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Water Quality Challenges in Central Veracruz, Mexico: A Comprehensive Review
Desafíos de la Calidad del Agua en el Centro de Veracruz, México: Una Revisión Integral

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SUMMARY

Major rivers in Veracruz show significant levels of contamination, closely linked to agro-industrial activities—particularly sugarcane cultivation—and the intensive use of fertilizers and pesticides, with implications for human health, the environment, and productive activities. In the central region of the state of Veracruz, Mexico, water quality faces increasing pressure due to the discharge of domestic and industrial wastewater, leachates from sanitary landfills, climate change, and accelerated population growth. These factors affect water availability and compromise its safety for human consumption and environmental balance. The purpose of this research was to identify the main sources of contamination, analyze their impacts on the environment and public health, and recognize knowledge gaps to guide future research and public policies. The PRISMA 2020 methodology was applied to conduct a rigorous and replicable systematic review of the scientific literature. The search was carried out in Google Scholar, Springer, Taylor & Francis, and ScienceDirect. From 380 initial records, 30 articles that met the inclusion criteria (related to water quality, findings from similar regions, and studies in central Veracruz) were selected for detailed analysis. Using VosViewer, a bibliometric analysis was performed, identifying two major thematic axes: one ecological-geographical (ecosystem services, land use, wetlands, and regional characteristics) and another technical, focused on the evaluation and efficiency of treatment systems, particularly constructed wetlands. The findings show sustained growth in scientific production since 2015, reflecting increasing interest in sustainable solutions and integrated water management strategies. This study provides an updated overview of water-related challenges in Veracruz and highlights the urgency of strengthening public policies and appropriate technologies to improve water quality and protect this essential resource for life.

Index words: *agriculture, constructed wetlands, deforestation, pollution, wastewater discharge.*

RESUMEN

Los principales ríos de Veracruz registran niveles importantes de contaminación, estrechamente vinculados con actividades agroindustriales —particularmente el cultivo de caña de azúcar— y el uso intensivo de fertilizantes y plaguicidas, con implicaciones para la salud humana, el ambiente y las actividades productivas. En la zona centro del estado de Veracruz, México, la calidad del agua enfrenta una presión creciente debido a la descarga de aguas residuales domésticas e industriales,

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lixiviados de rellenos sanitarios, cambio climático y acelerado crecimiento poblacional. Estos factores afectan la disponibilidad del recurso hídrico y comprometen su seguridad para el consumo humano y el equilibrio ambiental. El propósito de esta investigación fue identificar las principales fuentes de contaminación, analizar sus impactos en el ambiente y la salud pública, y reconocer vacíos de conocimiento que orienten futuras investigaciones y políticas públicas. Se aplicó la metodología PRISMA 2020 para realizar una revisión sistemática rigurosa y replicable de la literatura científica. La búsqueda se efectuó en Google Scholar, Springer, Taylor & Francis y ScienceDirect. De 380 registros iniciales, se seleccionaron 30 artículos que cumplieron los criterios de inclusión (relacionados con calidad del agua, regiones similares y estudios en el centro de Veracruz). Mediante VosViewer se realizó un análisis bibliométrico que identificó dos ejes temáticos: uno ecológico-geográfico (servicios ecosistémicos, uso del suelo, humedales y características regionales) y otro técnico, enfocado en la evaluación y eficiencia de sistemas de tratamiento, especialmente humedales construidos. Los hallazgos muestran un crecimiento sostenido de la producción científica desde 2015, reflejando interés por soluciones sostenibles y estrategias de gestión integrada del agua. El estudio ofrece una visión actualizada de los desafíos hídricos en Veracruz y subraya la urgencia de fortalecer políticas públicas y tecnologías adecuadas para mejorar la calidad del agua y proteger este recurso esencial.

Palabras clave*: agricultura, humedales construidos, desforestación, contaminación, descarga de aguas residuales*.

INTRODUCTION

Water is essential for human and ecosystem health; however, the exponential demand for water represents a growing global challenge that compromises its quality (Mishra, 2023; Yan, Shen, and Zhou, 2022). Approximately 80% of wastewater globally is discharged untreated, exacerbating water pollution and negatively affecting ecosystems and human health (Peralta-Vega, Vergara, Marín, García, and Sandoval, 2024; Sandoval-Herazo, Alvarado, Marín, Méndez, and Zamora, 2018a). Both human activities and natural phenomena have contributed to the progressive deterioration of surface water quality in recent decades (Huang *et al.*, 2021; Uddin, Nash, Rahman, and Olbert, 2022). Agriculture and urban expansion significantly impact the water quality in many regions (Siqueira *et al.*, 2023). Each year, about 1260 km³ of agricultural runoff and 330 km³ of urban wastewater are released into water systems, emphasizing their major role in water quality decline (FAO, 2018). Moreover, Bamal *et al.* (2025) report that most global studies indicate a negative impact of hydroclimatic variables (precipitation, temperature, runoff, and discharge) on water quality indicators; however, a deeper understanding of the interactions between climate change, hydroclimatic variables, and water quality is still needed.

In Mexico, particularly in the central area of Veracruz, water is subjected to anthropogenic pressure from industrial, agricultural, and domestic activities (Escamilla-Pérez, Hernández, León, and López, 2024; Shi *et al.*, 2024). In this region, corresponding to Hydrological-Administrative Region X (Gulf-Central), approximately 12.4% of the total available renewable water volume is used (CONAGUA, 2021). At the state level, Veracruz accounts for about 11% of Mexico's renewable water (CONAGUA, 2023). However, this same area, considered one of the most deforested in the country, has historically faced recurring problems with floods and poor drinking water quality (Nava-López *et al.*, 2018). For example, Valdespino, Guillen, Albino, von Osten, and Vázquez (2024) reported concentrations of organochlorine pesticides (OCPs) in different compartments of riverine ecosystems flowing through mountain cloud forest and two types of land use, namely pasture lands and coffee plantations, in the upper La Antigua watershed, Veracruz, Mexico. In addition, factors such as climate change and population growth exert pressure on water resources (Maldonado, Alfaro, and Hidalgo, 2018; Singh, Chaudhary, Giri, and Mishra, 2025). This affects their availability in quantity and quality (Aragón *et al.*, 2022; Bănăduc *et al.*, 2022). For this reason, the challenges linked to water quality are crucial for the sustainable progress of Veracruz and Mexico.

In the Central Veracruz region (Figure 1), water quality is primarily influenced by domestic and industrial wastewater discharge into water bodies (Castañeda-Chávez, and Lango, 2022; Sandoval-Herazo *et al.*, 2024). Another factor affecting water quality is land-use change, such as applying excessive fertilizers and pesticides in the agricultural sector (Anh, Can, Nhan, Schmalz, and Luu, 2023; Villers, Equihua, Tobón, and Gutiérrez, 2011). On the other hand, leachate from landfills leaching into groundwater should also be considered part of the problem affecting water quality (Dash and Kalamdhad, 2021; Tariq and Mushtaq, 2023).

Figure 1. Study area: Central Veracruz, Mexico.

Previous studies have identified overexploitation in watersheds in Veracruz owing to human consumption, industry, agriculture, livestock, and energy generation (González, Rodríguez, Arreguín, Fuentes, and Arriaga, 2025; Mokondoko, Manson, and Pérez, 2016; Torres-Beristáin, González, Rustrián, and Houbron, 2013). This review aims to comprehensively analyze the challenges and problems related to water quality in Central Veracruz. It identifies the primary sources of contamination and their impacts on environmental and human health and reviews the methodologies and results of comparative studies. This review also aims to highlight knowledge gaps specific to Veracruz, identify key areas for future local research, and provide recommendations based on the reviewed literature to enhance water quality management and regional policies.

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 methodology was used in this review (Page *et al.*, 2021). Its application reduces bias in selecting and analyzing studies, guaranteeing reliable and reproducible information (Agrawal *et al.*, 2024). The application of this methodology to water quality challenges in central Veracruz allowed us to synthesize existing knowledge, identify research gaps, and guide future studies (Aguilar-Aguilar *et al.*, 2023; Madrid *et al.*, 2024; Ngamile, Madonsela, and Kganyago, 2025). It also helps to assess environmental and social impacts, providing a foundation for enhancing public policies and water resource management strategies.

MATERIALS AND METHODS

According to Hernández-Sampieri, Fernández, and Baptista (2014) and Tamayo y Tamayo (2004), this research is qualitative, with a documentary type and an exploratory and descriptive nature. It was developed through a systematic review to detect, consult, and obtain a bibliography of water quality in Central Veracruz. To elaborate on this review, the criteria established in the PRISMA 2020 statement (Page *et al.*, 2021) were followed, referring to Higgins *et al.* (2019) based on their manual for elaborating systematic reviews. For the correct analysis of the information collected, quantitative and qualitative studies were used as references because they are closely related to the objectives and questions of this review.

Google Scholar, Springer, Taylor & Francis, and ScienceDirect were the databases in which the advanced literature search was performed to compile the analysis studies. The keywords selected for this review included water quality, water quality index, central Veracruz, Misantla, contamination, and pollutants. The search strings used by Boolean operators were as follows: ("water quality" OR "water quality index") AND ("Central Veracruz" OR "Misantla") AND (pollution OR contaminant). This procedure guarantees, owing to the descriptors and prepositions, that the results of the information banks are strictly linked to the selected keywords.

In this research, we sought to comply with most of the rules established in the PRISMA checklist for developing research publication guidelines (Hutton, Catalá-López, and Moher, 2016), which were best adapted to this work (Sánchez, Pedraza, and Donoso, 2022). The following steps were performed to develop the PRISMA statement:

First search. the first search was conducted on October 08, 2024, using the following search string: ("water quality" OR "water quality index" AND ("Central Veracruz" OR "Misantla")) AND (pollution OR contaminat*AND ("health impacts" OR "environmental health" OR "future research" OR "water management" OR "water policy")), in the following databases: Google Scholar, Springer, Taylor & Francis and ScienceDirect. This preliminary search yielded results that were not useful for the analysis because the resulting bibliographic information was not related to the objective of this research. Therefore, the search string was modified to perform the subsequent search, as shown in the second search.

