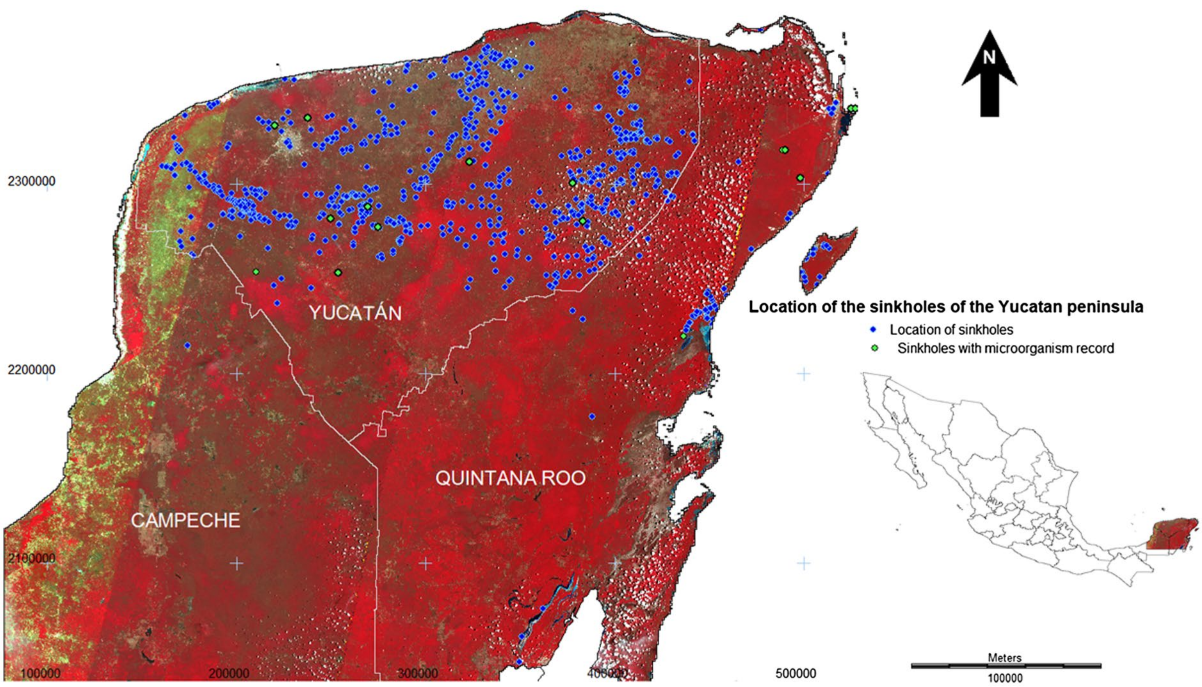

Fig. 1. Distribution of the SYP according to the coordinates of the UTM

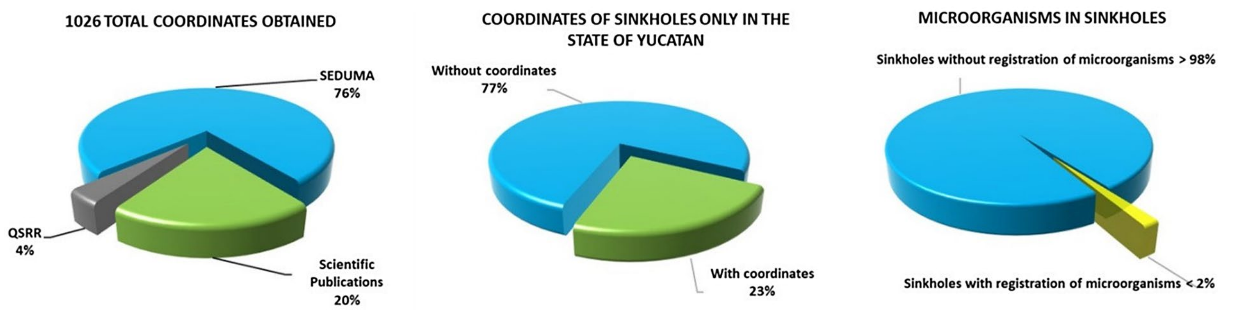

Fig. 2. Generalities of the sinkhole coordinates of the Yucatan Peninsula

location, due to the difficulty of access, because they are generally surrounded by a dense heterogeneous vegetation, a characteristic more evident in the states of Campeche and Quintana Roo (MacSwiney *et al.*, 2007), consequently the assistance of a local guide is usually required for their location.

Though the biodiversity in the SYP is known, with the presence of phytoplankton, rotifers, cladocerans, copepods, macroscopic invertebrates (Iliffe, 1993), more than 45 species of crustaceans (Alvarez *et al.*, 2015) and almost 40 species of fish (Schmitter-Soto and Gamboa-Pérez, 1996), in the present decade new taxa continue to be registered. However, research carried out on microorganisms living in these environments is scarce, without taking into account the reports due to anthropogenic contamination, they are found in plankton and phytoplankton (Sánchez *et al.*, 2002; Aké-Castillo, 2014; Irola-Sansores *et al.*, 2014; Szeroczyńska and Zawisza, 2015; Villafañe *et al.*, 2015); fungal biomass (Gómez-Reyes *et al.*, 2017); tropical microscopic fungi (Gamboa-Angulo *et al.*, 2012; Moreno-Pérez *et al.*, 2014; Moreno-Pérez *et al.*, 2016); sediments from anchialine caves (Van Hengstum *et al.*, 2009); and moderately halotolerant bacteria (De La Rosa-García *et al.*, 2007). In comparison with the bacterioplankton estimations of 5.8×10^2–8.0×10^3 cells/mL in some sinkholes and their associated caves (Alcocer *et al.*, 1999), the proportion of microorganisms identified is scarce; however, they have given notoriously relevant evidence of their biotechnological potential as mentioned below.

