JWMM

Occupational Health Risks for Shrimp Farm Workers Exposed to Seasonal Fecal Contamination in Nayarit Estuarine Waters

Kenia Sarai Arce-Navarro[1], Gloria Marisol Castañeda-Ruelas[2], Francisco Javier Valdez-González[1], and Maribel Jiménez-Edeza[2] (2026)

[1]Escuela Nacional de Ingeniería Pesquera, Universidad Autónoma de Nayarit, Bahía de Matanchén San Blas, Nayarit, México

[2]Laboratorio de Investigación y Diagnóstico Microbiológico, Facultad de Ciencias Químico-Biológicas, Universidad Autónoma de Sinaloa, Culiacán, Sinaloa, México

DOI: https://doi.org/10.14796/JWMM.C582

ABSTRACT

Anthropogenic discharges into coastal waters introduce fecal pathogens that threaten both aquaculture sustainability and human health. In shrimp farming, workers are frequently exposed to contaminated estuarine water, underscoring the importance of evaluating occupational health risks. This study assessed fecal contamination in estuarine water used for shrimp aquaculture in San Blas, Nayarit, Mexico, and estimated the probability of gastrointestinal infection (GI) of shrimp farm workers across dry and rainy seasons under two exposure scenarios: immersion (INM) and hand-to-mouth contact (HMC). *Escherichia coli* (EC) and *Enterococcus* (ENT) were used as microbial indicators in a quantitative microbial risk assessment model. A total of 56.7% and 96.7% of samples (n = 30) exceeded recommended limits for EC (1.00×10^3 CFU/100 mL) and ENT (35 CFU/100 mL), respectively. Microbial loads did not differ significantly among sites ($p > 0.05$) but showed seasonal variation ($p < 0.05$). The highest GI risk was associated with INM exposure, particularly in the dry season for EC (1.65×10^{-1}) and in both seasons for ENT (5.47×10^{-1} to 5.96×10^{-1}). HMC exposure presented lower but notable risks, ranging from 1.89×10^{-4} to 6.78×10^{-5} for EC, and from 3.85×10^{-2} to 7.59×10^{-2} for ENT. Seasonal dynamics of contamination pose significant occupational health risks for shrimp farm workers and highlight the need to reinforce water quality management and safer aquaculture practices.

Arce-Navarro, K.S., G.M. Castañeda-Ruelas, F.J. Valdez-González, and M. Jiménez-Edeza. 2026. "Occupational Health Risks for Shrimp Farm Workers Exposed to Seasonal Fecal Contamination in Nayarit Estuarine Waters." *Journal of Water Management Modeling* 34: C582. https://doi.org/10.14796/JWMM.C582
www.chijournal.org ISSN: 2292-6062 © Arce-Navarro et al. 2026

1. INTRODUCTION

Aquaculture is among the fastest-growing food production industries worldwide, providing an important source of protein for human consumption (Ahmad et al. 2021). In Mexico, an annual aquaculture production of 404,551 tons has been reported, with shrimp being one of the main cultured species with 270,000 tons, recorded mainly in the states of Sonora, Sinaloa and Nayarit (Rodríguez-Camacho et al. 2014; Cortés et al. 2021).

Shrimp production has intensified in response to the rising global demand. As a result, it generates large volumes of effluents containing nutrients and emerging contaminants, which are often discharged uncontrollably into coastal waters (Ahmad et al. 2021). Additionally, coastal water quality is affected by human activities such as agricultural runoff, domestic water discharges, and inadequate wastewater treatment, altering physicochemical and microbiological conditions and ecological imbalance of water (Akita et al. 2021; Turcios et al. 2021; Mustafa et al. 2022). Besides, microbial water quality is strongly influenced by seasonal variation. During the rainy season, agricultural runoff and wastewater discharges increase the input of fecal microorganisms into estuarine systems, while the dry season is often characterized by higher salinity and temperature, conditions that may favour the persistence of pathogens (Rivas-Montaño et al. 2018; Gyraite et al. 2019). Consequently, shrimp farm workers are subject to different levels of microbial exposure depending on seasonal conditions. Despite efforts to maintain water quality through the implementation of wastewater treatment (Priya et al. 2018; Gupta et al. 2022), this objective has not yet been fully achieved.