Second search. The second search was conducted from October 22, 2024, to December 11, 2024, with the string ("water quality" OR "water quality index") AND ("Central Veracruz" OR "Misantla") AND (pollution OR contaminant) in the previously established databases. This systematic search yielded good results and provided access to the information shown in Table 1.

Specific inclusion and exclusion criteria were defined to select the literature from the 380 results obtained in the search and comprehensively analyze the challenges and problems related to water quality in central Veracruz (Table 2). These criteria allowed us to compare the findings with those of studies conducted in other similar regions. Once the selection criteria were established, the documents excluded from the analysis were eliminated based on the previous Table.

Of the 312 documents from the Google Scholar search, 178 were empty, 9 were duplicates, and 19 were eliminated. This leaves 106 papers for review, of which 66 documents were excluded (13 books, five book chapters, and 48 articles) based on the reading of the title and abstract, considering that they are not directly related to the subject of this review. We read the full text of the remaining 40 documents (39 articles and one book chapter). Eighteen papers were discarded, and 22 were selected for this systematic analysis.

Of the 55 documents obtained from the Springer search, seven duplicates and one conference were eliminated. This resulted in 47 papers for review, of which 41 were excluded (23 books, seven book chapters, and 11 articles) with titles and abstracts unrelated to the research. Six documents remained (two articles, two books, and two book chapters). We proceeded by reading the complete text, and from this, we discarded three documents (two books and one article) unrelated to the topic. Three papers were selected from this database for this systematic analysis: 3 (two chapters and one article).

The search query yielded two articles in the Taylor and Francis search engines. One was excluded because its title and abstract did not match the review's objective. One document remained for full-text review and was selected for the systematic analysis because it met the inclusion criteria.

The search of the ScienceDirect database yielded 11 documents. According to the exclusion criteria, one duplicate and six articles were eliminated because they did not have a title or abstract related to the objective of the analysis. These four documents (three articles and one chapter book) were read in full text. All were found to be related to the topic, resulting in the four papers being selected for the systematic analysis. Once the inclusion and exclusion criteria stipulated in the methodology of this review were applied, 30 articles were obtained for systematic analysis.

Table 1. Number of systematic search results per database.

No.	Database	Boolean Expression	Search Results
1	Google Scholar	("water quality" OR "water quality index") AND ("Central Veracruz" OR "Misantla") AND (pollution OR contaminant)	312
2	Springer	("water quality" OR "water quality index") AND ("Central Veracruz" OR "Misantla") AND (pollution OR contaminant)	55
3	Taylor & Francis	("water quality" OR "water quality index") AND ("Central Veracruz" OR "Misantla") AND (pollution OR contaminant)	2
4	ScienceDirect	("water quality" OR "water quality index") AND ("Central Veracruz" OR "Misantla") AND (pollution OR contaminant)	11
Total			380

Table 2. Inclusion and exclusion criteria for bibliographic selection.

Inclusion criteria	Exclusion criteria
Related to water quality.	Empty documents.
Findings from similar regions.	Duplicate bibliography.
Studies were conducted in central Veracruz.	Bibliography from academic repositories (thesis, dissertations).
Studies were conducted in the municipality of Misantla.	Bibliography of conference proceedings (conferences, posters).
	Books, book chapters, and articles unrelated to the Center of Veracruz and with an affinity to the subject.

This inclusion and exclusion procedure for selecting articles is shown graphically in the selection diagram established by the PRISMA 2020 guidelines in Figure 2.
Finally, a database composed of 30 documents was entered .*RIS* format in the VosViewer software (Van Eck and Waltman, 2010) to perform the mapping and visualization of the correlations, and to perform the bibliometric analysis for this research.

RESULTS AND DISCUSSION

To establish a comprehensive picture of this systematic review, we also included a bibliometric analysis of the 30 papers using *VosViewer*, a specialized data mining tool (Dash and Kalamdhad, 2021). *VosViewer* provides a data-driven visualization of bibliographic networks (Van Eck and Waltman, 2010), where the density of nodes and the distance between them reflect their relative proximity (Melijosa, Pino, and Del Valle, 2022). This analysis made it possible to identify the most relevant approaches to water management, highlighting the main topics of study and their interconnectivity.

From the 30 documents analyzed, 1,438 terms described by the authors in their publications were identified. Of these, the 10 terms with the highest frequency are highlighted. Figure 3a shows a thematic network comprising these terms, which are grouped into two main clusters.

The first cluster (red color), made up of seven elements, groups research focused on topics such as "ecosystem services", "land use", "state", "water quality", "wetlands", "Mexico", and "Veracruz". These themes focused on ecological and geographical aspects linked to water management. The second cluster (green color), composed of three elements, focuses on terms such as "removal", "studies", and "constructed wetlands". It relates mainly to technical approaches and specific evaluations of treatment systems.

Figure 3b presents the network of bibliographic relationships derived from the analysis, which allows us to observe the temporal evolution of key terms according to the year of publication. This evolution shows how the lines of research have been progressively developing since 2015. In that year, ecosystem services and land use stand out; in 2016, Mexico and Veracruz emerge; in 2017, the term study is introduced; in 2018, state, water quality, and wetlands appear; in 2019, removal and constructed wetlands emerge. This chronological pattern allowed us to identify the consolidation of recurrent topics and the incorporation of recent technical approaches, particularly those linked to water treatment through Constructed Wetlands (CWs).

Figure 3c shows the node density map, where the proximity between terms and the intensity of the links reflect the relative relevance of the concepts within the field of study. Overall, these results show a clear trend in research: most studies focus on analyzing ecosystem services provided by natural wetlands, with special emphasis on regional contexts such as Mexico and, particularly, the state of Veracruz. To a lesser extent, research on the technical evaluation of pollutant removal efficiency in CWs has been identified, suggesting an emerging area of academic interest.

In addition, Figure 4 shows the terms of the most frequent topics in the bibliometric analysis of text mining.

Based on these findings of key words identified in different research works, the following key sub-themes have been structured to guide this review: (1) Wastewater, addressing its general context and challenges in its management; (2) Water quality and land use, analyzing the relationship between human activities and water pollution; (3) Rivers and ecosystem services, highlighting the importance of river ecosystems and the threats they face; (4) Natural wetlands, exploring their role in water quality regulation and biodiversity conservation; and, (5) CWs, evaluating their potential as a sustainable alternative for wastewater treatment. Table 3 shows the number of articles addressing each section identified in *VosViewer*, highlighting wastewater, water quality, land use, rivers, and ecosystem services with the highest proportion.

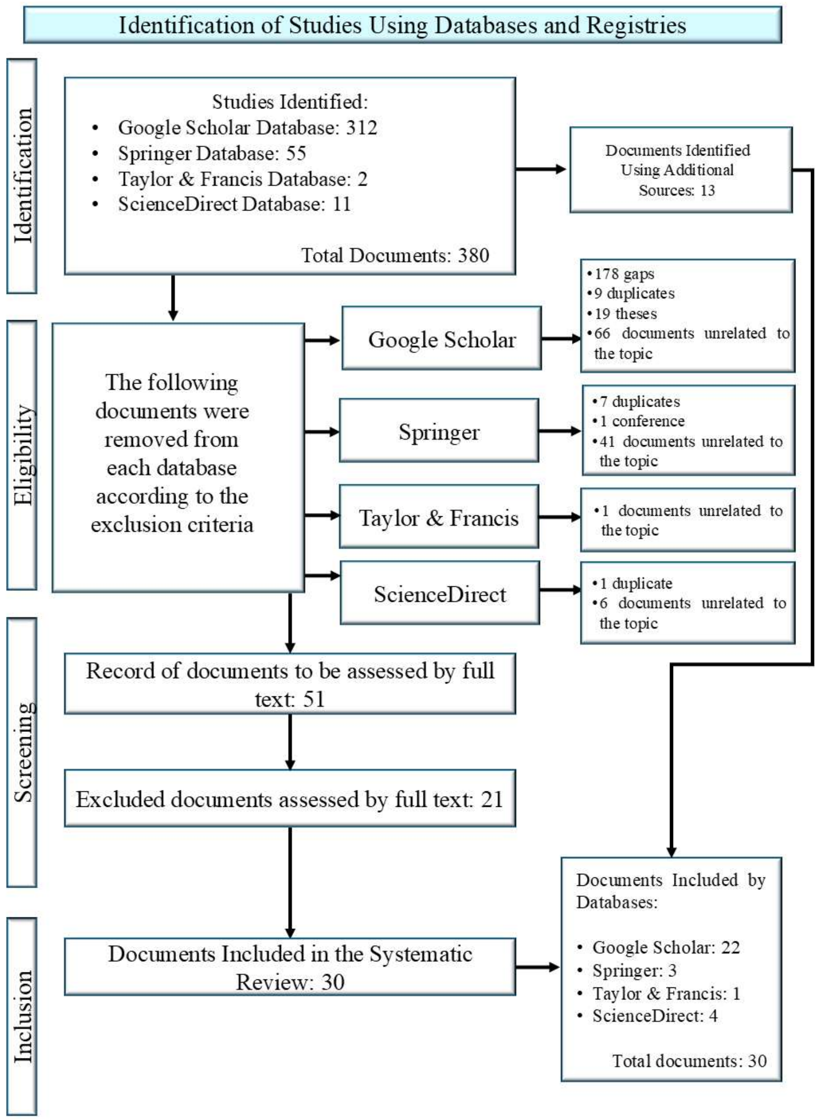

Figure 2. Diagram of document selection process following the PRISMA 2020 statement.