Bioremediation agents

In some SYPs (Medina-Moreno *et al.*, 2014), polycyclic aromatic hydrocarbons (PAH) have been detected; these are compounds formed by two or more fused aromatic rings formed by carbon and hydrogen atoms and are generated when substances such as coal, oil and organic waste are partially burned, with anthropogenic activities being the main sources of contamination (*Committee on Herbal Medicinal Products,* 2016; Tongo *et al.*, 2017). According to the United States Environmental Protection Agency (2009), PAH are considered priority pollutants due to the damage they cause to human health. Research conducted by Gómez-Reyes *et al.* (2017) found microbial biomass belonging to the genus *Cladosporium*[a] which was able to degrade diesel and oil; additionally, Lizardi-Jiménez *et al.* (2015), identified the bacterial genera *Pseudomona*[a], *Diplococcus*[a] and *Enterobacter*[a] (Table 1) as promissory *ex situ* bioremediators of hydrocarbons such as benzene, phenanthrene and naphthalene. Though the predictions suggest a significant decrease in global PAH emissions, estimated at 592 Gg in 1995 (Shen *et al.*, 2013), they are still present in the environment. Considering that microorganisms are essential components of ecological systems, the use of biotechnology in remediation processes has profitable advantages and environments.

Natural pesticide producers

Currently, more than 20,000 commercial products have been registered as pesticides by the United States Environmental Agency of Protection (Prieto Garcia *et al.*, 2012). In 2012 alone, 500 thousand tons of pesticide active ingredients were used worldwide (Nava-Pérez *et al.*, 2012) and there global trade is estimated at 50 billion dollars (Jouzani *et al.*, 2017). Synthetic pesticides are persistent in the environment and biological systems, causing short-term toxic effects in directly exposed organisms (Food and Agriculture Organization of the United Nations, 1996; Pesticide Action Network Europe, 2016). Each year they cause a million cases of poisoning and almost 20,000 deaths (Martínez-Valenzuela and Gómez-Arroyo, 2007). Investigations carried out on organic extracts of microscopic fungi (Moreno-Pérez *et al*, 2014; Moreno Pérez *et al.*, 2016), showed that the extracts of *Fusarium* sp. KS-15[a], *Penicillium* sp.OSE-61[a] and *Hypocrea lixii* OSN-37[a] inhibited the growth of the phytopathogens *Xanthomonas campestris*, *Alternaria chrysanthemi* and *Mycosphaerella fijiensis* at a minimum

Table 1 Microorganisms registered in sinkholes or their associated caves in the last 10 years