For decades, exposure to water contaminated with infectious agents has been reported to represent a major cause of morbidity and mortality worldwide (Lee et al. 2023). The World Health Organization (WHO) estimates 842,000 deaths annually worldwide due to gastrointestinal diseases associated with water of inadequate quality. Of these, 59.61% (502,000 deaths) are attributed to ingesting unsafe water and 35.27% (297,000 deaths) to inadequate hand hygiene practice (WHO 2014). In Mexico, the DGE reported 4,203,260 cases of gastrointestinal infections (GI) in 2024, of which 63,302 cases occurred in Nayarit, making GI the second most frequent disease in the state (DGE 2025).

Previous epidemiological studies have reported the potential risk of GI associated with exposure to coastal recreational waters, where enteric pathogens (Astrovirus, Adenovirus, Norovirus, *Salmonella, Campylobacter, Shigella, Entamoeba, Cryptosporidium* and Giardia), fecal indicator organisms such as *Escherichia coli* (EC) and *Enterococcus* (ENT), and opportunists (*Vibrio parahaemolyticus, Vibrio cholerae* and *Vibrio vulnificus*) are detected at elevated levels (Jáuregui Medina et al. 2010; Huang et al. 2017; Noman et al. 2021; Vieira et al. 2022)

Regardless of its economic relevance, shrimp farming in estuarine environments involves close contact between workers and water bodies that may be contaminated with fecal microorganisms, creating potential occupational health risks that have received limited scientific attention. During pond harvesting, direct contact with seawater is a common practice that may involve exposure to contaminated water (Yajima and Kurokura 2008). According to INEGI, 33,768 individuals were employed in aquaculture and fisheries activities in 2019, of which 3,665 were active in Nayarit. These figures underscore the need to better understand potential occupational hazards in this sector and their broader social and public health implications. (Ponce Palafox et al. 2018; CESANAY 2023; INEGI 2021).

The World Health Organization (WHO) has recommended values lower than 1.00×10^3 CFU of EC per 100 mL of pond water to guarantee a risk of enteric infection of 1/10,000 exposed traders (i.e., 0.0001) (WHO 2006). The US Environmental Protection Agency (USEPA) points to ENT as a primary indicator in the context of seawater. It proposes geometric means of < 35 and < 30 CFU/100 mL for risks of 36 and 32 diseases per 1000 users, respectively, as an acceptable risk reference for primary contact during recreation (USEPA 2012; Sklar et al. 2023). In Mexican legislation, limits of 600 MPN /100 mL have been established for EC and ENT as a microbiological standard to evaluate the sanitary suitability of water discharges in maritime areas (DOF 2021).

In recent years, quantitative microbial risk assessment (QMRA) has become a tool for the development of management strategies to improve the safety of seawater and seafood. Research on opportunistic marine pathogens of fecal origin such as *Vibrio spp*., with important implications in the development of GI (USFDA 2005; FAO/WHO 2002; Malcolm et al. 2016; Huang et al. 2017; Noman et al. 2021) isolated from coastal water (Hernández-Díaz et al. 2015), coastal lagoons (Rivas-Montaño et al. 2018) and estuaries (Rodríguez-Camacho et al. 2014) of Baja California Sur, Sinaloa, and Nayarit, have been published. However, these types of investigations tend to be expensive and time-consuming (Denissen et al. 2023). Consequently, information can be sparse and discontinuous for a QMRA model (Federigi et al. 2020). Alternatively, the WHO recognizes the use of indicator bacteria to infer the presence of pathogens in environmental samples as an epidemiological basis (WHO 2016; Sklar et al. 2023).

EC and ENT are historically used as the basis for water quality standards (Sklar et al. 2023). Through review of multiple recreational epidemiological studies in marine waters with point sources of pollution, mathematical models have found a strong correlation between EC and ENT density and GI (Sunger and Haas 2015).

Although occupational exposure to contaminated water has been recognized in other contexts (Yajima and Kurokura 2008; Dorevitch et al. 2012; Abia et al. 2016; Zhang et al.

2019; Denissen et al. 2023; Sklar et al. 2023), little research has specifically addressed shrimp farm workers. Therefore, this study evaluates the seasonal variation of fecal contamination (EC and ENT) in estuarine waters used for shrimp farming in San Blas, Nayarit, while also estimating the occupational health risks for shrimp farm workers during rainy and dry seasons through quantitative microbial risk assessment (QMRA). Worker exposure was assessed considering the volume of water ingested by immersion (INM) and hand-to-mouth contact (HMC) during aquaculture activities. By combining microbial indicators with risk assessment models, this research aims to generate evidence to guide safer aquaculture practices and water management strategies that protect both human health and the sustainability of shrimp production.