These topics will be developed in detail, providing an analysis based on scientific literature and recent studies that contribute to understanding the problems and possible solutions in water management in Veracruz and other similar regions.

Wastewater

Wastewater is an inevitable by-product of human and industrial activities, and proper management is essential for preserving water resources and public health (Cooper, Finzi, Hasbrouck, and Todd, 2004). In Mexico, particularly in Veracruz, wastewater management faces several challenges due to population growth, accelerated urbanization, and intensive agroindustrial activity (Martínez-Aguilar, Marín, Álvarez, Delfín, and Zamora, 2024). The untreated wastewater discharge into water bodies has generated severe pollution, affecting aquatic biodiversity and the ecosystem services they provide (Temino-Boes, Romero, and Romero 2019).

Wastewater in Mexico represents an environmental and public health challenge, especially in regions with a high population density and intensive industrial and agricultural activities (Mendelssohn, Byrnes, Kneib, and Vittor, 2017).

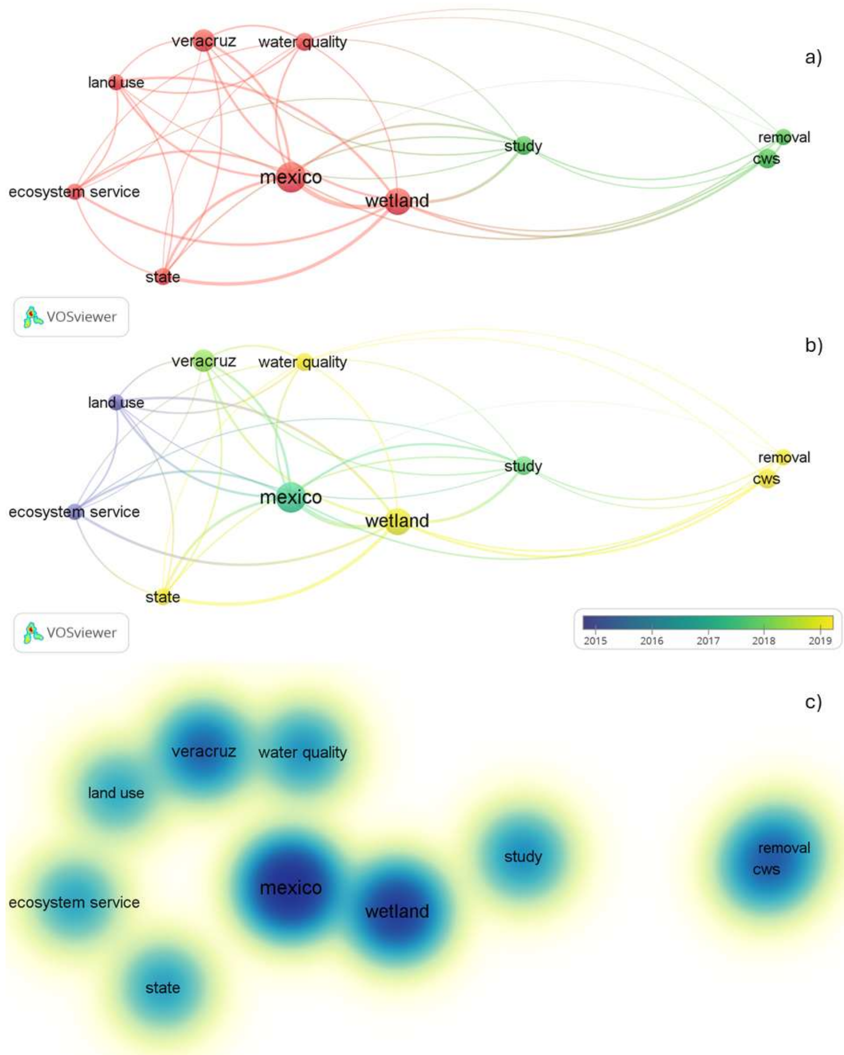

Figure 3. Mapping of traditional journals in the water management nndex domain: (a) Thematic network visualization, (b) Full analysis network visualization, (c) Density analysis visualization.

Veracruz operates only eight wastewater treatment plants (WWTPs), while 82 are out of service. WWTPs are affected by high operating costs and a lack of technical resources. In addition, their management falls directly into the municipalities, representing one of the main obstacles to efficiently managing these facilities (CONAGUA, 2024). Contamination of water bodies by wastewater discharge without adequate treatment is a recurrent problem (Mendoza-González, Martínez, Lithgow, Pérez, and Simonin, 2012). Factors such as uncontrolled urban growth, lack of sanitation infrastructure, and absence of effective governance have exacerbated the region's pollution of rivers and wetlands (Cloter, Cuevas, Landa y Frausto, 2022). In addition, the discharge of domestic and industrial wastewater contributes to the deterioration of water quality, thereby affecting biodiversity and ecosystem services (Sandoval-Herazo, Marín, Alvarado, Castelán, and Ramírez, 2016).

In this context, sanitation systems have failed to meet the demand for wastewater treatment in Veracruz, leading to the proliferation of water bodies contaminated with nutrients, organic matter, and pathogenic microorganisms (McGinnis, Shady, and Ju-Chin, 2021). In addition, inadequate infrastructure in many rural communities complicates the efficient management of liquid wastes (Cloter *et al.*, 2022). Developing CWs and other alternative technologies has been explored as a possible sustainable solution for decentralized wastewater treatment (Sandoval-Herazo *et al.*, 2018a).

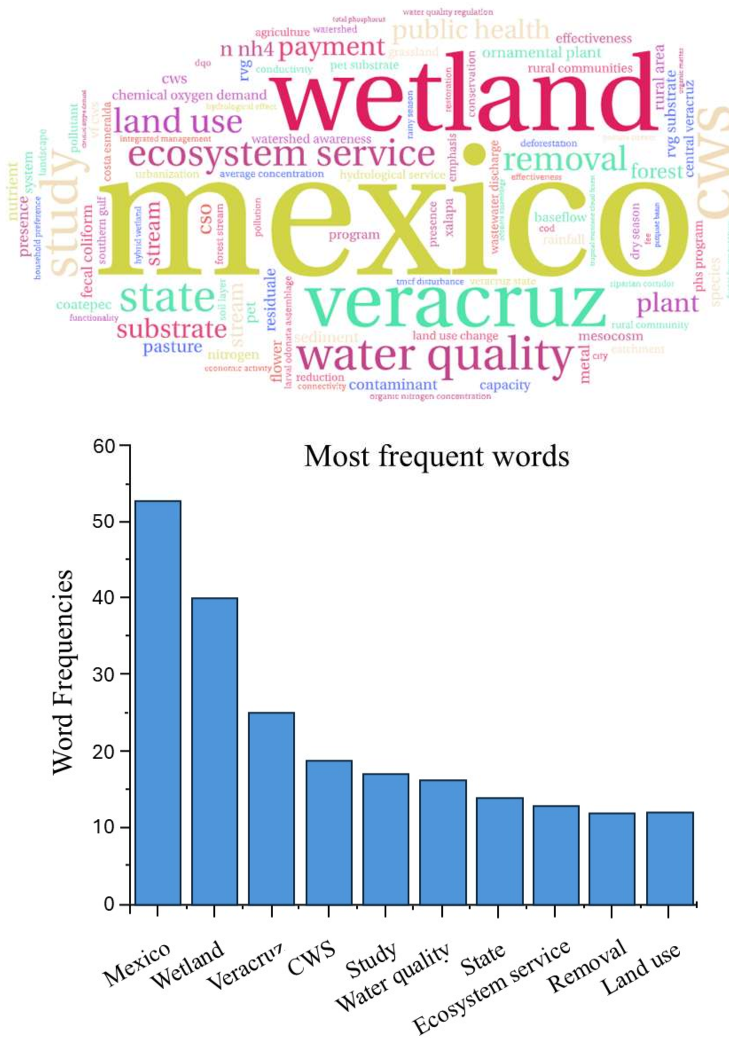

Figure 4. WordCloud and frequency histogram.

Recent studies have evaluated alternative methods for wastewater treatment, highlighting the implementation of CWs as a sustainable strategy to reduce pollutants, such as nitrogen, phosphorus, and organic matter (Marín-Muñíz, Sandoval, Zamora, and Celis, 2022). In addition, it has been documented that using ornamental plants in CWs systems improves pollutant removal, representing a viable option for rural communities with restricted access to conventional water treatment infrastructure (Sandoval-Herazo *et al.*, 2018b). However, the adoption of these technologies remains limited owing to a lack of investment and environmental awareness (Cloter *et al.*, 2022).

Water pollution in Veracruz is also related to soil quality and agroindustrial activity in the region (Oropeza-Orozco *et al.*, 2011). For example, the intensive cultivation of sugarcane involves excessive use of fertilizers and pesticides (Torres-Beristáin *et al*., 2013). In this context, agro-industrial crops such as sugarcane, coffee, orange, lemon, banana, and pineapple cover approximately 1 096 396 hectares, accounting for about 43% of the total agricultural area of active farming units (INEGI, 2023). Research has shown that agricultural practices and excessive fertilizer application contribute to the entrainment of nutrients into water bodies, exacerbating algal blooms and decreasing water oxygenation (Temino-Boes *et al.*, 2019). Additionally, in Veracruz, river pollution directly threatens human health: in the lower Coatzacoalcos basin, PCBs and PAHs have been detected, with carcinogenic and non-carcinogenic effects linked to fish consumption (Morales-Mora, Rodríguez, Martínez, Rosa, and Nolasco, 2014). In 2020, 20 people in Tezonapa were poisoned due to contaminated water, with severe cases of acute diarrheal diseases reported (Secretaría de Salud de Veracruz, 2020). These incidents further show that water quality directly influences the prevalence of waterborne gastrointestinal diseases, such as cholera, bacillary dysentery, and typhoid fever (Megchún-García *et al.*, 2015; Mokondoko *et al*., 2016).