Organism	Strain	Name of the sinkhole	Location	Reference
Diatom	*Achnantidium* sp.	Mumutdzonot	Tunkás, Yucatán	Irola-Sansores *et al.* (2014)
Fungi	*Acremonium pseudozeylanicum*	X´kan ho ho che	Dzibilchaltún, Yucatán	Gamboa-Angulo *et al.* (2012)
Fungi	*Acremonium kiliense*	Temozon	Temozón, Yucatán	
Fungi	*Acremonium musicola*	X´kan ho ho che	Dzibilchaltún, Yucatán	
Bacteria	*Aeromonas salmonicida* 2X71[a]	N.S	Dzibilchaltún o Temozón, Yucatán	De La Rosa-García *et al.* (2007)
Microcrustaceans	*Alona* sp.	Cristal, Actum Ha, Sian Ka'an	Tulum, Quintana Roo	Szeroczyńska and Zawisza, (2015
Fungi	*Alternaria* sp.	Temozon	Temozón, Yucatán	Gamboa-Angulo *et al.* (2012)
Cianobacteria	*Aphanocapsa delicatissima*	Las Mojarras	Quintana Roo	Villafañe *et al.* (2015)
Fungi	*Aspergillus* sp.	X´kan ho ho che	X´kanón, Yucatán	Gamboa-Angulo *et al.* (2012)
Bacteria	*Bacillus cereus* 1T41[a]	N.S	Dzibilchaltún o Temozón, Yucatán	De La Rosa-García *et al.* (2007)
Fungi	*Beltrania rhombica*	Temozon	Temozón, Yucatán	Gamboa-Angulo *et al.* (2012)
Fungi	*Beltrania* sp.	Temozon	Temozón, Yucatán	
Fungi	*Beltrania* sp.	Temozon	Temozón, Yucatán	
Fungi	*Bionectria ochroleuca*	Oxola	Homun, Yucatán	Moreno-Pérez *et al.* (2014)
Bacilariofita	*Brachysira microcephala*	Las Mojarras	Quintana Roo	Villafañe *et al.* (2015)
Bacteria	*Burkholderia cepacia* 1T31[a]	N.S	Dzibilchaltún o Temozón, Yucatán	De La Rosa-García *et al.* (2007)
Bacteria	*Burkholderia gladioli* 1X02[a]	N.S	Dzibilchaltún o Temozón, Yucatán	
Bacteria	*Burkholderia* sp 1X41[a]	N.S	Dzibilchaltún o Temozón, Yucatán	
Microcrustaceans	*Camptocercus* sp.	Cristal, Actum Ha, Sian Ka'an	Tulum, Quintana Roo	Szeroczyńska and Zawisza, (2015)
Cianobacteria	*Chroococcus minor*	Leona Vicario	Quintana Roo	Villafañe *et al.* (2015)
Fungi	*Cladosporium cladosporioides*	Temozon	Temozón, Yucatán	Gamboa-Angulo *et al.* (2012)
Fungi	*Cladosporium cladosporioides*	X´kan ho ho che	X´kanón, Yucatán	
Fungi	*Cladosporium* sp.	X´kan ho ho che	X´kanón, Yucatán	
Fungi	*Cladosporium* sp.	X´kan ho ho che	X´kanón, Yucatán	
Fungi	*Cladosporium* spp.[a]	N.S	Cancun, Quintana Roo	Gómez-Reyes *et al.* (2017)
Fungi	*Clonostachys rosea*	Temozon	Temozón, Yucatán	Gamboa-Angulo *et al.* (2012)
Fungi	*Clonostachys* sp.	Oxola	Homun, Yucatán	Moreno-Pérez *et al.* (2014)
Fungi	Colletotrichum sp.	X´kan ho ho che	X´kanón, Yucatán	Gamboa-Angulo *et al.* (2012)
Protista	Criptofitas	Calcuch	Sabacché, Yucatán	Irola-Sansores *et al.* (2014)
Clorofita	*Cryptomonas curvata*	Leona Vicario	Quintana Roo	Villafañe *et al.* (2015)
Fungi	*Cylindrocarpon congoense*	X´kan ho ho che	X´kanón, Yucatán	Gamboa-Angulo *et al.* (2012)
Fungi	*Cylindrocarpon* sp. XH9B[a]	X´kan ho ho che	X´kanón, Yucatán	
Bacterium	*Diplococcus* sp.[a]	N.S	Cancun, Quintana Roo	Medina-Moreno *et al.* (2014)
Bacterium	*Diplococcus*	Xca–ha	Playa del Carmen, Quintana Roo	Medina-Moreno *et al.* (2014)
Bacterium	*Diplococcus* spp.	N.S	Cancun, Quintana Roo	Gómez-Reyes *et al.* (2017)
Diatomea	*Diploneis* sp.	Mumutdzonot	Tunkás, Yucatán	Irola-Sansores *et al.* (2014)
Fungi	*Emericella variecolor*	X´kan ho ho che	X´kanón, Yucatán	Gamboa-Angulo *et al.* (2012)
Bacilariofita	*Encyonopsis cesatii*	Leona Vicario	Quintana Roo	Villafañe *et al.* (2015)
Bacilariofita	*Encyonopsis cesatii*	Las Mojarras	Quintana Roo	
Bacterium	Enterobacter *aerogenes*[a]	N.S	Cancun, Quintana Roo	Medina-Moreno *et al.* (2014)

(Continues)

Table 1 (Continued)

