Topics of limnological research in Mexico

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Universidad de Colima

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Avenida Universidad 333
C.P 28040, Colima, Colima, México
Dirección General de Publicaciones
Telephone numbers: 312 316 1081 and 312 316 1000, extension: 35004
Email: publicaciones@ucol.mx
www.ucol.mx

ISBN electrónico: 978-968-9733-13-3
DOI: 10.53897/LI.2025.0032.UCOL
5E.1.1/317000/308/2024 Edición de publicación no periódica

Cover and interior photographs: Juan Franco Rodríguez

Certified Publishing Process with ISO since 2005
Double blind ruling and editing are registered in the PRED Electronic Publishing System

Registration: LI-020-24
Received: September 2024
Dictamination: November 2024
Published: December 2025

This book is dedicated to
Dr. Singaraju Sri Subrahmanya Sarma,
in gratitude for all his teachings in the world of limnology.

Index

Free Living Continental Aquatic Ciliates (Alveolata: Ciliophora) from Mexico: An Overview of their Species Richness and Distribution

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Abstract

We present the data of the ciliate species including free-swimming and sessile that have been recorded in Mexico inhabiting different types of continental water bodies. We found that 294 ciliate species were documented in 16 Mexican states through the period from 1922 to 2023. This species richness represents around 28.7 % of the more than 1,000 ciliate species recorded for Mexico and indicates that its study is still incomplete and that there exist possibilities for new records and new species descriptions.

Keywords

Protists, historical approach, biogeographic areas.

Introduction

Ciliates are a group of protists distinguished by the presence of cilia derived from kinetosomes with three fibrillar associates, two types of nuclei (nuclear dimorphism), and conjugation as a sexual process, and with more than 8,000 described species (Lynn, 2008, 2017). They are mainly heterotrophs and very common in aquatic ecosystems which have been studied around the world.

Their functional role as primary consumers has been documented, playing a key role in aquatic planktonic and benthic food webs, and the study of their diversity and ecology is essential to understanding limnological processes, providing valuable perspectives into ecosystem functioning. Ciliates participate in the microbial loop which is an important process of the trophic food web affecting carbon, nutrient, and energy flows being an important link in lake ecosystems to higher trophic levels such as copepods and fish (Pomeroy, 1974; Azam et al., 1983; Sanders et al., 1989; Sherr et al., 1991; Pomeroy et al., 2007). In sediments of freshwater ecosystems, benthic ciliate communities are usually the dominant protists (Finlay et al., 1988; Finlay & Esteban, 1998).

The community structure of ciliates is highly dynamic and responds rapidly to changes in the environment and ecosystem; for example, their abundance and biomass tend to increase along a trophic gradient from oligotrophy to eutrophy (Zingel, 2001). A progressive replacement of large cell ciliates (40-50 µm) by small cell ciliates (20-30 µm) has been observed as a trophic state increased in freshwater lakes as a response to changes in food availability (Beaver & Crisman, 1982). Aleya et al. (1992) suggested that some facultative anaerobic species such as *Loxodes striatus* may be significant contributors to denitrification in eutrophic lakes. Barouillet et al. (2022) documented that in recent times, some lowland lakes exposed to local human pressures have shown a decreasing β-diversity of ciliates, by changing assemblages of species with mixotrophs; benthic ciliates communities have also changed in response to increasing in deep water anoxia.

In Mexico, due to its geographic position where two biogeographical regions (Neotropical and Neartic) are present (Morrone, 2019), the habitats that provide suitable conditions for their presence are distributed along the entire area, even so, the knowledge of the ciliate species is still incomplete despite its ecological importance. The purpose of this review is to compile the ciliate species that have been recorded in aquatic continental ecosystems to show their distribution across the country and the historical development of its taxonomic knowledge.

Methodology

We search for the recorded binomial species from Mexico in continental aquatic environments including rivers, lakes, dams, temporal reservoirs, channels, swamps, wetlands, waterfalls, caves, fish farms, and plant reservoirs such as phytotelmae. We consulted López-Ochoterena and Roure-Cane (1970), Madrazo-Garibay and López-Ochoterena (1982), Aladro-Lubel et al. (2006), the search engine Google Scholar, and the https://tesiunam.dgb.unam.mx/, http://ri.uaemex.mx/,http://redi.uady.mx/, https://www.riudg.udg.mx/, https://repositorioinstitucional.buap.mx/, https://ri.ujat.mx/, https://cdigital.uv.mx/, https://ri-ng.uaq.mx/, http://bdigital.dgse.uaa.mx:8080/, https://www.repositoriodigital.ipn.mx/, http://tesiuami.izt.uam.mx/, https://bibliotecavirtual.dgb.umich.mx/, and https://repositorio.unicach.mx/ databases.