Table 3. List of authors by section and databases.

Section	Authors of the 30 systematic review documents	Documents by section
Wastewater	Marín-Muñíz, Sandoval, Zamora, and Celis (2022).*	11
	Sandoval-Herazo, Alvarado, Marín, Méndez-Contreras, and Zamora. (2018a).	
	Sandoval-Herazo *et al*. (2018b)*	
	Sandoval-Herazo *et al*. (2020)	
	Sandoval, Zurita, Del Ángel, Adame, and Marín (2020)	
	Sandoval *et al*. (2024)	
	Arrechea, Gómez, Muñoz, Marín, and Zamora (2023).	
	García-García, Ruelas, and Marín (2016)	
	Martínez-Aguilar, Marín, Álvarez, Delfín, and Zamora (2024)	
	Mendelssohn, Byrnes, Kneib, and Vittor (2017)	
	Mokondoko, Manson, and Pérez (2016)*	
Water quality and land use	Peréz-Quezadas *et al*. (2017).	9
	Cloter, Cuevas, Landa, and Frausto. (2022)	
	De la Rosa and Valdés (2021)	
	Cooper, Finzi, Hasbrouck, and Todd (2004)	
	Dupont, Martinez, Rodriguez, Hernandez, and Guadarrama (2024).	
	Temino-Boes, Romero, and Romero (2019)	
	García, Vázquez, Novelo, and Favila. (2017)	
	Muñoz, Equihua, Tobón, and Gutiérrez (2011)	
	Hudson *et al*. (2005).	
Rivers and ecosystem services	Escamilla-Pérez, Hernández, León, and López (2024).	5
	McGinnis, Shady, and Ju-Chin (2021)	
	Vázquez-González, Fermán, Moreno, and Espejel (2014)	
	Oropeza-Orozco *et al*. (2011)	
	Mokondoko *et al*. (2016)*	
Natural wetlands	Mendoza-González, Martínez, Lithgow, Pérez, and Simonin (2012)	4
	Ballut-Dajud *et al*. (2022)	
	Sandoval-Herazo, Marín, Alvarado, Castelán, and Ramírez (2016)*	
	Von Thaden, Manson, Congalton, López, and Jones (2021)	
Constructed wetlands	Marín-Muñíz *et al*. (2022).*	4
	McGinnis *et al*. (2021)	
	Sandoval-Herazo *et al*. (2018b)*	
	Monteagudo-Hernández *et al*. (2024).	

* Documents that are repeated in several thematic sections.

The Seco River in central Veracruz illustrates water pollution closely tied to agro-industrial activities and the intensive use of fertilizers and pesticides. These inputs, along with point and nonpoint discharges of untreated wastewater, are carried by runoff into aquatic systems. The combined impact of these factors increases nutrient and organic matter loads, degrades water quality, damages ecosystem services, and poses a continuous risk to the human water supply at various points within the basin (Torres-Beristáin *et al*., 2013). This situation not only compromises the availability of drinking water for local communities but also negatively affects the regional economy, particularly in water-dependent sectors such as fisheries and tourism (Escamilla-Pérez *et al*., 2024).

Water governance in Mexico has also been identified as a key factor for wastewater treatment. Cloter *et al*. (2022) highlight the importance of civil society organizations in regulating and protecting water resources, emphasizing that greater citizen participation could drive improvements in sanitation infrastructure and the implementation of more sustainable technologies.

The wastewater situation in Veracruz reflects a combination of structural, social, and environmental challenges that demand comprehensive solutions adapted to the regional context. The lack of adequate infrastructure, fragmented governance, and unsustainable agro-industrial practices have intensified the contamination of water bodies, affecting ecosystems and human communities. Against this backdrop, promoting alternative technologies, such as CWs, with greater social awareness and community participation, appears to be a promising path towards more sustainable management of water resources.

Water Quality and Land Use

Water quality is intrinsically related to land use, as agricultural, urban, and industrial activities significantly impact the availability and purity of water resources (Mendoza-González *et al.*, 2012). In Veracruz, the Actopan River Basin is an example of how agricultural expansion and fertilizer use have modified the hydrogeochemical composition of groundwater, as evidenced by the presence of nitrates and other contaminants in the surface and groundwater bodies (Arrechea, Gómez, Muñoz, Marín y Zamora 2023; Peréz-Quezadas *et al.*, 2017). This phenomenon results from the intensive use of agrochemicals and inadequate soil management practices, contributing to water quality degradation. Previous studies in coastal regions of Mexico have shown that aquifer overexploitation significantly deteriorates groundwater quality, promoting saline intrusion and the accumulation of dissolved salts beyond regulatory limits. In the La Paz aquifer (Baja California Sur), most agricultural wells exhibited high total dissolved solids (TDS) concentrations, whereas drinking water wells remained below 1000 mg L^{-1}, the maximum limit established by Mexican standards, a pattern associated with marine intrusion linked to overexploitation (Cruz-Falcón, Troyo, Murillo, García, and Murillo, 2018).

In addition, inadequate soil management can intensify mass removal and erosion processes, as observed in the Nautla River Basin (De la Rosa and Valdés, 2021). These processes increase sedimentation in water bodies, affecting their quality and altering aquatic ecosystems (Dupont, Martinez, Rodriguez, Hernandez, and Guadarrama 2024). The reduction in the capacity of rivers and wetlands to provide ecosystem services, such as regulating the hydrological cycle and natural water filtration, has become a priority environmental concern (Muñoz, Equihua, Tobón, and Gutiérrez, 2011).

In Veracruz, converting forest land into croplands, pastures, and urban settlements has increased the load of pollutants in rivers and aquifers, decreasing the availability of drinking water (Peréz-Quezadas *et al.*, 2017). Pollution derived from the indiscriminate use of fertilizers and pesticides in agriculture and the discharge of urban waste without adequate treatment represents a significant threat to water quality (Temino-Boes *et al.*, 2019).

Several studies have shown that changes in land-use patterns impact infiltration and surface runoff, increasing turbidity and nutrient concentrations in water bodies (Mokondoko *et al.*, 2016). A clear example of this problem is the Pixquiac River, one of the primary sources of drinking water for the city of Xalapa, the capital of the state of Veracruz. Worrying levels of contamination have been registered due to deforestation in its watershed and the discharge of untreated wastewater (Dupont *et al.*, 2024).

Therefore, implementing environmental governance strategies in urban watersheds has become a fundamental tool for the conservation of water resources (Cloter *et al.*, 2022). The participation of civil organizations and the adoption of sustainable land use practices have proven to be key to mitigating the impact of pollution in water bodies and guaranteeing the availability of resources for future generations (Von Thaden, Manson, Congalton, López, and Jones, 2021). It is necessary to continue promoting the integration of public policies focused on the protection and sustainable management of water and to strengthen environmental awareness and investment in sanitation technologies to reduce the pollutant load of land use on water quality (Siqueira *et al.*, 2023).

The relationship between water quality and land use in Veracruz shows that land management decisions directly impact the health of aquatic ecosystems and water availability for human consumption. Agricultural expansion, uncontrolled urbanization, and intensive use of agrochemicals have altered the natural balance of key watersheds, affecting infiltration, runoff, and water filtration processes. Against this backdrop, promoting an integrated approach that combines environmental governance, community participation, and sustainable land-use practices is crucial to preserve water quality and ensure its long-term use.

Rivers and Ecosystem Services

Rivers are fundamental ecosystems that play a key role in providing essential ecosystem services, such as drinking water supply, climate regulation, flood control, biodiversity support, and natural pollutant removal (Von Thaden *et al.*, 2021). In Veracruz, several rivers have been affected by human activities, which have compromised their capacity to provide these services sustainably (Hudson *et al.*, 2005).

Agroindustrial activity and urbanization have contributed significantly to river degradation in this region (Mendelssohn *et al.*, 2017). For example, the Filobobos River has been affected by crop expansion and industrial waste discharge, which have caused a deterioration in water quality and decreased aquatic biodiversity (Sandoval-Herazo *et al.*, 2020). Similarly, the Pixquiac River Basin, a crucial source of drinking water for the city of Xalapa, faces pollution problems due to deforestation, erosion, and excessive use of agrochemicals (Dupont *et al.*, 2024). These threats have reduced the capacity of river ecosystems to filter pollutants and maintain proper ecological balance (Peréz-Quezadas *et al.*, 2017).

The relationship between watershed management and riparian vegetation conservation is crucial for mitigating these adverse effects (McGinnis *et al.*, 2021). Studies have shown that riparian vegetation conservation and restoration can improve water quality, reduce erosion, and increase the resilience of aquatic ecosystems to climate change (Hudson *et al.*, 2005). In response to these issues, payments for environmental service programs have been implemented in Veracruz as a strategy to promote the protection of river ecosystems. These programs encourage landowners to conserve or restore forest cover in areas of water importance, reducing sedimentation and improving water quality (Von Thaden *et al.*, 2021).

Another relevant case in Veracruz is the Actopan River, where an alteration in water quality due to waste discharge and intensive agriculture has been documented (Arrechea *et al.*, 2023). Urban expansion without adequate regulation has led to increased sedimentation and contamination of water bodies (De la Rosa and Valdés, 2021). These problems highlight the need for integrated watershed management strategies and the application of ecological restoration practices to recover river functionality (Torres-Beristáin *et al*., 2013).