Organism	Strain	Name of the sinkhole	Location	Reference
Bacterium	*Enterobacter* spp.	N.S	Cancun, Quintana Roo	Gómez-Reyes *et al.* (2017)
Cianobacteria	*Epigloeosphaera glebulenta*	Las Mojarras	Quintana Roo	Villafañe *et al.* (2015)
Bacterium	*Escherichia coli*	N.S	Cancun, Quintana Roo	Medina-Moreno *et al.* (2014)
Fungi	*Fomitopsis meliae*	Kikal	Homun, Yucatán	Moreno-Pérez *et al.* (2014)
Fungi	*Fusarium solani*	Oxola	Homun, Yucatán	
Fungi	*Fusarium solani*	Oxola	Homun, Yucatán	
Fungi	*Fusarium solani*	Kikal	Homun, Yucatán	
Fungi	*Fusarium* sp.	X´kan ho ho che	X´kanón, Yucatán	Gamboa-Angulo *et al.* (2012)
Fungi	*Fusarium* sp.	X´kan ho ho che	X´kanón, Yucatán	
Fungi	*Fusarium* sp. TA54[a]	Temozon	Temozón, Yucatán	
Fungi	*Fusarium* sp.	Temozon	Temozón, Yucatán	
Fungi	*Fusarium* sp. XH1Ga[a]	X´kan ho ho che	X´kanón, Yucatán	
Fungi	*Fusarium* sp.	X´kan ho ho che	X´kanón, Yucatán	
Fungi	*Fusarium* sp.	X´kan ho ho che	X´kanón, Yucatán	
Fungi	*Fusarium* sp.	X´kan ho ho che	X´kanón, Yucatán	
Fungi	*Fusarium* sp.	X´kan ho ho che	X´kanón, Yucatán	
Fungi	*Fusarium* sp.	Oxola	Homun, Yucatán	Moreno-Pérez *et al.* (2014)
Fungi	Fusarium *sp.* KS-15[a]	Kikal	Homun, Yucatán	
Fungi	Fusarium *sp.*	Oxola	Homun, Yucatán	
Fungi	Fusarium *sp.*	Kikal	Homun, Yucatán	
Fungi	*Gliocladium penicillioides* TH21	Temozon	Temozón, Yucatán	Gamboa-Angulo *et al.* (2012)
Fungi	*Gliocladium* sp. TH16[a]	Temozon	Temozón, Yucatán	
Fungi	*Hypocrea lixii* OSN-37[a]	Oxola	Homun, Yucatán	Moreno-Pérez *et al.* (2014)
Diatom	*Mastogloia* spp.	Mumutdzonot	Tunkás, Yucatán	IIrola-Sansores *et al.* (2014)
Fungi	*Minteriella cenotigena*	N.S	Merida, Yucatán	Heredia *et al.* (2013)
Fungi	*Monodictys* sp.	Oxola	Homun, Yucatán	Moreno-Pérez *et al.* (2014)
Clorofita	*Monoraphidium irregulare*	Las Mojarras	Quintana Roo	Villafañe *et al.* (2015)
Fungi	*Myrothecium* sp.	Temozon	Temozón, Yucatán	Gamboa-Angulo *et al.* (2012)
Microalgae	*Ochromonas* sp.	Nohmozón	Pixyah, Yucatán	Irola-Sansores *et al.* (2014)
Microcrustaceans	*Oxyurella* sp.	Cristal, Actum Ha, Sian Ka'an	Tulum, Quintana Roo	Szeroczyńska and Zawisza. (2015)
Fungi	*Papulaspora pallidula*	X´kan ho ho che	X´kanón, Yucatán	Gamboa-Angulo *et al.* (2012)
Fungi	*Penicillium citrinum*	X´kan ho ho che	X´kanón, Yucatán	
Fungi	*Penicillium* sp. OSE-61[a]	Oxola	Homun, Yucatán	Moreno-Pérez *et al.* (2014)
Fungi	*Penicillium* sp.	Kikal	Homun, Yucatán	
Fungi	*Pestalotiopsis maculans*	X´kan ho ho che	X´kanón, Yucatán	Gamboa-Angulo *et al.* (2012)
Fungi	*Pestalotiopsis mangiferae* OH-02	Oxola	Homun, Yucatán	Moreno-Pérez *et al.* (2014)
Cianobacteria	*Phormidium* sp.	Mumutdzonot	Tunkás, Yucatán	Irola-Sansores *et al.*, (2014)
Bacterium	*Photobacterium* sp.[a]	N.S	Dzibilchaltún o Temozón, Yucatán	De La Rosa-García *et al.* (2007)
Cianobacteria	*Pseudanabaena limnetica*	Las Mojarras	Quintana Roo	Villafañe *et al.* (2015)
Bacterium	*Pseudomonas* sp.[a]	N.S	Cancun, Quintana Roo	Medina-Moreno *et al.* (2014)
Bacterium	*Pseudomonas* sp.	Xca–ha	Playa del Carmen, Quintana Roo	Medina-Moreno *et al.* (2014)
Bacterium	*Pseudomonas aeruginosa* 2T16[a]	N.S	Dzibilchaltún o Temozón, Yucatán	De La Rosa-García *et al.* (2007)
Bacterium	*Pseudomonas luteola* 1T17[a]	N.S	Dzibilchaltún o Temozón, Yucatán	
Bacterium	*Pseudomonas* spp.	N.S	Cancun, Quintana Roo	Gómez-Reyes *et al.* (2017)

(Continues)

Table 1 (Continued)

Organism	Strain	Name of the sinkhole	Location	Reference
Fungi	*Pseudorobillarda sojae*	Oxola	Homun, Yucatán	Moreno-Pérez *et al.* (2014)
Fungi	*Rhizoctonia solani OSE-73*[a]	Oxola	Homun, Yucatán	
Fungi	*Scopulariopsis* sp.	Kikal	Homun, Yucatán	
Bacterium	*Serratia plymuthica* 1T23[a]	N.S	Dzibilchaltún o Temozón, Yucatán	De La Rosa-García *et al.* (2007)
Bacterium	*Shewanella putrefaciens* 2T41[a]	N.S	Dzibilchaltún o Temozón, Yucatán	
Fungi	*Stachybotrys nephrospora*	Temozon	Temozón, Yucatán	Gamboa-Angulo *et al.* (2012)
Fungi	*Stagonospora* sp.	Temozon	Temozón, Yucatán	
Bacterium	*Stenotrophomonas maltophilia* 1X25[a]	N.S	Dzibilchaltún o Temozón, Yucatán	De La Rosa-García *et al.* (2007)
Bacterium	*Stenotrophomonas* sp. 1T202[a]	N.S	Dzibilchaltún o Temozón, Yucatán	
Clorofita	*Tetrastrum komarekii*	Leona Vicario	Quintana Roo	Villafañe *et al.* (2015)
Microalgae	*Thompsodinium intermedium*	Dzityá o Chen-Ha	Dzityá, Yucatán	Aké-Castillo (2014)
Alga	*Tribonema* sp.	Mumutdzonot	Tunkás, Yucatán	Irola-Sansores *et al.* (2014)
Fungi	*Verticillium* sp. TH28[a]	Temozon	Temozón, Yucatán	Gamboa-Angulo *et al.* (2012)
Fungi	*Verticillium* sp.	Temozon	Temozón, Yucatán	
Bacterium	*Vibrio* sp.	N.S	Cancun, Quintana Roo	Lizardi-Jiménez *et al.* (2015)
Bacterium	*Vibrio* sp.	Xca–ha	Playa del Carmen, Quintana Roo	Medina-Moreno *et al.* (2014)
Fungi	*Volutella* sp.	Temozon	Temozón, Yucatán	Gamboa-Angulo *et al.* (2012)
Fungi	*Volutella* sp.	Temozon	Temozón, Yucatán	
Fungi	*Volutella* sp.	Temozon	Temozón, Yucatán	
Fungi	*Zygosporium minus*	Temozon	Temozón, Yucatán	