2. MATERIALS AND METHODS

2.1 Study area

A cross-sectional study was conducted to comprehensively evaluate the microbiological quality of water for aquaculture use in the municipality of San Blas, Nayarit, Mexico. In total, 30 samples were collected at 15 sites (inlet channels) (Table 1) distributed in the towns of San Blas, La Chacalilla, and La Chiripa (Figure 1), measured twice and distributed in January–March (dry season) and in August–September (rainy season) 2023. The samples were transported to the laboratory for analysis immediately upon arrival.

Table 1 Location of farms in San Blas, Nayarit, México.

Fig. 1 ID	Location	Estuary	Site	Latitude (°N)	Longitude (°W)
1	San Blas	San Cristobal	Tsikuri	21.580348°	−105.286359°
2	La Chacalilla	San Cristobal	La Providencia	21.599018°	−105.272304°
3	La Chacalilla	Chacalilla	Gran Nayar	21.614054°	−105.287026°
4	La Chiripa	Papayitos	Plebes	21.606210°	−105.312713°
5	La Chiripa	La Poma	Venancio Torres	21.624632°	−105.305837°
6	La Chiripa	Papayitos	Lamosa 3	21.628427°	−105.341657°
7	La Chiripa	Papayitos	Lamosa 4	21.627143°	−105.334881°
8	La Chiripa	Papayitos	Callejones	21.621455°	−105.330929°
9	La Chiripa	Papayitos	Isla	21.613304°	−105.315383°
10	La Chiripa	Camaronai	Papayitos	21.620727°	−105.316175°
11	La Chiripa	Papayitos	Puntilla	21.623487°	−105.322604°
12	La Chiripa	Callejones	Familia	21.629705°	−105.323366°
13	La Chiripa	La Poma	Cocodrila	21.621082°	−105.302625°

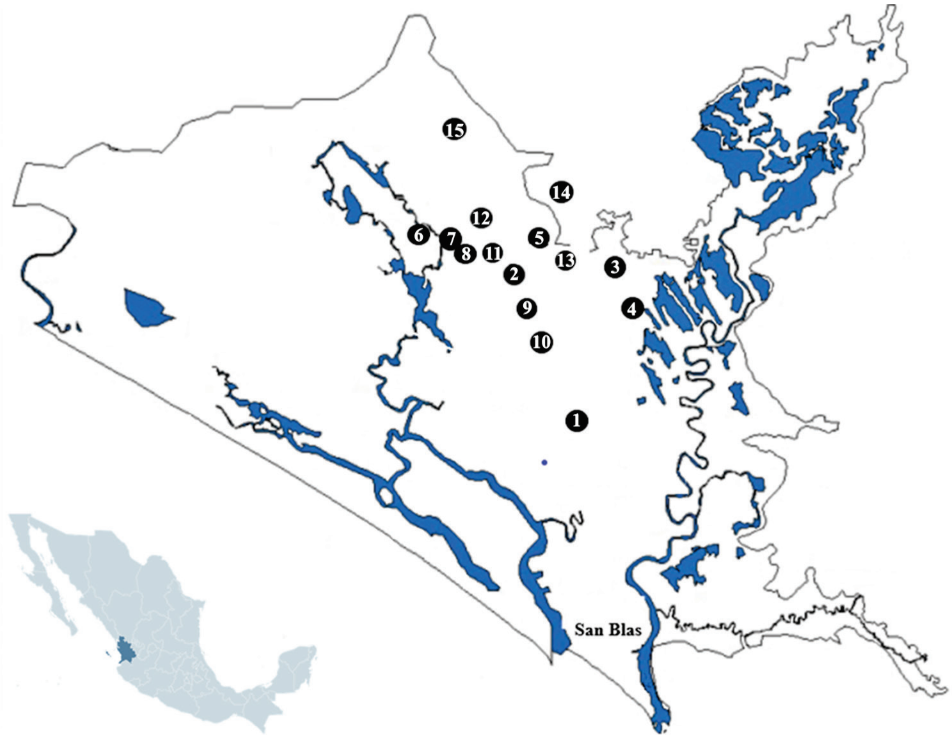

Figure 1 Map of the farms located in San Blas, Nayarit, Mexico.

NOTE: Numbers 1-15 correspond to the Site IDs detailed in Table 1.