Various human activities are constantly threatening the vital role of rivers as providers of ecosystem services in Veracruz. Intensive agriculture, urban expansion, and deforestation have compromised their ability to provide clean water, regulate the climate, and sustain biodiversity. Cases such as those of the Filobobos, Pixquiac, and Actopan Rivers illustrate how environmental degradation directly affects water quality and the health of aquatic ecosystems. Given this, the importance of implementing strategies such as riparian vegetation conservation, integrated watershed management, and incentive programs for ecological restoration has become evident. Only through responsible and sustained management will it be possible to ensure that these ecosystems continue to provide essential benefits to the present and future communities.

Natural Wetlands

Natural wetlands are crucial in regulating water quality and providing habitats for diverse species (Vázquez-González, Fermán, Moreno, and Espejel, 2014). These ecosystems act as natural filters, trapping sediments and pollutants and improving water quality before reaching rivers, lakes, or subway aquifers (Temino-Boes *et al.*, 2019). In addition, wetlands are fundamental in regulating the hydrological cycle, helping mitigate the effects of floods and droughts by gradually storing and releasing water (Villers *et al.*, 2011).

In Veracruz, wetlands in the Papaloapan watershed are essential for fisheries and other local economic activities, functioning as water regulators and carbon sinks (Escamilla-Pérez *et al.*, 2024). However, these ecosystems are at risk due to agricultural expansion and urbanization, reducing their extent and water storage capacity (Ballut-Dajud *et al.*, 2022). The conversion of wetlands to farmland and urban areas has caused a significant loss of biodiversity, threatening the ecological stability and ecosystem services these environments provide (García, Vázquez, Novelo, and Favila 2017).

Changes in land use and the degradation of wetlands also affect local biodiversity, decreasing the presence of aquatic species and altering the ecological dynamics of the system (Mendelssohn *et al.*, 2017). The fragmentation of these ecosystems has reduced the connectivity between habitats, hindering species mobility and affecting their life cycles (Vázquez-González *et al.*, 2014). Likewise, introducing exotic species and agrochemical contamination into these ecosystems has intensified pressure, reducing their capacity for self-regulation and affecting their ecological functionality (Villers *et al.*, 2011).

Natural wetlands not only play a fundamental ecological role but also contribute to the economy and water security of local communities (Mendoza-González *et al.*, 2012). Their ability to sequester carbon makes them key allies in the fight against climate change, helping reduce the concentration of greenhouse gases in the atmosphere (Ballut-Dajud *et al.*, 2022). However, the lack of conservation strategies and poor implementation of public policies have led to their progressive degradation (Cooper *et al.*, 2004).

The wetland system of the lower Papaloapan River Basin is an example of an ecosystem threatened by unregulated fishing activity and agricultural expansion (Escamilla-Pérez *et al.*, 2024). These wetlands are vital for local biodiversity and provide refuge for diverse bird, fish, and amphibian species (Martínez-Aguilar *et al.*, 2024). In addition, their role as natural filters allows for reducing pollutants in water, contributing to the quality of water resources available to the surrounding communities. However, their degradation has led to a decrease in their capacity to maintain water balance in the region (Mendoza-González *et al.*, 2012). The restoration and conservation of these ecosystems are crucial to guarantee their functionality and the benefits they provide to both natural and human populations (McGinnis *et al.*, 2021).

Given these challenges, it is essential to strengthen wetland conservation and restoration strategies to promote sustainable land management and participation of local communities in protecting these ecosystems (Mendelssohn *et al.*, 2017). The implementation of policies that promote the reforestation of riparian areas, control of agricultural activities, and regulation of urban growth are key measures to ensure the sustainability of wetlands and their ability to continue providing essential ecosystem services in the future (McGinnis *et al.*, 2021; Oropeza-Orozco *et al.*, 2011).

Natural wetlands are fundamental to water improvement, water regulation, and the sustenance of biodiversity. In addition to their ecological value, the Papaloapan watershed supports activities such as fishing and contributes to climate change mitigation. However, threats such as intensive agriculture, urbanization, and loss of vegetation reduce their functionality. Therefore, promoting conservation through comprehensive actions, including community participation, is crucial.

Constructed Wetlands (CWs)

CWs have emerged as a viable and sustainable alternative for wastewater treatment in Mexico, especially in rural and peri-urban communities, where sanitation infrastructure is limited (García-García, Ruelas, and Marín, 2016). These systems have proven effective in reducing pollutants, such as chemical oxygen demand (COD), nitrogen, and phosphorus, and improving treated water quality. Several studies have evaluated ornamental plant species, such as *Spathiphyllum blandum*, in artificial wetlands, with promising results in pollutant removal (Sandoval, Zurita, Del Ángel, Adame, and Marín, 2020).

Recent research has explored alternative materials as fill in CWs, including reused plastic and tezontle, to improve the efficiency of the water filtration and purification process; they showed a retention efficiency of over 90% after 20 days of contact (Sandoval-Herazo *et al.*, 2018b). Using these materials optimizes the retention and removal of pollutants and represents a strategy for reusing solid waste, promoting a circular economy (Escamilla-Pérez *et al.*, 2024). In addition, the adaptation of these systems to the specific climatic and ecological conditions of Veracruz has been identified as a key factor in their effectiveness and social acceptance (Martínez-Aguilar *et al.*, 2024).

The design and operation of CWs require constant monitoring to ensure their long-term efficiency (García-García *et al.*, 2016). In locations such as Pastorías and Actopan, a constructed wetland mesocosm has been implemented and has shown promising results in pollutant removal, serving as a model for future initiatives in the region (Sandoval-Herazo *et al.*, 2016). These projects have shown that the combination of natural substrates and plants with high purification capacity can enhance the effectiveness of artificial wetlands in the removal of pollutants such as nitrogen, phosphorus, and fecal coliforms (Marín-Muñíz *et al.*, 2022; Sandoval *et al.*, 2020).

Despite the ecological and economic benefits of CWs, their large-scale implementation poses significant challenges (García-García *et al.*, 2016). These include the lack of public policies that encourage their use, scarcity of funding for their development, and the need for greater dissemination of their functioning and environmental advantages (Cooper *et al.*, 2004). Likewise, these systems' social acceptance and integration into water management strategies require coordinated efforts between governments, academic institutions, and local communities.

CWs represent an effective and sustainable alternative for wastewater treatment, particularly in areas with limited infrastructure. As in Veracruz, their ability to remove pollutants and adapt to local conditions has been demonstrated. In addition, the use of recycled plants and materials improves efficiency and promotes a circular economy.

Final Considerations

A review of studies on water quality in central Veracruz revealed a diversity of methodologies applied to evaluate and mitigate water pollution in different water bodies, as shown in Table 4. In CWs, mesocosms with ornamental plants such as *Spathiphyllum blandum*, PET, and tezontle substrates have been implemented, demonstrating variable efficiencies in the removal of pollutants, such as Biochemical Oxygen Demand (BOD), nitrogen, phosphorus, and fecal coliforms. In the Actopan River Basin, hydrogeochemical and isotopic analyses have been used to determine the origin and circulation of groundwater and identify the influences of both local recharge and deep flows. Studies on the impact of agricultural activities, such as the citrus industry in the Filobobos River, have used physicochemical analyses to evaluate the water quality and propose sustainable management strategies. In addition, research on land use change along the Gulf of Mexico coast has used spatial analysis to assess the loss of ecosystem services. These studies demonstrate the need for comprehensive approaches adapted to the specific characteristics of each water body and region, highlighting knowledge gaps that require attention in future local research.

Table 4. Methodological approaches for water quality assessment in Veracruz's aquatic systems.

No.	Systems or Water bodies	Spatial/regional approach	Methodology used	Reference
1	CWs	Community of Pastorías, Actopan	Mesocosm design with alternative materials and ornamental plants.	Sandoval-Herazo *et al*. (2016)
2	CWs	Veracruz	Evaluation of removal efficiency with ornamental species and PET/tezontle substrates.	Sandoval *et al*. (2020)
3	Filobobos River	Regional sub-basin	Physicochemical analysis of water for industrial impact (citrus).	Sandoval-Herazo *et al*. (2024)
4	Topiltepec River (Actopan)	Hydrographic sub-basin	Physicochemical water quality diagnosis (pH, nutrients, coliforms, etc.).	Arrechea *et al*. (2023)
5	Actopan River Basin	Watershed approach	Hydrogeochemical and isotopic analysis to determine the origin of groundwater.	Pérez-Quezadas *et al.* (2017)
6	Nautla River	Watershed	Analysis of the relationship between land use and landslide processes.	De la Rosa and Valdés (2021)
7	Pixquiac River Basin	Urban Supply Basin (Xalapa)	Sediment and water quality analysis (nutrients, metals, etc.).	Dupont *et al*. (2024)
8	CWs	Veracruz (rural)	Evaluation of pollutant removal efficiency in hybrid wetlands (with swine wastewater).	Monteagudo-Hernández *et al*. (2024)
9	Coastal wetlands	Gulf of Mexico coastal zone	Land use change modeling and ecosystem vulnerability analysis.	Mendoza-González *et al*. (2012); Vázquez-González *et al*. (2014)
10	Central mountain region	Microbasins of Veracruz	Hydrological modeling and correlation with land use changes.	Muñoz *et al.* (2011)
11	Topilejo–Actopan Basin	Xalapa–Actopan region	Social perception analysis and economic studies on hydrological services.	McGinnis *et al*. (2021); Von Thaden, Manson, Congalton, López, and Jones (2021)
12	Large-scale wetlands	Veracruz state	Technical and management review of large-scale artificial wetlands.	Martínez-Aguilar *et al*. (2024)
13	Rivers and streams (coffee-growing area)	Central mountainous region (Veracruz)	Evaluation of bioindicator organisms (Odonata larvae) for water quality.	García *et al*. (2017)
14	Coastal mangroves	Southern Gulf of Mexico	Spatio-temporal analysis of nitrogen pollution (remote sensing and field sampling).	Temino-Boes, Romero, and Romero (2019)
15	General (multi-bodies)	Veracruz state	Review of water governance and civil society participation in urban watersheds.	Cloter *et al*. (2022)

Recent studies on wetlands, water quality, and ecosystem services in Veracruz have employed mixed methodologies that combine qualitative and quantitative approaches, as shown in Table 5. Techniques such as spatial analysis using Geographical Information Systems (GIS), social perception studies, field experiments with CWs, and statistical methods such as multivariate analysis, ANOVA, t-tests, and correlation analysis have been used.