N.S = not specified.
[a]Organisms evaluated with notorious biotechnological potential.

inhibitory concentration (MIC) of 25, 500 and 1000 µg/mL, respectively. Additionally, they determined the antagonistic capacity of the species *H. lixii* OSN-37[a], *Rhizoctonia solani* OSE-73[a] and *Pestalotiopsis mangiferae* OH-02[a] (Table 1) against the phytopathogens *Colletrotrichum gloeosporioides*, *Corynespora cassiicola*, *Curvularia* sp. and *Fusarium* spp., inhibiting the growth of at least three of the four phytopathogens by more than 50%. The trade in natural pesticides is estimated at 3.5 billion dollars with an annual growth of 16% (Jouzani *et al.*, 2017). The increasingly demanding market regarding food safety and health regulations worldwide will continue to drive this trend.

Producers of antimicrobial compounds

According to the World Health Organization (2017), the research and development of new antibiotics to address the resistance of microorganisms to current antibiotics, which is estimated to cause 700 000 deaths per year. Research conducted by Gamboa-Angulo *et al.* (2012; 2013) evaluated the effects of extracts of microscopic fungi, against *Mycobacterium tuberculosis*, which in 2016 caused more than 10 million infected and 1.7 million deaths (World Health Organization, 2015), finding that the extracts of the species *Cylindrocarpon* sp. XH9B[a], *Fusarium* sp. TA54[a] and XH1Ga[a], *Gliocladium penicillioides* TH21[a], *Gliocladium* sp. TH16[a] and *Verticillium* sp.TH28[a], inhibited the growth of *M. tuberculosis* with an MIC of 1.56–25 µg/mL; they also evaluated them against promastigotes of *Leishmania mexicana*, which causes ulcerative lesions and disfiguring scars, finding that *Fusarium* sp. TA54[a] and *Verticillium* sp. TH28[a] (Table 1), caused a mortality in *L. mexicana* of IC50 = 14.23–100 µg/mL and IC100 = 50–100 µg/mL, respectively. In addition, they evaluated the antimicrobial activity of extracts of 96 fungal species against *Bacillus subtilis, Candida albicans* and *Staphylococcus aureus* among other pathogens, finding that 78 had activity against at least one of the evaluated targets. On the other hand, research conducted by De la Rosa-García *et al.* (2007) found moderately halotolerant bacteria of the genus *Aeromonas*[a], *Bacillus*[a], *Burkholderia*[a], *Photobacterium*[a], *Pseudomonas*[a], *Serratia*[a], *Shewanella*[a] and *Stenotrophomonas*[a] (Table 1) which presented a broad spectrum of antimicrobial action against the pathogens *B. subtilis* (ATCC-6633), *C. albicans* (ATCC-10231), *Erwinia carotovora* subp. *Carotovorum* (ATCC-138) *Pseudomonas syringae* pathovar. Pisi (ATCC-11043), *S. aureus* (ATCC-6536) and *Xanthomonas campestris* pathovar. *Carotae* (ATCC-10547).

Despite the increase in microorganisms resistant to current antibiotics, the number of antibiotics available is limited; the urgent search for new antimicrobial drugs is an alternative to this problem (Naradala *et al.*, 2016). Considering that the world market in medicines is estimated at almost 1.2 trillion dollars for the year 2016 (*Institute for Healthcare Informatics*, 2012), obtaining compounds or molecules with potential to develop drugs has an enormous biotechnological potential.

The relevance of the SYP is the distribution, location and quantity of these aquifer bodies, associated with their microorganisms with demonstrated biotechnological potential. Given the ignorance of the totality of the sinkholes that are found in YP, their associated environments, as well as the diversity of practically unknown microorganisms that inhabit them, it is necessary to manage the conservation and environmental protection of these environments. The sinkholes are a promising model of bioremediation of emerging pollutants, industrial and hydrocarbons in aquatic environments, for their immediate application in environmental contingencies. Obtaining natural compounds 'friendly to the environment' obtained from these microorganisms, as pesticides of natural origin, represent an alternative for their implementation in crops of economic interest and the production of safe food for health. Decreasing the use of synthetic chemical compounds with proven harm to human health. In addition to obtaining novel antimicrobials, as an alternative to combat pathogenic bacteria that are resistant to most commercially available drugs, mainly those belonging to the ESKAPE group: *Enterococcus faecium, Staphylococcus aureus, Klebsiella, Acinetobacter baumannii, Pseudomonas aeruginos* and *Escherichia coli*, which are the main causes of nosocomial infections or intra-hospital infections worldwide.

Conclusions

(1) The first step is to create a systematic proposal of recognition, identification, registration and conservation of microscopic species of these environments.

(2) SYP is a reservoir of practically unexplored microorganisms and the paucity of microbiological research in these environments has limited the biotechnological potential as an alternative to reduce the negative impact of many current concerns. The microorganisms that inhabit these environments are a viable alternative which, as yet has been poorly explored.