2.2 Microbiological analysis

The simple membrane filtration protocol was used for four sample volumes (100, 10, 1, and 0.1 mL; lower volumes were filled to 10 mL with 1× PBS for uniform distribution on the filter). They were directly filtered through nitrocellulose filters (Milipore) of 0.45 µm pore size (47 mm diameter), transferred to mEndo agar plates (Difco, USA, # 273620) for E. coli (EC), Enterococcus Confirmatory Agar (Condalab, Spain, no. 1018) for ENT, and incubated for 18 to 24 hours at 37°C ± 1°C. Mean values were calculated and expressed as CFU/100 mL.

2.3 Water intake

Two different scenarios were used to calculate the ingestion rate (*I*): one of primary contact through breeding activity with immersion of the aquaculturist's body in shrimp production ponds (INM), where a uniform distribution was considered for *I*. (0−53 mL/h) (Bortagaray et al. 2022); and the other from secondary contact, due to hand-to-mouth contact during harvest (HMC). The *I* due to wet hand-to-mouth contact (I_{HM}, in mL/h) was calculated (Poma et al. 2019) as follows:

$$I_{HM} = h \cdot A \cdot f_{HM} \tag{1}$$

Where:

h (cm) = thickness of the water film on the hands,
A (cm^2) = skin surface area of the hand that touched the mouth, and
f_{HM} (number/h) = frequency of hand-to-mouth contact (Poma et al. 2019).

For the simulations, h and A were considered to have a uniform distribution between 0.00197 and 0.00234, and between 1 and 20, respectively. For f_{HM}, a Gamma distribution was considered, with the shape parameter equal to 2 and the scale parameter equal to 0.5 (Poma et al. 2019).

For exposure assessment, the ingestion rate (mL/h) was converted to total ingested volume by multiplying by exposure time (t, h), allowing estimation of water intake per exposure event under each scenario.

2.4 Exposure analysis

The exposure of the workers was estimated by multiplying the total volume of water ingested for both scenarios and the microbial concentration quantified in the present investigation.

Since ingestion was initially expressed as a rate (mL/h), the total ingested volume was calculated by incorporating exposure time (t, h), allowing estimation of intake per exposure event.

The exposure dose was calculated separately for each scenario in Equations 2 and 3:

$$D = I \cdot C \cdot t \tag{2}$$

$$D = I_{HM} \cdot C \cdot t \tag{3}$$

Where:

D = exposure dose,
I = volume of water ingested by immersion (mL/h),
I_{HM} = volume of water ingested by hand-to-mouth contact (mL/h),
C = bacterial concentration, and
t = exposure time (h/event).

2.5 Dose-response model and hazard characterization

With the purpose of evaluating the Dose-Response, a relationship was established between the level of microbial exposure and the probability of occurrence of an adverse health effect given the intake during aquaculture activities. The risk assessment was determined by developing the mathematical function β-Poisson (Equation 4) (Haas et al. 2014):

$$Pi = 1 - \left[1 + \frac{D}{N50}\left(2^{1/\alpha} - 1\right)\right]^{-\alpha} \quad (4)$$

Where:

Pi = probability of infection,

D (CFU/mL) = bacterial dose, and

a and $N50$ = model parameters that reflect the dose-response.

For EC, the values $a = 0.49$ and $N50 = 5.9\times10^5$ were considered; while $a = 0.312$, and $N50 = 236$ for ENT (Haas et al. 2014).

2.6 Data analysis

The indicator bacteria data were entered into a non-parametric Kruskal Wallis statistical test to determine the significant difference of the data in relation to their origin, and Mann-Whitney U to compare seasonality. Statistical tests were performed using Minitab 18 software with a confidence level of 95% and a significant value of $P < 0.05$. The QMRA was estimated using Oracle Crystal Ball software (vs.11.1.2.3.500).

3. RESULTS

Table 2 presents EC and ENT concentrations across dry and rainy seasons. EC levels were higher in the dry season (mean = 3217 CFU/100 mL) while ENT peaked in the rainy season (mean = 602 CFU/100 mL). Both indicators showed wide variability among sites, with many samples exceeding recommended thresholds (EC: 1.00×10^3 CFU/100 mL; ENT: 35 CFU/100 mL). Geometric means confirm higher ENT prevalence during rains, and extreme EC values in the dry season. The results indicate distinct seasonal dynamics, as EC was more abundant in the dry season, while ENT showed higher values in the rainy season; these findings could indicate that occupational exposure risks for shrimp farming workers vary seasonally, highlighting the need for targeted preventive measures.