Table 5. Methodologies and Analysis in Studies on Wetlands, Water Quality, and Ecosystem Services in Veracruz.

Methodological Approach	Methods / Techniques	Type of Analysis	Regional context	Reference
Quantitative Experimental	Microcosms/mesocosms, measurement of parameters	ANOVA, significance, and correlation tests	Constructed wetlands for wastewater treatment in rural communities of Veracruz.	Sandoval-Herazo *et al*. (2018, 2020) and Hernández-Sampieri, Fernádez, and Baptista (2014)
Quantitative with hydrological data	Water sampling, physico-chemical, and biological analysis	Descriptive and multivariate statistics	Watersheds (Actopan, Pixquiac, south-central Veracruz).	Marín-Muñíz *et al*. (2022), Pérez-Quezadas *et al*. (2017) y Mokondoko *et al*. (2016)
Economic / Preference assessment	Surveys, discrete choice models	Econometric models	Veracruz, rural and semi-urban areas, with hydrological services programs.	McGinnis *et al*. (2021)
Spatial y GIS	Remote sensing, multitemporal analysis of imagery	Spatial analysis, change of coverage	Gulf Coast, coastal basins of Veracruz.	Mendoza-González *et al*. (2012), Von Thaden *et al*. (2014) and Vázquez-González *et al*. (2014)
Evaluation of Ecosystem Services	Economic valuation, interviews, and spatial analysis	Integrated quantitative/ qualitative	Coastal areas of the Gulf of Mexico, central Veracruz.	Mendoza-González *et al*. (2012) and Von Thaden *et al*. (2021)
Participatory / Socio-ecological	Interviews, surveys, and participant observation	Qualitative analysis and descriptive frequencies	Cuenca baja del Papaloapan, zonas urbanas y periurbanas.	Escamilla-Pérez *et al*. (2024) and Cloter *et al*. (2022)
Hydrogeochemical / Isotopic	Deep sampling, isotope analysis, and geochemistry	Principal Component Analysis (PCA)	Hydrographic basin of the Actopan River, Veracruz.	Pérez-Quezadas *et al*. (2017)
Vulnerability assessment	Scenarios and spatial analysis with GIS	Risk mapping, qualitative/ quantitative analysis	Coastal municipalities of the Mexican tropics.	Vázquez-González *et al*. (2014)
Spatiotemporal with an environmental focus	Remote sensing and time series	Temporal analysis and correlations	Mangrove coastal region of the southern Gulf of Mexico.	Temino-Boes *et al*. (2019)

These approaches have allowed us to comprehensively address the relationships between land use, water quality, and ecosystem functionality in different regional contexts of the state, from watersheds to coastal zones. Using robust statistical tools has been key to validating results and proposing evidence-based, sustainable solutions.

The growing problem of water pollution in local contexts, such as the Misantla River and Veracruz River, highlights the urgency of developing rigorous scientific studies that analyze the sources, patterns, and drivers of pollutants in river ecosystems. However, these studies need to be turned into practical management and mitigation actions that enhance water quality and support the health of communities relying on these resources. Such research is essential for understanding the interaction between human activities such as urban, agricultural, and industrial land use and water quality, especially in regions where data are scarce or scattered. The implementation of integrated methodologies, which combine multivariate statistical analysis, geospatial tools, and monitoring of physicochemical and biological parameters, allows the precise identification of the determinants of pollution. These studies not only strengthen scientific knowledge on the environmental dynamics of watersheds but also generate key inputs to design strategies for sustainable management, impact mitigation, and conservation of water resources. They also provide scientific evidence for developing more effective public policies and informed community actions that align with national and international environmental priorities.

From this perspective, a review of studies on water quality and ecosystem services in Veracruz shows significant progress in applying diverse methodological approaches, both qualitative and quantitative, that respond to the ecological and social complexities of water bodies in the region. From CWs to watersheds and coastal zones, research has used tools such as multivariate statistical analysis, hydrogeochemical studies, spatial modeling, and community participation to address challenges related to water pollution and loss of ecosystem functionality.

However, there are still information gaps and areas with limited research coverage. This reinforces the need to promote comprehensive studies with interdisciplinary approaches and basin scales, considering the territories' socio-environmental dynamics. The articulation between science, public policy, and social participation will be key to advancing towards more equitable and sustainable water management in Veracruz.

CONCLUSIONS

This systematic review identified the region's main challenges regarding water pollution, its sources, impacts, and the methodologies used for its study. The findings showed that the primary sources of contamination were untreated wastewater discharge, intensive use of fertilizers and pesticides, deforestation, and uncontrolled urban expansion. These activities affect the water quality and functionality of strategic ecosystems, such as rivers and wetlands, both natural and constructed.

Methodologically, the studies reviewed have employed both qualitative and quantitative approaches: physicochemical, hydrogeochemical, and isotopic analyses; design of mesocosms in CWs; spatial modeling using GIS; social perception surveys; and economic studies on ecosystem services. The integration of these techniques has made it possible to address the problem from ecological, technical, and social perspectives. However, relevant knowledge gaps were identified, especially the lack of continuous monitoring, scarce multiscale integration, and limited coverage in rural micro-watersheds such as the Misantla River.

Therefore, it is recommended that research be strengthened by combining robust statistical tools, geospatial monitoring, and community participation. Studies use a basin approach that incorporates socio-environmental variables and considers that specific territorial dynamics must be promoted. It is also necessary to evaluate and transfer sustainable technologies such as CWs by adapting them to local contexts through participatory management strategies.

Finally, articulation between science, public policy, and social actors is crucial for improving water management. This review's results can serve as a basis for developing more comprehensive environmental policies and as a key input for environmental education programs, ecological restoration projects, and financing schemes that promote water sustainability in Veracruz.

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CONSENT FOR PUBLICATION

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AVAILABILITY OF SUPPORTING DATA

Not applicable.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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REFERENCES

Agrawal, S., Oza, P., Kakkar, R., Tanwar, S., Jetani, V., Undhad, J., & Singh, A. (2024). Analysis and recommendation system-based on PRISMA checklist to write systematic review. *Assessing Writing*, *61*, 100866. https://doi.org/10.1016/J.ASW.2024.100866

Aguilar-Aguilar, A., de León-Martínez, L. D., Forgionny, A., Acelas Soto, N. Y., Mendoza, S. R., & Zárate-Guzmán, A. I. (2023). A systematic review on the current situation of emerging pollutants in Mexico: A perspective on policies, regulation, detection, and elimination in water and wastewater. *Science of The Total Environment*, *905*, 167426. https://doi.org/10.1016/J.SCITOTENV.2023.167426

Anh, N. T., Can, L. D., Nhan, N. T., Schmalz, B., & Luu, T. Le. (2023). Influences of key factors on river water quality in urban and rural areas: A review. *Case Studies in Chemical and Environmental Engineering*, *8*, 100424. https://doi.org/10.1016/J.CSCEE.2023.100424

Aragón, C. A., López, H. J. R., Ávila, F. O., Aragón, C. A., López, H. J. R., & Ávila, F. O. (2022). Agua subterránea en Norteamérica, un caso de estudio: riesgo de contaminación y uso de los manantiales en San Simón Almolongas, Oaxaca, México. *Norteamérica*, *17*(1), 1-26. https://doi.org/10.22201/CISAN.24487228E.2022.1.522

Arrechea-Villacampa, A., Gómez-Urquiola, R., Muñoz-Aguilar, C. L., Marín-Muñiz, J. L., & Zamora, S. (2023). Diagnóstico de calidad del agua del río Topiltepec, afluente de la cuenca Actopan. *RINDERESU, 8*(1-2), 95-107.

Ballut-Dajud, G. A., Sandoval Herazo, L. C., Fernández-Lambert, G., Marín-Muñiz, J. L., López Méndez, M. C., & Betanzo-Torres, E. A. (2022). Factors affecting wetland loss: A review. *Land*, *11*(3), 434.https://doi.org/https://doi.org/10.3390/land11030434

Bamal, A., Uddin, M. G., & Olbert, A. I. (2025). Assessing the impact of hydro-climatic factors on surface water quality: A global review and synthesis. *Journal of Hydrology: Regional Studies*, *61*, 102677. https://doi.org/10.1016/j.ejrh.2025.102677

Bănăduc, D., Simić, V., Cianfaglione, K., Barinova, S., Afanasyev, S., Öktener, A., ... & Curtean-Bănăduc, A. (2022). Freshwater as a Sustainable Resource and Generator of Secondary Resources in the 21st Century: Stressors, Threats, Risks, Management and Protection Strategies, and Conservation Approaches. *International Journal of Environmental Research and Public Health*, *19*(24), 16570. https://doi.org/10.3390/IJERPH192416570

Castañeda-Chávez, M. del R., & Lango-Reynoso, F. (2022). Impact of the Jamapa River Basin on the Gulf of Mexico. En *River deltas research recent advances* (pp. 1-16). London, United Kingdom: IntechOpen. https://doi.org/10.5772/intechopen.97021

Cloter, H., Cuevas, M. L., Landa, R., & Frausto, J. M. (2022). Environmental governance in urban watersheds: the role of civil society organizations in Mexico. *Sustainability, 14*(2), 988.https://doi.org/https://doi.org/10.3390/su14020988