The species recorded in published articles, books, book chapters, and thesis, were included encompassing a period from 1922 to 2023. Each ciliate genera and species names were checked by consulting Aescht (2001), Lynn (2008), and Mayén-Estrada et al. (2020), to eliminate the synonyms and to update their taxonomy. The ciliate species were organized according to the Mexican states and localities, and the number of species was counted. We grouped the genera according to their species number. We also performed a distributional map by states and one for biogeographical areas.

Results

We obtained that, 153 genera including 294 ciliate species, have been reported for Mexico distributed along 16 states (Tables 1 and 2). Most of the genera contained only one species each, and only for the genus *Paramecium*, we found 14 species (Table 1). The total species richness obtained represents around 28.6 % of the more than 1,000 ciliate species reported for Mexico (Mayén-Estrada et al., 2020). Some examples of species are shown in Fig. 1.

Table 1. Genera of Ciliates and their Species Number Recorded in Mexican Continental Habitats.

Number of species	Genera
1	*Anigsteinia, Apoamphisiella, Apogastrostyla, Askenasia, Balantidion, Belonophrya, Bromeliophrya, Bromeliothrix, Bursaria, Bursellopsis, Calyptotricha, Carchesium, Chlamydonellopsis, Cinetochilum, Cladotricha, Clathrostoma; Climacostomum, Codonella, Coriplites, Cotterillia, Cryptochilum, Ctedoctema, Cyrtohymena, Cyrtolophosis, Dexiostoma, Dexiotricha, Didinium, Discophrya, Enchelydium, Enchelyomorpha, Enchelys, Fragmocirrus, Gastrostyla, Glaucomides, Halteria, Heliophrya, Holophrya, Holosticha, Ileonema, Isocyclidium, Lambornella, Lembadion, Limnostrombidium, Linostomella, Loxocephalus, Loxophyllum, Luxophrya, Malacophrys, Microthorax, Monochilum, Monodinium, Multifasciculatum, Mykophagophrys, Neobryophyllum, Obertrumia, Odontochlamys, Onychodromus, Ophrydium, Opisthonecta, Parabryophrya, Paracolpidium, Paracolpoda, Paradileptus, Parapodophrya, Paroxytricha, Pelagohalteria, Phascolodon, Philasterides, Plagiopyla, Platynematum, Plesiocaryon, Pleuronema, Podophrya, Propyxidium, Pseudoblepharisma, Pseudocyrtolophosis, Pseudoglaucoma, Pseudokeronopsis, Pseudomonilicaryon, Pseudourostyla, Rimaleptus, Rimostrombidium, Sathrophilus, Siroloxophyllum, Sphaerophrya, Sterkiella, Stichotricha, Stokesia, Strombidium, Systylis, Tachysoma, Telotrochidium, Thuricola, Tintinnidium, Trachelius, Trachelophyllum, Trichophrya, Trichodina, Trimyema, Trithigmostoma, Trochilioides, Urocentrum, Urosoma, Vorticellides, Zosterodasys*
2	*Acineta, Actinobolina, Anteholosticha, Brachonella, Caenomorpha, Frontonia, Metacineta, Metopus, Nassula, Pelagovorticella, Platyophrya, Protocyclidium, Pseudovorticella, Rhabdostyla, Strobilidium, Trochilia, Uronema, Zoothamnium*
3	*Amphileptus, Aspidisca, Chilodonella, Colpidium, Cothurnia, Drepanomonas, Epistylis, Spirostomum, Urotricha*

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4	*Cyclidium, Glaucoma, Gonostomum, Lacrymaria, Leptopharynx, Loxodes, Spathidium, Tetrahymena, Tokophrya*
5	*Blepharisma, Litonotus, Opercularia, Stylonychia, Uroleptus*
6	*Coleps*
7	*Colpoda, Oxytricha*
8	*Stentor*
11	*Euplotes*
12	*Vorticella*
14	*Paramecium*

Table 2. Mexican States and Continental Localities with Ciliate Records.

States/Localities	References
Aguascalientes	
Abelardo L. Rodríguez Water Dam	Tiscareño-Silva, 2008; Silva-Briano et al., 2022
Aguascalientes City, Phytotelmata of Epiphytic Bromeliads	Romero-García, 2007
Bordo El Salitre	Tiscareño-Silva, 2008
Bordo La Cotorra	Tiscareño-Silva, 2008
El Bordo	Tiscareño-Silva, 2008
El Huarache water dam	Tiscareño-Silva, 2008
El Refugio Puddle	Silva-Briano et al., 2022
El Tecuancillo Dam	Silva-Briano et al., 2022
La Carreta Water Dam	Tiscareño-Silva, 2008
La Providencia Water Dam	Tiscareño-Silva, 2008
La Tomatina Pond	Silva-Briano et al., 2022
Los Jiménez Tank	Tiscareño-Silva, 2008
Lumbreras Water Dam	Tiscareño-Silva, 2008
Malpaso Wáter Dam	Silva-Briano et al., 2022
Rincón de Romos	Flores and Martínez, 1993; Silva-Briano et al., 2022
San Pedro River	Tiscareño-Silva, 2008
San Pedro Swamp	Tiscareño-Silva, 2008