(3) The results allow concluding that there is no complete database with the georeferencing of the location of the SPYs in each State and municipality of the Yucatan Peninsula, and even less is known regarding their location in the states of Campeche and Quintana Roo.

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Conflict of interest

The authors state that they do not have any type of conflict of interests.

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References

Aké-Castillo, J.A. (2014) Thompsodinium intermedium (Dinophyceae), a freshwater planktonic species in Mexico. *Revista Mexicana de Biodiversidad*, **85**(3), 953–956. Available at: https://doi.org/10.7550/rmb.41270.

Alcocer, J., Lugol, A., Sánchez, M.R.Escobar, E., and Sánchez, M. (1999) Bacterioplankton from cenotes and anchialine caves of Quintana Roo, Yucatan Peninsula, Mexico. *Revista de Biología Tropical*, **47**(Culver 1994), 19–25.

Alvarez, F., Iliffe, T.M., Benitez, S., Brankovits, D. and Villalobos, J.L. (2015) New records of anchialine fauna from the New records of anchialine fauna from the Yucatan Peninsula. *Check List*, **11**(January). Available at: https://doi.org/10.15560/11.1.1505.

Bauer-Gottwein, P., Gondwe, B.R.N., Charvet, G., Marín, L.E., Rebolledo-Vieyra, M. and Merediz-Alonso, G. (2011) Review: The Yucatán Peninsula karst aquifer, Mexico. *Hydrogeology Journal*, **19**(3), 507–524. Available at: https://doi.org/10.1007/s10040-010-0699-5.

Committee on Herbal Medicinal Products (HMPC) (2016) *European Medicines Ageny*. Available at: http://www.ema.europa.eu/docs/en_GB/document_library/Scientific_guideline/2016/06/WC500209467.pdf.

De la Rosa-García, S.C., Muñoz-García, A.A., Barahona-Pérez, L.F. and Gamboa-Angulo, M.M. (2007) Antimicrobial properties of moderately halotolerant bacteria from cenotes of the Yucatan peninsula. *Letters in Applied Microbiology*, **45**(3), 289–294. Available at: https://doi.org/10.1111/j.1472-765X.2007.02185.x.

Food and Agriculture Organization of the United Nations (1996) *Eliminación de Grandes Cantidades de Plaguicidas en Desuso en los Países en Desarrollo*. Available at: http://www.fao.org/docrep/W1604S/W1604S00.htm [Accessed 5 May 2017].

Gamboa-Angulo, M., De la Rosa, S.D.C., Heredia-Abarca, G. and Medina-Baizabal, I.L. (2012) Antimicrobial screening of tropical microfungi isolated from sinkholes located in the Yucatan peninsula, México. *African Journal of Microbiology Research*, **6**(1), 2305–2312. Available at: https://doi.org/10.5897/AJMR11.1129.

Gamboa-Angulo, M., Molina-Salinas, G.M., Chan-Bacab, M., Peraza-Sánchez, S.R., Heredia, G., De la Rosa-García, S.C. and Reyes-Estebanez, M. (2013) Antimycobacterial and antileishmanial effects of microfungi isolated from tropical regions in México. *Parasitology Research*, **112**(2), 559–66. Available at: https://doi: 10.1007/s00436-012-3167-4.

Gómez-Reyes, R., Medina-Moreno, S.A., Jiménez-González, A. and Lizardi-Jiménez, M.A. (2017) Aislamiento y análisis cualitativo de biomasa microbiana fúngica degradadora de hidrocarburos de un cenote de quintana roo. *Revista Internacional de Contaminacion Ambiental*, **33**, 53–61. Available at: https://doi.org/10.20937/RICA.2017.33.esp01.05.

Heredia, G., Ruiz, R.F.C., Arias, R.M., Gamboa-Angulo, M. and Susana, C. (2013) *Minteriella cenotigena* anam. gen. & sp. nov. from submerged plant material in Mexico. *Mycological Progress*, **12**(2), 271–275. Available at: https://doi.org/10.1007/s11557-012-0831-0.

Hildebrand, A.R., Pilkington, M., Connors, M., Ortiz-Aleman, C. and Chavez, R.E. (1995) Size and structure of the Chicxulub crater revealed by horizontal gravity gradients and cenotes. *Nature*, **376**, 415–417. Available at: https://doi.org/10.1038/376415a0.

Iliffe, T.M. (1993) Fauna Troglobia Acuatica de la Peninsula de Yucatin. *Biodiversidad Marina y Costera de México*, 865.

IMS Institute for Healthcare Informatics (2012) *The Global Use of Medicines: Outlook Through 2016. Report by the IMS Institute for Healthcare Informatics*. Available at: http://apps.who.int/medicinedocs/en/d/Js20306en/ [Accessed 6 January 2018].

Irola-Sansores, E.D., Almazán-Becerril, A., Hernández-Terrones, L.M., Ortega-Camacho, D., Escobar-Morales, S. and Delgado-Pech, B. (2014) Limitación por fósforo de la biomasa fitoplanctónica en cenotes de la península de Yucatán. In: Botello, AV, von Osten, JR, Benítez, JA and Gold-Bouchot, G. (Eds.) *Contaminación e impacto ambiental: diagnóstico y tendencias*. UAC, UNAM-ICMYL, CINVESTAV-Unidad Mérida, pp. 41–54.