CONAGUA (Comisión Nacional del Agua). (2021). Programa Hídrico Regional 2021-2024: Región Hidrológico-Administrativa X (Golfo-Centro). Consulted on August 15, 2024, retrieve from https://www.gob.mx/conagua

CONAGUA (Comisión Nacional del Agua). (2023). Comisión Nacional del Agua. Estadísticas del agua en México 2023. Ciudad de México. Consulted on August 15, 2024, retrieve from https://www.gob.mx/conagua

CONAGUA (Comisión Nacional del Agua). (2024). Inventario de Plantas Municipales de Potabilización y de Tratamiento de Aguas Residuales en Operación. Consulted on August 15, 2024, retrieve from https://www.gob.mx/conagua/documentos/inventario-de-plantas-municipales-de-potabilizacion-y-de-tratamiento-de-aguas-residuales-en-operacion

Cooper, C., Finzi, J., Hasbrouck, J., & Todd, V. (2004). *A case study of sustainability: Jalcomulco, Veracruz*. Los Angeles, CA, USA: Center for Sustainable Cities, University of Southern California,

Cruz-Falcón, A., Troyo-Diéguez, E., Murillo-Jiménez, J. M., García-Hernández, J. L., & Murillo-Amador, B. (2018). Familias de agua subterránea y distribución de sólidos totales disueltos en el acuífero de La Paz Baja California Sur, México. *Terra Latinoamericana, 36*(1), 39-48. https://doi.org/10.28940/terra.v36i1.316

Dash, S., & Kalamdhad, A. S. (2021). Science mapping approach to critical reviewing of published literature on water quality indexing. *Ecological Indicators*, *128*, 107862. https://doi.org/10.1016/J.ECOLIND.2021.107862

De la Rosa Portilla, A., & Valdés Rodríguez, O. A. (2021). Usos de suelo y su relación con procesos de remoción en masa en la cuenca del río Nautla, Veracruz, México. En *Miradas colectivas, rutas y aportes a la sustentabilidad* (49 pp). Xalapa, Veracruz, México: Secretaría de Medio Ambiente del Estado de Veracruz. ISBN 978-607-8716-43-2

Dupont, M. C., Martinez-Tavera, E., Rodriguez-Espinosa, P. F., Hernandez-Ramirez, A. G., & Guadarrama Guzmán, P. (2024). Sediment analysis and water quality assessment in the Pixquiac basin: drinking water supply of Xalapa city (Veracruz, Mexico). *Environmental Monitoring and Assessment, 196*(8), 687. https://doi.org/10.1007/s10661-024-12841-6

Escamilla-Pérez, B. E., Hernández-Velasco, M. J., León-Estrada, X. del A., & López-Rosas, H. (2024). The use of wetlands by fishermen in the region of the Lower Papaloapan River Basin (Veracruz, Mexico). *Wetland Science & Practice, 42*(3), 242-253. https://doi.org/10.1672/UCRT083-625

FAO (Food and Agriculture Organization of the United Nations). (2018). Retornos de escorrentía agrícola y aguas residuales urbanas en los sistemas hídricos: estimaciones globales. Rome Italy: FAO

García-García, P. L., Vázquez, G., Novelo-Gutiérrez, R., & Favila, M. E. (2017). Effects of land use on larval Odonata assemblages in cloud forest streams in central Veracruz, Mexico. *Hydrobiologia*, *785*(1), 19–33. https://doi.org/10.1007/s10750-016-2900-x

García-García, P. L., Ruelas-Monjardín, L., & Marín-Muñíz, J. (2016). Constructed wetlands: a solution to water quality problems in Mexico? *Water Policy, 18*(3), 654-669. https://doi.org/https://doi.org/10.2166/wp.2015.172

González, V. F. J., Rodríguez, M. R., Arreguín, C. F., Fuentes, M. J., & Arriaga, M. J. A. (2025). *Retos y oportunidades para la seguridad hídrica en el sureste de México: Chiapas, Tabasco y Veracruz*. Veracruz, México: UNAM

Hernández-Sampieri, R., Fernández, C. C., & Baptista, L. M. del P. (2014) *Metodología de la Investigación*. (6ª). D.F., México: Mc Graw Hill Education/Interamericana editores, S.A. de C.V.

Higgins, J. P. T., Thomas, J., Chandler, J., Cumpston, M., Li, T., Page, M. J., & Welch, V. A. (2019). *Cochrane Handbook for Systematic Reviews of Interventions* (2ª ed.). Hoboken, NJ, USA: John Wiley & Sons.

Huang, J., Zhang, Y., Bing, H., Peng, J., Dong, F., Gao, J., & Arhonditsis, G. B. (2021). Characterizing the river water quality in China: Recent progress and on-going challenges. *Water Research, 201*, 117309. https://doi.org/10.1016/J.WATRES.2021.117309

Hudson, P. F., Hendrickson, D. A., Benke, A. C., Varela-Romero, A., Rodiles-Hernández, R., & Minckley, W. L. (2005). Rivers of Mexico. En A. C. Benke & C. E. Cushing (Eds.). *Rivers of North America* (pp. 1031–1085). San Diego, CA, USA: Elsevier Academic Press.

Hutton, B., Catalá-López, F., & Moher, D. (2016). La extensión de la declaración PRISMA para revisiones sistemáticas que incorporan metaanálisis en red: PRISMA-NMA. *Medicina Clínica*, *147*(6), 262–266. https://doi.org/10.1016/J.MEDCLI.2016.02.025

INEGI (Instituto Nacional de Estadística y Geografía). (2023). *Censo Agropecuario 2022. Resultados definitivos. Veracruz de Ignacio de la Llave*. Consulted on August 15, 2024, retrieve from https://www.inegi.org.mx/programas/cagf/2022/

Madrid, E., Sampedro, Ma. L., Maganda, Ma. del C., Juárez, A. L., Reyes, M., & González, J. (2024). Calidad del agua superficial en la cuenca del Río Atoyac, Guerrero México. *Tecnología y Ciencias Del Agua*, 01-57. https://doi.org/10.24850/J-TYCA-16-4-8

Maldonado, T., Alfaro, E. J., & Hidalgo, H. G. (2018). A review of the main drivers and variability of Central America's Climate and seasonal forecast systems. *Revista de Biología Tropical*, *66*(S1), S153-S175. https://doi.org/10.15517/RBT.V66I1.33294

Marín-Muñíz, J. L., Sandoval-Herazo, L. C., Zamora-Castro, S. A., & Celis-Pérez, M. del C. (2022). Humedales con plantas ornamentales y relleno de plástico reutilizado como tratamiento sustentable de aguas residuales. *Journal of Basic Sciences*, *8*(23), 146-153.

Martínez-Aguilar, K. E., Marín-Muñiz, J. L., Álvarez-Hernández, L. M., Delfín-Portela, E., & Zamora-Castro, S. A. (2024). Current status of wastewater treatment through large-scale treatment wetlands in the State of Veracruz, Mexico. *Renewable Energy, Biomass & Sustainability, 6*(2), 32-42. https://doi.org/https://doi.org/10.56845/rebs.v6i2.105

McGinnis, I., Shady S, A., & Ju-Chin, H. (2021). Household preferences for hydrological services in Veracruz, Mexico: The importance of results versus program design. *Journal of Environmental Management*, *300*, 113763. https://doi.org/https://doi.org/10.1016/j.jenvman.2021.113763

Megchún-García, J. V., Landeros-Sánchez, C., Soto-Estrada, A., Castañeda-Chávez, M., Martínez-Dávila, J. P., Nikolskii-Gavrilov, I., ... & Lango-Reynoso, F. (2015). Total, coliforms and Escherichia coli in surface and subsurface water from a sugarcane agroecosystem in Veracruz, Mexico. *Journal of Agricultural Science, 7*(6), 110. https://doi.org/10.5539/jas.v7n6p110

Melijosa, I. S., Pino, J. F. B., & Del Valle Tuero, E. (2022). Análisis de la investigación sobre destinos turísticos inteligentes mediante la visualización de redes bibliométricas. *Investigaciones Turísticas, 23*, 266-289. https://doi.org/10.14198/INTURI2022.23.12

Mendelssohn, I. A., Byrnes, M. R., Kneib, R. T., & Vittor, B. A. (2017). Coastal Habitats of the Gulf of Mexico. In *Habitats and Biota of the Gulf of Mexico: Before the Deepwater Horizon Oil Spill* (pp. 359–640). New York, NY, USA: Springer https://doi.org/10.1007/978-1-4939-3447-8_6

Mendoza-González, G., Martínez, M. L., Lithgow, D., Pérez-Maqueo, O., & Simonin, P. (2012). Land use change and its effects on the value of ecosystem services along the Gulf of Mexico coast. *Ecological Economics, 82,* 23-32. https://doi.org/https://doi.org/10.1016/j.ecolecon.2012.07.018

Mishra, R. K. (2023). Fresh Water availability and Its Global challenge. *British Journal of Multidisciplinary and Advanced Studies*, *4*(3), 1-78. https://doi.org/10.37745/BJMAS.2022.0208

Monteagudo-Hernández, G., Hernández-Castelán, D. A., Zamora-Lobato, T., Sandoval-Herazo, M., Hernández-Orduña, M. G., & Herazo, L. C. S. (2024). Evaluation of the pollutant removal efficiency of swine wastewater through two configurations of hybrid wetlands with tropical ornamental plants. *Results in Engineering, 24*, 102864.