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Chiapas	
Montebello Lakes	Méndez-Sánchez, 2017; Ramírez-Ballesteros et al., 2021
Montebello Lakes National Park, Phytotelmata of Epiphytic Bromeliads	Durán-Ramírez et al., 2020; Ramírez-Ballesteros et al., 2021; Durán-Ramírez and Mayén-Estrada, 2022
Tziscao Lake	Méndez-Sánchez, 2017; Méndez-Sánchez et al., 2018b, 2022
Guerrero	
Cacalotenango Waterfall	Teyer-Santiago et al., 2021
La Joya Cave	Sigala-Regalado, 2011
Hidalgo	
Endhó Water Dam	Potekhin and Mayén-Estrada, 2020; Melekhin et al., 2022
La Mora de Actopan Spring	Sokoloff, 1936
La Noria de Tula	Sokoloff and Ancona, 1937
Requena Water Dam	Melekhin et al., 2022
Tlanchinol El Tegolome Phytotelmata of Epiphytic Bromeliads	Durán-Ramírez et al., 2020; Durán-Ramírez and Mayén-Estrada, 2022
Tula River	Sokoloff and Ancona, 1937
Tula spring	Sokoloff and Ancona, 1937
Mexico City	
Atlapulco Channel	Moreno-Barón, 1976; Moreno-Barón and López-Ochoterena, 1976
Chapultepec Lakes	Bravo-Hollis, 1922; Sokoloff, 1931; Sámano and Sokoloff, 1931; Elliot and Hayes, 1955; Pérez-Reyes and Salas-Gómez, 1961; López-Ochoterena, 1962, 1965, 1992; López-Ochoterena and Barajas de López, 1963; González-Labastida, 1995; Lugo-Vázquez et al., 1998; Potekhin and Mayén-Estrada, 2020; Melekhin et al., 2022
Consulado River	Elliot and Hayes, 1955
Cuemanco Channel	López-Ochoterena, 1999
Eastern Quarry (Cantera Oriente)	Aladro-Lubel et al., 2007, 2009; Lugo-Vázquez et al., 2017; Saadi-Gómez, 2018; Sánchez-Sánchez, 2018; Potekhin and Mayén-Estrada, 2020; Melekhin et al., 2022
Fuentes Brotantes Lake	Elliot and Hayes, 1955

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Instituto de Salubridad y Enfermedades Tropicales Pond	Pérez-Reyes and Salas-Gómez, 1961
La Magdalena River	Elliot and Hayes, 1955; Nomdedeu and López-Ochoterena, 1988; Mayén-Estrada et al., 2022
Los Dinamos Water Dam	Potekhin and Mayén-Estrada, 2020
San Luis Tlaxialtemalco	Pérez-Reyes and Salas-Gómez, 1961
Tezozómoc Lake	Cabral-Dorado, 2006; Ortíz-Haro, 2011; Sánchez-Rodríguez et al., 2011
Tláhuac Lake	Potekhin and Mayén-Estrada, 2020; Melekhin et al., 2022
Xochimilco Lake	Bravo-Hollis, 1922; Beltrán, 1929; Sokoloff, 1930a-c; Sámano and Sokoloff, 1931; Elliot and Hayes, 1955; Pérez-Reyes and Salas-Gómez, 1961; Roure-Cané, 1969; Madrazo-Garibay and López-Ochoterena, 1973a, 1985; Moreno-Barón, 1976; Moreno-Barón and López-Ochoterena, 1976; Serrano-Limón and López-Ochoterena, 1992; López-Ochoterena, 1999; Potekhin and Mayén-Estrada, 2020
Mexico State	
Atarasquillo Wetland (=Chignahuapan Lake)	Méndez-Sánchez, 2014, Méndez-Sánchez et al., 2018a
Chalco Lake	Bravo-Hollis, 1924
Dolores Water Dam	Pérez-Reyes and Salas-Gómez, 1961
El Velo de la Novia Waterfall	Flores-Flores, 2012
Guadalupe Water Dam	Pérez-Reyes and Salas-Gómez, 1961; Gallegos-Neyra et al., 2009
La Concepción San Pedro Spring	Flores-Flores, 2012
La Concha Water Dam	Pérez-Reyes and Salas-Gómez, 1961
Lerma Swamps	Madrazo-Garibay and López-Ochoterena, 1985; Gallegos-Neyra et al., 2009; Potekhin and Mayén-Estrada, 2020; Melekhin et al., 2022
Los Remedios River	Chilpa-Navarrete, 1998
Ocotal Lake	Méndez-Sánchez, 2017
San Juan Teotihuacán	Pérez-Reyes and Salas-Gómez, 1961
San Miguel Almaya	Melekhin et al., 2022
Sierra de Tepotzotlán Streams	González-Palma, 2016
Tiacaque Spring	Méndez-Sánchez, 2017
Valle de Bravo Water Dam (Miguel Alemán Water Dam)	Peštová, 2007; Gallegos-Neyra et al., 2009