Jet Propulsion Laboratory (2003) *National Aeronautics and Space Administration (NASA), California Institute Laboratory*. Available at: https://photojournal.jpl.nasa.gov/catalog/PIA03380.

Jouzani, G.S., Valijanian, E. and Sharafi, R. (2017) Bacillus thuringiensis: a successful insecticide with new environmental features and tidings. *Applied Microbiology and Biotechnology*, **101**(7), 2691–2711. Available at: https://doi.org/10.1007/s00253-017-8175-y.

Kambesis, P.N. and Coke, J.I. (2016) The Sac Actun System, Quintana Roo, Mexico. *Boletín Geológico y Minero*, **127**(1), 177–192. Available at: http://www.igme.es/Boletin/2016/127_1/BG_127-1_Art-12.pdf.

Lara-Lara, J.R., Arreola Lizárraga, A., Calderón Aguilera, L.E., Camacho Ibar V.F., De la Lanza Espino G., Escofet Giansone A.M., *et al.* (2008) Los ecosistemas costeros, insulares y epicontinentales, en Capital natural de México, vol. I: Conocimiento actual de la biodiversidad. Edited by Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO).

Lizardi-Jiménez, M.A., Leal-Bautista, R.M., Ordaz, A. and Reyna-Velarde, R. (2015) Airlift bioreactors for hydrocarbon water pollution remediation in a tourism development pole. *Desalination and Water Treatment*, **54**(1), 44–49. Available at: https://doi.org/10.1080/19443994.2013.876670.

MacSwiney, M.C., Vilchis, P., Clarke, F.M. and Racey, P.A. (2007) The importance of cenotes in conserving bat assemblages in the Yucatan, Mexico. *Biological Conservation*, **136**(4), 499–509. Available at: https://doi.org/10.1016/j.biocon.2006.12.021.

Martínez-Valenzuela, C. and Gómez-Arroyo, S. (2007) Riesgo genotóxico por exposicion a plaguicidas en trabajadores agrícolas. *Revista Internacional de Contaminación Ambiental*, **23**(4), 185–200.

Medina-Moreno, S.A., Jiménez-González, A., Gutiérrez-Rojas, M. and Lizardi-Jiménez, M. A. (2014) Hydrocarbon pollution studies of underwater sinkholes along Quintana Roo as a function of tourism development in the Mexican Caribbean. *Revista Mexicana de Ingenieria Quimica*, **13**(2), 509–516.

Mejia-Ortiz, L.M., Yanez, G., Lopez-Mejia, M. and Zarza-Gonzalez, E. (2007) Cenotes (anchialine caves) on Cozumel Island, Quintana Roo, México. *Journal of Cave and Karst Studies*, **69**(2), 250–255.

Moreno Pérez, P., Gamboa-Angulo, M., Heredia, G., Canto Canché, B., Rodríguez García, C.M., Medina Baizabal, I.L. and Peraza Echeverría, L. (2016) Antimicrobial evaluation of extracts obtained from tropical micromycetes against phytopathogens. *Phyton-International Journal of Experimental Botany*, **85**(130), 7–14.

Moreno-Pérez, P., Gamboa-Angulo, M., Heredia, G., Canto-Canché, B., Rosado-Vallado, M., Medina-Baizabal, I.L., *et al.* (2014) Antagonistic properties of Micromycetes isolated from sinkholes of the Yucatán Península against fungal phytopathogens. *Revista Mexicana de Micología*, **40**, 27–36 Available at: https://www.researchgate.net/publication/317438288_Antagonistic_properties_of_micromycetes_isolated_from_sinkholes_of_the_Yucatan_Peninsula_against_fungal_phytopathogens.

Naradala, P., Vijayalakshmi, M., Mangamuri, U. and Kavi Kishore, P.B. (2016) Exploration of potent actinobacterium nocardiopsis halotolerans VJPR–2 isolated from mangrove habitats. *Asian Journal of Pharmaceutical and Clinical Research*, **9**(4), 113-117.

Nava-Pérez, E., García-Gutiérrez, C., Camacho-Báez, J.R. and Vázquez-Montoya, E.L. (2012) Bioplaguicidas: una opción para el control biológico de plagas. *Ra Ximhai*, **8**(3), 41–49.

Pesticide Action Network Europe (2016) *Pesticide Environmental Risk Assessment: Environment unprotected?* Available at: https://www.pan-europe.info/sites/pan-europe.info/files/20161115_Angeliki_Environment_unprotected.pdf [Accessed: 27 June 2017].

Polanco Rodríguez, Á.G., López, M.I.R., Casillas, T.A.D., León, J.A.A., Prusty, B.A.K. and Cervera, F.J.Á. (2017) Levels of persistent organic pollutants in breast milk of Maya women in Yucatan, Mexico. *Environmental Monitoring and Assessment*, **189**(2). Available at: https://doi.org/10.1007/s10661-017-5768-y.

Prieto Garcia, F., Ascencio, S.Y.C., Oyarzun, J.G., Hernandez, A.C. and Alavarado, P.V. (2012) Pesticides: classification, uses and toxicity. Measures of exposure and genotoxic risks. *Journal of Research in Environmental Science and Toxicology*, **1**(11), 2315–5698 Available at: http://www.interesjournals.org/JREST.

Quintana Roo Speleological Survey (2018) *Cuevas por longitud*. Available at: https://caves.org/project/qrss/qrlongesp.htm [Accessed 13 September 2017].