Morales-Mora, M. A., Rodríguez-Pérez, B., Martínez-Delgadillo, S. A., Rosa-Domínguez, E., & Nolasco-Hipólito, C. (2014). Human and ecotoxicological impacts assessment from the Mexican oil industry in the Coatzacoalcos region, as revealed by the USEtox model. *Environmental Science and Pollution Research, 21*(16), 9819–9831. https://doi.org/10.1007/s11356-014-2942-4

Mokondoko, P., Manson, R. H., & Pérez-Maqueo, O. (2016). Assessing the service of water quality regulation by quantifying the effects of land use on water quality and public health in central Veracruz, Mexico. *Ecosystem Services*, *22*, 161-173. https://doi.org/10.1016/J.ECOSER.2016.09.001

Muñoz, V. L. E., Equihua, M., Tobón, C., & Gutiérrez-Mendieta, F. J. (2011). Effects of Land Use in the Hydrology of Montane Catchments in Central-eastern Mexico. *In Water Resources in Mexico* (pp. 155-166). Heidelberg, Berlin, Germany: Springer. https://doi.org/10.1007/978-3-642-05432-7_11

Nava-López, M., Selfa, T. L., Cordoba, D., Pischke, E. C., Torrez, D., Ávila-Foucat, S., ... & Maganda, C. (2018). Decentralizing payments for hydrological services programs in Veracruz, Mexico: Challenges and implications for long-term sustainability. *Society & Natural Resources, 31*(12), 1389-1399. https://doi.org/10.1080/08941920.2018.1463420

Ngamile, S., Madonsela, S., & Kganyago, M. (2025). Trends in remote sensing of water quality parameters in inland water bodies: a systematic review. *Frontiers in Environmental Science*, *13*, 1549301. https://doi.org/10.3389/FENVS.2025.1549301

Oropeza-Orozco, O., Sommer-Cervantes, I., Carlos-Gómez, J., Preciado-López, J. C., Ortiz-Pérez, M. A., & Lopez-Portillo, J. (2011). Assessment of Vulnerability and Integrated Management of Coastal Dunes in Veracruz, Mexico. *Coastal Management*, *39*(5), 492-514. https://doi.org/10.1080/08920753.2011.598817

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., ... & Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*, 372. https://doi.org/10.1136/BMJ.N71

Peralta-Vega, A. J., Vergara-Flórez, V., Marín-Peña, O., García-Aburto, S. G., & Sandoval-Herazo, L. C. (2024). Treatment of Domestic Wastewater in Colombia Using Constructed Wetlands with Canna Hybrids and Oil Palm Fruit Endocarp. *Water*, *16* (16), 2290. https://doi.org/10.3390/W16162290

Pérez-Quezadas, J., Cortés-Silva, A., Salas-Ortega, M. D. R., Araguás-Araguás, L., Morales-Puente, P., & Carrillo-Chávez, A. (2017). Evidencias hidrogeoquímicas e isotópicas sobre el origen del agua subterránea en la cuenca hidrográfica Río Actopan, Estado de Veracruz. *Revista Mexicana de Ciencias Geológicas, 34*(1), 25-37. http://dx.doi.org/10.22201/cgeo.20072902e.2017.1.467

Sánchez, S. S., Pedraza, N. I., & Donoso, G. M. (2022). ¿Cómo hacer una revisión sistemática siguiendo el protocolo PRISMA?: Usos y estrategias fundamentales para su aplicación en el ámbito educativo a través de un caso práctico. *Bordón: Revista de Pedagogía*, *74*(3), 51-66. https://doi.org/10.13042/Bordon.2022.95090

Sandoval-Herazo, L. C., González-Moreno, H. R., Carreto-Hernandez, L. G., Zurita, F., Nani, G., Zamora, S., ... & Martínez-Reséndiz, G. (2024). Impact of the Citrus Industry on the Water Quality of the Filobobos River in Veracruz, Mexico. *Sustainability, 16*(4), 1536. https://doi.org/10.3390/SU16041536

Sandoval-Herazo, L. C., Marín-Muñiz, J. L., Alvarado-Lassman, A., Castelán, R., & Ramírez-López, D. (2016). Diseño de un mesocosmo de humedal construido con materiales alternativos para el tratamiento de aguas residuales en la comunidad de Pastorías, Actopan, Ver. En *Actas del Congreso Interdisciplinario de Ingenierías*. Actopan, Hidalgo, México: Congreso Interdisciplinario de Ingenierías.

Sandoval, L., Zurita, F., Del Ángel-Coronel, O., Adame-García, J., & Marín-Muñiz, J. L. (2020). Influence of a new ornamental species (Spathiphyllum blandum) on the removal of COD, nitrogen, phosphorus and fecal coliforms: A study in a mesocosm wetland with PET and tezontle substrates. *Water Science and Technology*, *81*(5), 961-970. https://doi.org/https://doi.org/10.2166/wst.2020.185

Sandoval-Herazo, L. C., Alvarado-Lassman, A., Marín-Muñiz, J. L., Méndez-Contreras, J. M., & Zamora-Castro, S. A. (2018a). Effects of the use of ornamental plants and different substrates on the removal of wastewater contaminants through constructed wetland microcosms. *Sustainability, 10*(5), 1594.https://doi.org/https://doi.org/10.3390/su10051594

Sandoval-Herazo, L. C., Alvarado-Lassman, A., Marín-Muñiz, J. L., Méndez-Contreras, J. M., Martínez-Sibaja, A., & Aguilar-Lasserre, A. (2018b). Desarrollo de plantas ornamentales terrestres en microcosmos de humedales construidos. En *Investigación en el sistema de educación superior tecnológica del estado de Veracruz* (p. 124). Xalapa, Veracruz, México: Instituto Tecnológico Superior de Xalapa. ISBN: 978-607-8212-09-5

Sandoval-Herazo, M., Nani, G., Sandoval, L., Rivera, S., Fernández-Lambert, G., & Alvarado-Lassman, A. (2020). Evaluation of the performance of vertical partially saturated constructed wetlands for sewage treatment swine. *Tropical and Subtropical Agroecosystems, 23*(2), 38. https://doi.org/10.56369/tsaes.3138

Secretaría de Salud de Veracruz. (2020, 15 de marzo). Reportan 20 personas intoxicadas con agua contaminada en Veracruz. Milenio. https://www.milenio.com/estados/reportan-20-personas-intoxicadas-agua-contaminada-veracruz

Shi, X., Mao, D., Song, K., Xiang, H., Li, S., & Wang, Z. (2024). Effects of landscape changes on water quality: A global meta-analysis. *Water Research*, *260*, 121946. https://doi.org/10.1016/J.WATRES.2024.121946

Singh, G., Chaudhary, S., Giri, B. S., & Mishra, V. K. (2025). Assessment of geochemistry and irrigation suitability of the River Ganga, Varanasi, India: PCA reduction for water quality index and health risk evaluation. *Environmental Science and Pollution Research, 32*(7), 4199-4218.

Siqueira, T. D. S., Pessoa, L. A., Vieira, L., Cionek, V. D. M., Singh, S. K., Benedito, E., & do Couto, E. V. (2023). Evaluating land use impacts on water quality: perspectives for watershed management. *Sustainable Water Resources Management*, *9*(6), 1-24. https://doi.org/10.1007/S40899-023-00968-2

Tamayo y Tamayo, M. (2004). *El proceso de la investigación científica*. D. F., México: Limusa.

Tariq, A., & Mushtaq, A. (2023). Untreated Wastewater Reasons and Causes: A Review of Most Affected Areas and Cities. *International Journal of Chemical and Biochemical Sciences*, *23*(1), 121-143.

Temino-Boes, R., Romero-López, R., & Romero, I. (2019). A spatiotemporal analysis of nitrogen pollution in a coastal region with mangroves of the southern Gulf of Mexico. *Water, 11*(10), 2143. https://doi.org/https://doi.org/10.3390/w11102143

Torres-Beristáin, B., González, L. G., Rustrián, P. E., & Houbron, E. (2013). Enfoque de cuenca para la identificación de fuentes de contaminación y evaluación de la calidad de un río, Veracruz, México. *Revista Internacional de Contaminación Ambiental*, *29*(3), 135–146.

Uddin, M. G., Nash, S., Rahman, A., & Olbert, A. I. (2022). A comprehensive method for improvement of water quality index (WQI) models for coastal water quality assessment. *Water Research*, *219*, 118532. https://doi.org/10.1016/J.WATRES.2022.118532

Valdespino, C., Guillen-Guillen, Z. G., Albino-Miranda, S., von Osten, J. R., & Vázquez, G. (2024). Spatiotemporal distribution of organochlorine pesticides in the upper La Antigua watershed, Veracruz Mexico. *Scientific Reports, 14*(1), 25084. https://doi.org/10.1038/s41598-024-77223-x

Van Eck, N., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics, 84*(2), 523-538. https://doi.org/10.1007/s11192-009-0146-3

Vázquez-González, C., Fermán-Almada, J. L., Moreno-Casasola, P., & Espejel, I. (2014). Vulnerability scenarios in coastal municipalities of the Mexican tropics: an analysis of land use in wetlands. *Ocean & Coastal Management*, *89*, 11-19. https://doi.org/10.1016/j.ocecoaman.2013.12.004

Villers, L. E. M., Equihua, M., Tobón, C., & Gutiérrez-Mendieta, F. J. (2011). Effects of land use in the hydrology of montane catchments in central-eastern Mexico. En U. Oswald Spring (Ed.). *Water Resources in Mexico: Scarcity, degradation, stress, conflicts, management, and policy* (pp. 155–166). Berlin; Heidelberg, Germany: Springer. https://doi.org/10.1007/978-3-642-05432-7_11

Von Thaden, J., Manson, R. H., Congalton, R. G., López-Barrera, F., & Jones, K. W. (2021). Evaluating the environmental effectiveness of payments for hydrological services in Veracruz, México: A landscape approach. *Land Use Policy, 100*, 105055. https://doi.org/10.1016/j.landusepol.2020.105055

Yan, T., Shen, S. L., & Zhou, A. (2022). Indices and models of surface water quality assessment: Review and perspectives. *Environmental Pollution*, *308*, 119611. https://doi.org/10.1016/J.ENVPOL.2022.119611