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Michoacán	
Huarimio Caves	Sigala-Regalado, 2011
Los Espinos Crater Lake	Rendón-López, 2008
Pátzcuaro Lake	Ancona et al., 1940; Osorio-Tafall, 1944; López-Ochoterena and Roure-Cané, 1970
Tziranda Caves	Sigala-Regalado, 2011
Zacapu Fish Farm	Herróz-Zamorano, 1998
Morelos	
Cuernavaca Ricefields	Santiago-Fragoso, 1969
Salto de San Antón Waterfall	Madrazo-Garibay and López-Ochoterena, 1973b
Zempoala Lake	Pérez-Reyes and Salas-Gómez, 1961
Oaxaca	
Analco Lake	Méndez-Sánchez, 2017; Méndez-Sánchez et al., 2020
El Estudiante Water Dam	Méndez-Sánchez et al., 2020
Ixtlán de Juárez Phytotelmata of Epiphytic Bromeliads	Durán-Ramírez et al., 2015, 2020
La Azucena Water Dam	Méndez-Sánchez, 2017
Santa Catarina Ixtepeji Phytotelmata of Epiphytic Bromeliads	Durán-Ramírez and Mayén-Estrada, 2022
Zimatlán de Alvarez Fish Farm	Rivas-Beltrán et al., 2023
Puebla	
Alchichica Lake	Lugo-Vázquez, 1993, 2000; Lugo-Vázquez et al., 1998; Peštová, 2007; Macek et al., 2008; Peštová et al., 2008; Sánchez-Medina, 2013
Aljojuca Lake	Lugo-Vázquez, 1993
Atexcac Lake	Lugo-Vázquez, 1993; Macek et al., 1994; Lugo-Vázquez et al., 1998; Peštová, 2007
Cuetzalan Phytotelmata of Epiphytic Bromeliads	Durán-Ramírez et al., 2020, Durán-Ramírez and Mayén-Estrada, 2022
Karmidas Caves	Sigala-Regalado, 2011
La Preciosa Lake	Lugo-Vázquez, 1993; Sánchez-Medina, 2013
Quechulac Lake	Lugo-Vázquez, 1993
Tecuitlapa Lake	Lugo-Vázquez, 1993
Querétaro	
Amealco Wetland	Potekhin and Mayén-Estrada, 2020
El Cajón Water Dam	Velázquez-Medina et al., 2020
Los Riscos Cave	Sigala-Regalado, 2008; Sigala-Regalado et al., 2011
San Miguel Almaya Wetland	Potekhin and Mayén-Estrada, 2020; Melekhin et al., 2022

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Quintana Roo	
Bacalar Lagoon	Potekhin and Mayén-Estrada, 2020; Cruz-Jiménez, 2022; Melekhin et al., 2022
Cenote Azul	Potekhin and Mayén-Estrada, 2020
Chunyaxché-Sian Ka'an Lagoon	Potekhin and Mayén-Estrada, 2020
Sian Ka'an Biosphere Reserve	Melekhin et al., 2022
San Luis Potosí	
Moctezuma River	Elliot and Hayes, 1955
Tamaulipas	
Tamesí River	Elliot and Hayes, 1955
Veracruz	
Acajete Phytotelmata of Epiphytic Bromeliads	Durán-Ramírez et al., 2019, 2020
Bosque de Niebla Sanctuary	Potekhin and Mayén-Estrada, 2020
Bosque de Niebla Sanctuary Phytotelmata of Epiphytic Bromeliads	Durán-Ramírez et al., 2019, 2020; Durán-Ramírez and Mayén-Estrada, 2022
Coatepec Phytotelmata of Epiphytic Bromeliads	Durán-Ramírez, 2010, Durán-Ramírez et al., 2015, 2019, 2020
Galicia Grottoes	Sigala-Regalado, 2011
Jalcomulco Phytotelmata of Epiphytic Bromeliads	Durán-Ramírez et al., 2019, 2020
Tuzamapan phytotelmata of Epiphytic Bromeliads	Durán-Ramírez et al., 2019, 2020
Veracruz temporal pond near the harbor	Hernández-Anaya, 1981
Xalapa Phytotelmata of Epiphytic Bromeliads	Durán-Ramírez et al. 2015, 2020; Foissner, 2016; Foissner and Stoeck, 2011
Yucatan	
Oxkutzcab Biocultural Reserve Phytotelmata of Epiphytic Bromeliads	Durán-Ramírez et al., 2020, Durán-Ramírez and Mayén-Estrada, 2022
Temozon Reservoir	Potekhin and Mayén-Estrada, 2020