Ronald, E.J. (2016) *Software TerrSet*. Worcester, MA, USA.

Rosiles-González, G., Ávila-Torres, G., Moreno-Valenzuela, O.A., Acosta-González, G., Leal-Bautista, R.M., Grimaldo-Hernández, C.D., *et al.* (2017) Occurrence of pepper mild mottle virus (PMMoV) in groundwater from a karst aquifer system in the Yucatan Peninsula, Mexico. *Food and Environmental Virology*, **9**(4), 487–497. Available at: https://doi.org/10.1007/s12560-017-9309-1.

Rubio, F., Rolán, E., Worsaae, K., Martínez, A. and Gonzalez, B.C. (2016) Description of the first anchialine gastropod from a Yucatán cenote, Teinostoma brankovitsi n. sp. (Caenogastropoda: Tornidae), including an emended generic diagnosis. *Journal of Molluscan Studies*, **82**(1), 169–177. Available at: https://doi.org/10.1093/mollus/eyv049.

Šafanda, J., Heidinger, P., Wilhelm, H. and Čermák, V. (2005) Fluid convection observed from temperature logs in the karst formation of the Yucatán Peninsula, Mexico. *Journal of Geophysics and Engineering*, **2**(4), 326–331. Available at: https://doi.org/10.1088/1742-2132/2/4/S05.

Sánchez, Malinali, Javier Alcocer, E.E. and Lugo, L. (2002) Phytoplankton of cenotes and anchialine caves along a distance gradient from the northeastern coast of Quintana Roo, Yucatan Peninsula. *Hydrobiologia*, **467**, 79–89. Available at: https://doi.org/10.1023/A:1014936714964.

Schmitter-Soto, J.J. and Gamboa-Pérez, H.C. (1996) Composición y distribución de peces continentales en el sur de Quintana Roo, Península de Yucatán, México. *Revista de Biologia Tropical*, **44**(1), 199–212.

Schmitter-Soto, J.J., Comin, E.F.A., Escobar-Briones, J., Herrera-Silveira, J., Alcocer, E., Suárez-Morales, M., *et al.* (2002) Hydrogeochemical and biological characteristics of cenotes in the Yucatan Peninsula. *Hydrobiologia*, **467**, 215–228.

Secretariat of Human Development and the Environment (2018) *Cenotes y Grutas*. Available at: http://www.seduma.yucatan.gob.mx/cenotes-grutas/index.php [Accessed 13 December 2017].

Shen, H., Huang, Y., Wang, R., Zhu, D., Li, W., Shen, G., *et al.* (2013) Global atmospheric emissions of polycyclic aromatic hydrocarbons from 1960 to 2008 and future predictions. *Environmental Science and Technology*, **47**(12), 6415–6424. Available at: https://doi.org/10.1021/es400857z.

Szeroczyńska, K. and Zawisza, E. (2015) Cenotes – Lakes of the Yucatan Peninsula (Mexico). *Studia Quaternaria*, **32**(1), 53–57. Available at: https://doi.org/10.1515/squa-2015-0005.

Tongo, I., Ogbeide, O. and Ezemonye, L. (2017) ‘Human health risk assessment of polycyclic aromatic hydrocarbons (PAHs) in smoked fish species from markets in Southern Nigeria. *Toxicology Reports*, **4**, 55–61. Available at: https://doi.org/10.1016/j.toxrep.2016.12.006.

United States Environmental Protection Agency (2009) *Polycyclic Aromatic Hydrocarbons (PAHs) Fact Sheet*. Available at: https://www.epa.gov/sites/production/files/2014-03/documents/pahs_factsheet_cdc_2013.pdf [Accessed 13 September 2017].

Van Hengstum, P.J., Reinhardt, E.G., Beddows, P.A., Schwarcz, H.P. and Gabriel, J.J. (2009) Foraminifera and testate amoebae (thecamoebians) in an anchialine cave: Surface distributions from Aktun Ha (Carwash) cave system, Mexico. *Limnology and Oceanography*, **54**(1), 391–396. Available at: https://doi.org/10.4319/lo.2009.54.1.0391.

Vidal, L., Vallarino, A., Benítez, I. and Correa, J. (2015) Implementation of the Ramsar strategic plan in coastal wetlands of the Península de Yucatán: regulations and normativity. *Latin American Journal of Aquatic Research*, **43**(5), 873–887. Available at: https://doi.org/10.3856/vol43-issue5-fulltext-7.

Villafañe, V.E., Guendulain-García, S.D., Valadez, F., Rosiles-González, G., Helbling, E.W. and Banaszak, A.T. (2015) Antagonistic and synergistic responses to solar ultraviolet radiation and increased temperature of phytoplankton from cenotes (sink holes) of the Yucatán Peninsula, México. *Freshwater Science*, **34**(4), 1282–1292. Available at: https://doi.org/10.1086/682051.

Villalobos-Zapata, G.J., Mendoza Vega, J. (Coord.) (2010) *La Biodiversidad en Campeche: Estudio de Estado, La biodiversidad en Campeche*. Estudio de Estado. ISBN 978-607-7887-21-8.

World Health Organization (2015) *Bull World Health Organ*. Available at: https://doi.org/10.2471/BLT.15.152710.

World Health Organization (2017) *Tuberculosis nota descriptive*. Available at: http://www.who.int/mediacentre/factsheets/fs104/es/.