Table 2 Descriptive statistics.

Season	Description	EC (CFU/100 mL)	ENT (CFU/100 mL)
Dry	Mean	3217	254
	Mínimum	600	15
	Median	1500	220
	Maximum	15,950	1040
	Geometric mean	–	258
Rainy	Mean	1156	602
	Mínimum	5	85
	Median	900	430
	Maximum	5400	1760
	Geometric mean	–	572

Figure 2 illustrates the EC and ENT concentrations across sampling sites during dry and rainy seasons. For EC (panel a), concentrations were generally higher during the dry season, with notable peaks at sites such as Providencia, Gran Nayar, Lamosa 3 and 4, and Michoacanai. The statistical analysis confirms a significant seasonal effect (*P* = 0.014), indicating that lower water volumes during the dry season may lead to increased EC concentrations. In contrast, ENT (panel b) exhibited higher levels during the rainy season, with significant seasonal variation (*P* = 0.004) observed at sites including Michoacanai and Gran Nayar. The results reveal that microbial contamination is not uniform across sites, reflecting the influence of local environmental conditions and potential inputs of fecal matter. The differences between EC and ENT suggest that each indicator responds differently to seasonal factors; EC peaks during dry periods, likely due to concentration effects and persistence under lower flow conditions, whereas ENT increases in the rainy season, probably associated with runoff and discharge from urban and agricultural sources.