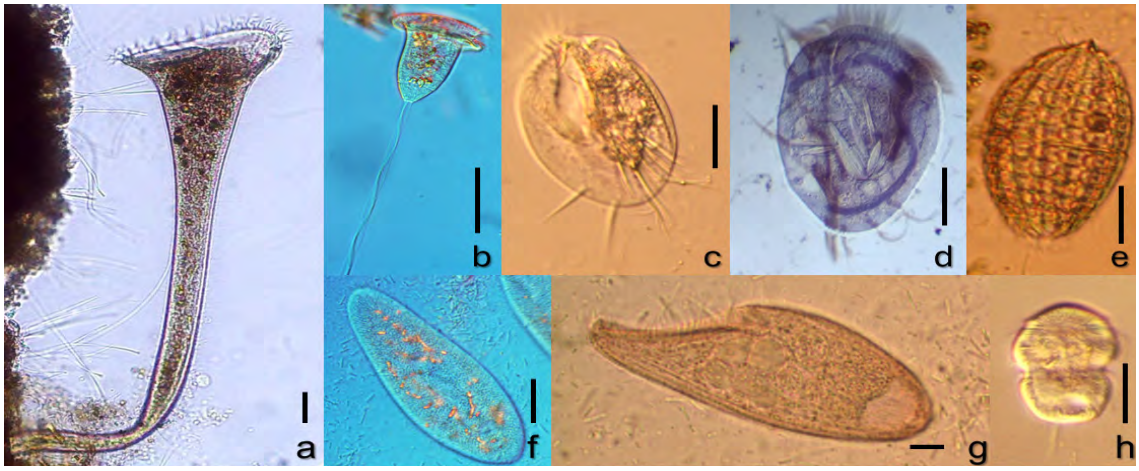

Figure 1. Some Ciliate Species from Continental Aquatic Escosystems in Mexico. a. *Stentor coeruleus* from El Cajón Dam (Querétaro); b. *Vorticella* sp. from Cantera Oriente (Mexico City); c. *Euplotes* sp. from Cantera Oriente (Mexico City); d. *Euplotes eurystomus* from Tziscao Lake (Chiapas); e. *Coleps hirtus*, f. *Paramecium* sp. and g. *Blepharisma* sp. from Cantera Oriente (Mexico City), h. *Urocentrum turbo* from Montebello Lakes (Chiapas). Images a-c and e-h: Cells *In Vivo*; d: Stained with Harris' Hematoxilin Technique. Scale Bar: 10 µm. Credits: M. Velázquez (a); V. M. Romero-Niembro (b, c, e, f, g); D. Méndez (d, h).

The largest number of species has been reported for central Mexico, being Mexico City, State of Mexico, Puebla, and Veracruz, the states that concentrate about 55 % of species richness (Fig. 2). For Mexico City, 201 species have been reported, and for Tamaulipas state, only one species was reported inhabiting a river (Table 1).

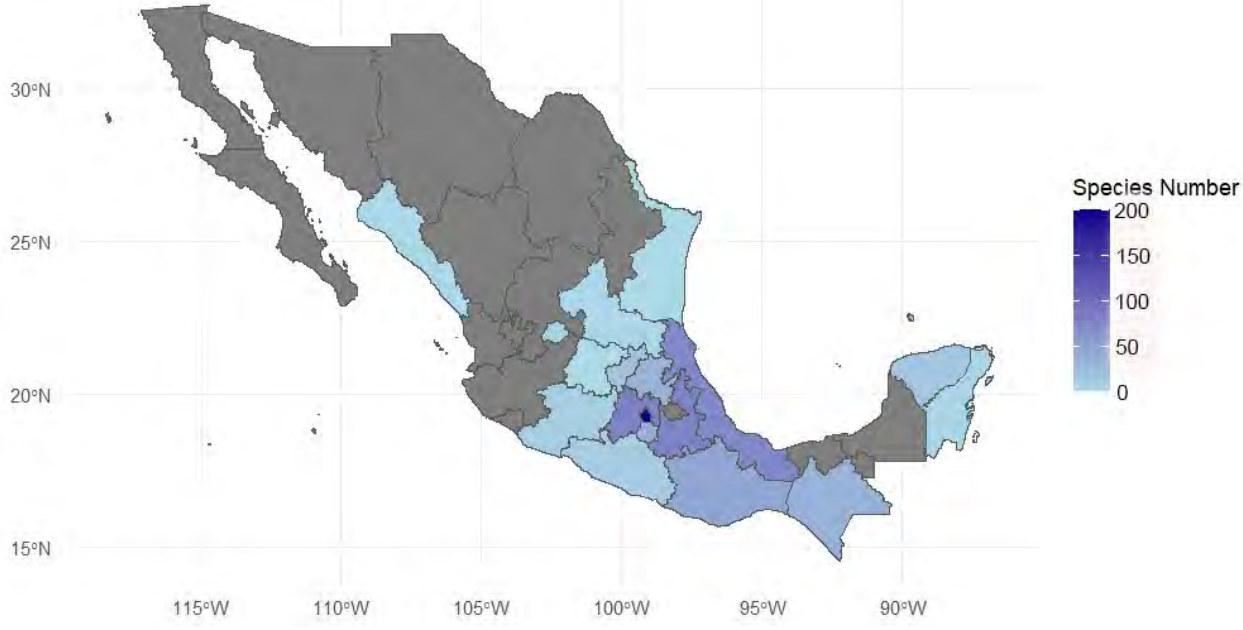

Figure 2. Number of Species in Continental Systems by Mexican States. The Gray Colour Indicates the Absence of Ciliate Species Record.

The biogeographical distribution of the continental ciliate species corresponds to two regions, Neartic and Neotropical, and eight Mexican provinces (Fig. 3 and 4). The biogeographic regionalization is according to Morrone (2019).

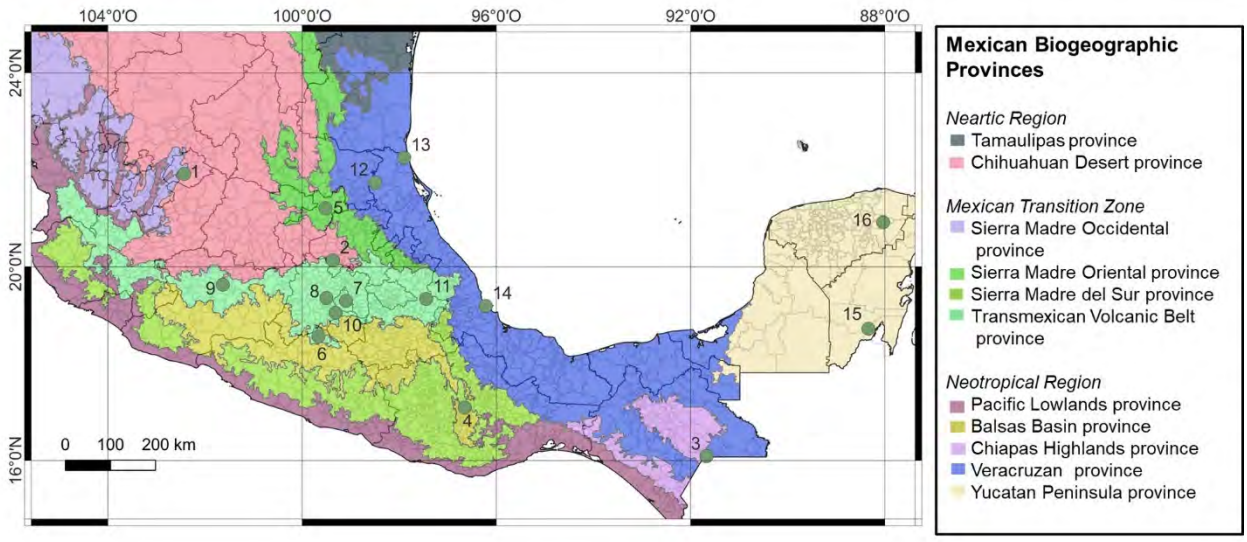

Figure 3. Biogeographic Mexican Provinces sensu Morrone (2019) of Mexican Republic States Where Species of Ciliated Protists Have Been Recorded in Continental Aquatic Environments. Chihuahuan Desert Province ([1]Aguascalientes State, [2]Hidalgo State); Chiapas Highlands Province ([3]Chiapas State); Sierra Madre del Sur Province ([4]Oaxaca State); Sierra Madre Oriental Province ([5]Querétaro State); Transmexican Volcanic Belt Province ([6]State of Guerrero, [7]México City, [8]State of México, [9]State of Michoacán, [10]State of Morelos, [11]State of Puebla) Province of Veracruz ([12]State of San Luis Potosí, [13]State of Tamaulipas, [14]State of Veracruz); Province of the Yucatan Península ([15]State of Quintana Roo, [16]State of Yucatan).