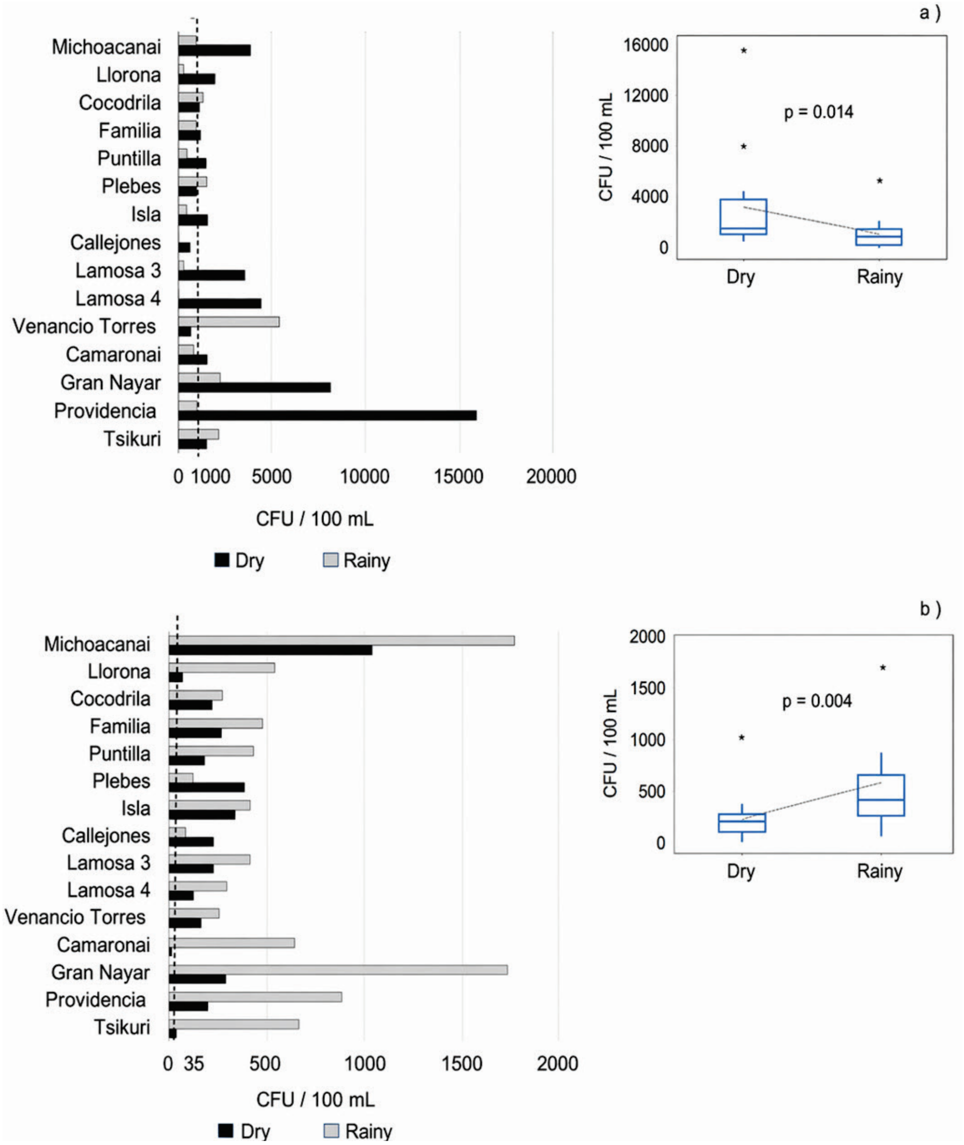

Figure 2 Histograms showing the concentrations corresponding to the mean values for each sampling point of EC (a), and ENT (b) in call canal water samples collected in the dry season and the rainy season.

NOTE: In (a–b), the mean concentration values reported in the boxplots for the dry season and the rainy season. (*) Represents an atypical value. The dashed line indicates the microbiological limit of ENT (35 CFU/100 mL) and EC (1.00×10^3 CFU/100 mL) for water.

3.1 Risk of GI associated with indicator bacteria

This study characterized a risk associated with GI inferred from the probabilistic determination of the distributions of EC and ENT concentrations in conjunction with the volume of water ingested by immersion (INM), and hand-to-mouth contact (HMC), during aquaculture activities at two times of the year, and the uncertainty or variability of QMRA was propagated. Figure 3 presents the risk per event of acquiring GI associated with exposure to EC and ENT in both scenarios. The box plot illustrates an increased health risk for operators associated with activities involving body immersion.