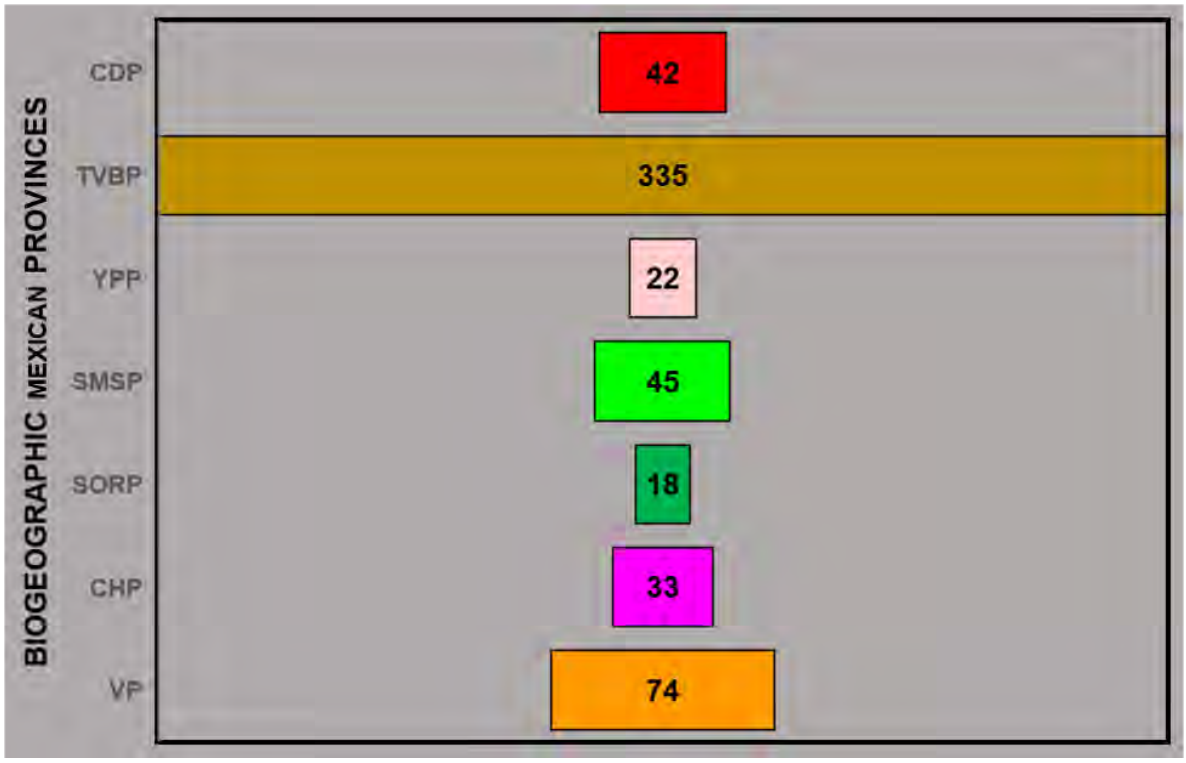

Figure 4. Number of Ciliated Protist Species by Biogeographic Provinces. Abbreviations: CDP, Province of the Chihuahuan Desert ; TVBP, Province of the Transmexican Volcanic Belt ; YPP, Province of the Yucatan Península ; SMSP, Province of the Sierra Madre del Sur; SORP, Province of the Sierra Madre Oriental; CHP, Province of the Chiapas Highlands; VP, Province of Veracruz.

Figure 5 shows the data of the historical analysis of the record of species over time between the period of 1922-2023. The first records were carried out by Bravo-Hollis (1922) for two lakes, Xochimilco and Chapultepec located in Mexico City; later, Sokoloff (1936) in Hidalgo state contributed with ciliate records. For the following decades, the works of Elliot and Hayes (1955) for San Luis Potosí, and López-Ochoterena (1965) for Mexico City could be mentioned. The diversity of ciliates since the year 2000 was focused on the study of very different continental systems as well as the coverage of a broader number of states (Durán-Ramírez, 2010; Sigala-Regalado, 2011; Méndez-Sánchez, 2017; Potekhin & Mayén-Estrada, 2020).

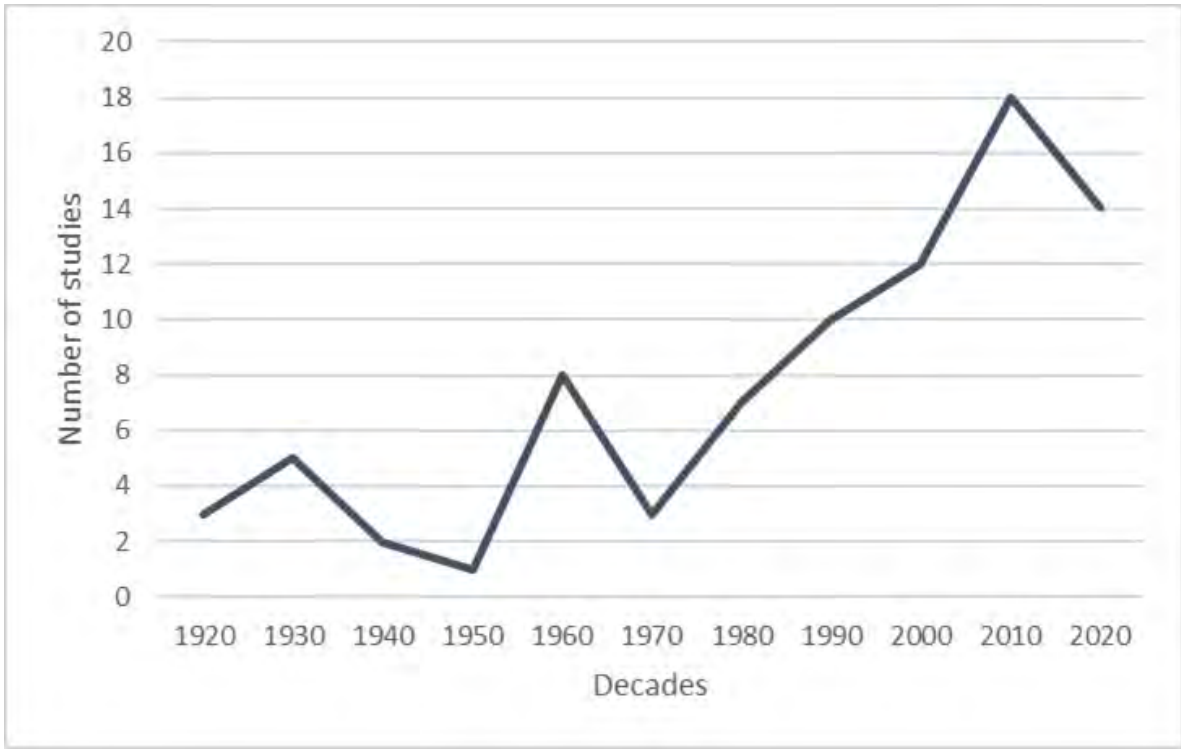

Figure 5. Number of Ciliate Species According to the Time Recorded in Mexican Continental Ecosystems.

However, there is a lack of studies in the north and west of the country where there are important bodies of water with a high risk of disappearance, such as Cuatro Ciénegas, Lake Chapala, Lake Cuitzeo, Pátzcuaro, and Yuriria, and important rivers such as the Balsas River, Lerma River, and even the border rivers such as the Bravo, Colorado on the northern border or the Usumacinta, Grijalva, and Suchiate, on the border with Guatemala and Belize. Despite the diversity of epicontinental water bodies in Mexico, the knowledge of the community of ciliates that inhabit them is scarce. Only records of ciliates account for 1.25 % of the water bodies inventoried by SINA (2020), and only a small fraction of natural environments is found within a Protected Natural Area or is categorized as part of a Ramsar site, as is the case of the Ciénegas de Lerma, the Lagos de Montebello National Park or the Bacalar Lagunar Complex.

Mexico has 28 main rivers (Maderey-Rascón & Carrillo-Rivera, 2005) and 6,332 inventoried wetlands (SINA, 2020) classified as marine, marsh, and lacustrine, occupying 6.5 % of the national territory. However, more than 60 % of these ecosystems have already been lost, except for the 142 protected Ramsar sites.

Conclusions

In Mexico only 294 ciliate species have been recorded for 16 Mexican states, which indicates that the studies of the ciliate species across the Mexican Country's continental waters are still incomplete, being only about 28.7 % reported species. The environmental crisis that Mexico is facing due to the severe drought throughout its territory has caused some continental water bodies to have gradually dried out. This scenario makes all the previous biological information valuable and the current information can be a guide for making decisions in future strategies for ecological and conservation studies based on the ciliate's roles in ecosystems, considering that new ciliate records and new species descriptions are possible due to the geographic position of the country encompassing two biogeographical regions.

Acknowledgements

To CONABIO for the support given to the CAT-KT 003 project "Protistas ciliados y flagelados heterótrofos".

Authors' Contibutions

Conceptualization RME; Data curation RME, CADR, VMRN, FOB; Formal analysis RME, CADR, VMRN, FOB; Investigation RME, CADR, VMRN, FOB; Methodology RME, CADR, VMRN, FOB; Software VMRN, FOB; Supervision RME; Validation RME; Visualization RME, CADR, VMRN, FOB; Writing RME, CADR, VMRN, FOB; Writing review, and editing RME.

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Topics of Limnological Research in Mexico, coordinated by Alfredo Pérez Morales, was published in Dirección General de Publicaciones of the Universidad de Colima, avenida Universidad 333, Colima, Colima, México, www.ucol.mx. The edition was completed in December 2025. The Arial family was used for typesetting. Non Periodical Editorial Program: Eréndira Cortés Ventura. Cover Design: Adriana Minerva Vázquez Chávez. English Proofreader: Yul Ceballos. Interior Design: José Luis Ramírez Moreno and Leticia Bermúdez Aceves.

This book takes a significant step in showcasing the relevance of limnology to our survival. Freshwater habitats, though they cover less than 1 % of the Earth's surface, are home to a substantial portion of the world's biodiversity—at least 10 % of all known species. Freshwater habitats and the biodiversity they support are under threat. Moreover, our survival depends on access to high-quality freshwater. This book not only highlights the beauty of limnology and the scientific methods used to study it, but it also draws attention to the major causes of biodiversity loss in freshwater ecosystems. It shows all readers what it means to deal with inland waters as a scientist interested in understanding ecosystems and protecting them.

ISBN: 978-968-9733-13-3
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