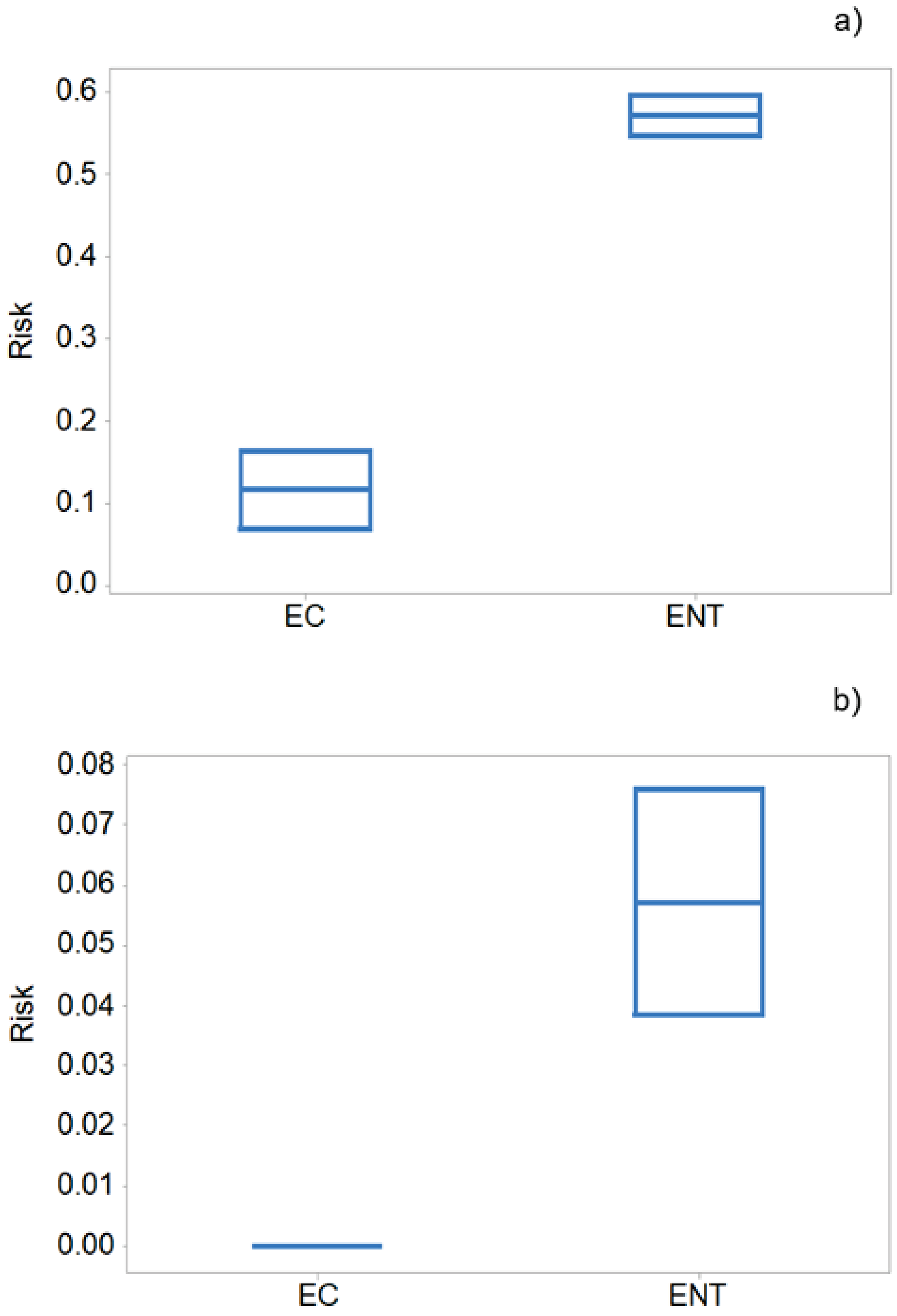

Figure 3 Probability of gastrointestinal (GI) infection per exposure event associated with *Escherichia coli* (EC) and *Enterococcus* (ENT) under two exposure scenarios: (a) immersion (INM), and (b) hand-to-mouth contact (HMC).

NOTE: Each box represents the distribution of simulated risk values across all sampling sites and seasons, combining data from both dry and rainy seasons.

Figure 4 breaks down the risks by activity using temporality. The INM is the scenario with the highest risk of GI in the dry season for EC (1.65×10^{-1}), and in both seasons for ENT (5.47×10^{-1}–5.96×10^{-1}). The risk of HMC ranges from dry-rainy season, 1.89×10^{-4}–6.78×10^{-5} and 3.85×10^{-2}–7.59×10^{-2} for EC and ENT, respectively. This association is particularly relevant during the warm months. Since our analysis was consistent with the highest risks of acquiring GI for both exposures (INM = 5.96×10^{-1}, HMC = 7.59×10^{-2}) (Figure 4) and an estimated disease rate of 588 GI cases per 1000 people for ENT, and 1.16 GI cases per 10,000 people for EC exceeded USEPA (3.6 cases per 100 people) and WHO (1 case per 10,000) standards.

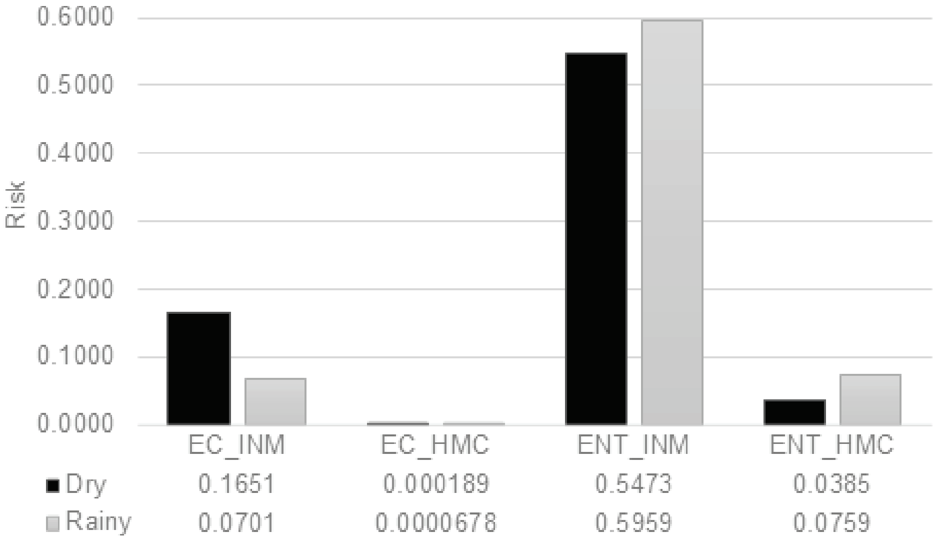

Figure 4 Risk of infection by immersion (INM), and hand-to-mouth contact (HMC), of EN and ENT during the dry season and the rainy season.

4. DISCUSSION

This study provides one of the first assessments of occupational health risks associated with fecal contamination in estuarine waters used for shrimp farming in San Blas, Nayarit.

Indicator bacteria are considered vital characteristics due to their important consequence on water quality standards (Sklar et al. 2023). EC and ENT are commensal bacteria from the intestine of animals and are allochthonous to coastal marine waters. Their survival in these environments is challenged by adverse conditions, which could explain their variability. In this study, the dominance of EC concentrations over ENT is observed. However, seasonality conditions impact the survival dynamics of these indicators, with the rainy season being favorable for ENT, and the dry season for EC. The decrease in EC concentration during the rainy season may be influenced by the effect of dilution with sea water and decomposition induced by solar radiation and salinity (Rivas-Montaño et al. 2018; Gyraite et al. 2020); whereas the persistence of ENT in seawater can be attributed to their cellular structure and survival rate (Akita et al. 2021). These characteristics have allowed ENT to be used as a reliable indicator of seawater quality according to national and international standards (USEPA 2012; DOF 2016). In addition, the literature suggests that *Enterococcus* is best correlated as a vehicle for the transmission of gastroenteritis in marine waters (Gyraite et al. 2020).

The seasonal dynamics in microbial contamination of estuarine waters used for shrimp farming in San Blas, Nayarit reveals EC concentrations peaked during the dry season, whereas ENT levels were higher in the rainy season. This pattern indicates that shrimp farm workers are subjected to seasonally variable occupational health risks, with elevated exposure to EC during low-flow dry periods, and to ENT during rainy conditions when runoff and fecal discharges are intensified. Similar seasonal contrasts have been observed in other aquatic environments (Yajima and Kurokura 2008; Abia et al. 2016; Denissen et al. 2023), underscoring the strong influence of hydrological factors on microbial dynamics and, consequently, on human exposure risks.

Previous research on fecal contamination of seawater has expanded the understanding of its suitability and potential risks to human health (Akita et al. 2021). The presence of EC and ENT is an indicator of the possible presence of groups of pathogens (Astrovirus, Adenovirus, Norovirus, *Salmonella*, *Campylobacter*, *Entamoeba*, *Cryptosporidium*, *Giardia,* and *Vibrio*) of epidemiological importance causing acute gastroenteritis in the water analyzed (Gyraite et al. 2019; Federigi et al. 2020; Vieira et al. 2022). For that reason, these findings show the seawater of Nayarit as a potential vehicle for infectious agents and a possible cause of acquiring GI for water handle through primary and/or secondary contact during different activities (WHO 2006; Poma et al. 2019; Bortagaray et al. 2022).

Aquaculture is not recognized as a primary contact activity, although the practices developed may expose operators to the risk of primary contact with water for a considerable period (Lee et al. 2023). Some studies show that a greater health risk is associated with primary contact, in which the body and head are submerged in water, compared to secondary contact, such as fishing and boating, where the volume of water ingested is lower, which agrees with what is reported here (Dorevitch et al. 2012; Sklar et al. 2023). In contrast, Bortagaray et al. (2022) found a higher risk of infection for fishermen (or secondary contact) than for swimmers (or primary contact) by Rotavirus and Astrovirus attributed to the variation in viral concentration and frequency in the sites analyzed. The difference between indicator levels suggests that the impact of various sources of fecal contamination should be investigated. The QMRA should be applied considering the different infectious risks posed by contamination from different sources (Federigi et al.

2020). In this research, the QMRA results highlight immersion (INM) as the dominant exposure pathway for shrimp farm workers for ENT, particularly during the rainy season. Although hand-to-mouth contact (HMC) represented a lower risk, it still exceeded acceptable thresholds in several scenarios, indicating that both exposure routes contribute to gastrointestinal (GI) infection risk.

Bortagaray et al. (2022) identified water exposure during the high shrimp production season as an important risk factor for the health of operators, when contact with seawater during aquaculture practices is greater. Nevertheless, GI caused by water manipulation for shrimp farming have not yet been widely recognized in Mexico. The risks declared in this investigation linked to water management, with the exception of the risk for HMC (6.78×10^{-5}) of EC in the rainy season, exceeded that acceptable by the WHO (1.00×10^{-4} for EC) for exposed operators and the USEPA (3.60×10^{-2} for ENT) for direct contact demonstrating a substantial risk faced by the local shrimp farm workers of San Blas. The risk estimated in this study is based on the assumptions adopted and could be overestimated. However, the State Aquaculture Health Committee of the State of Nayarit (CESANAY) annually records growth in shrimp production and culture area and therefore in exposed human capital (CESANAY 2023).

The DGE reported GI as the second most common disease in the world in 2024 with 63,302 annual cases (DGE 2025). Publications on sanitary quality of water in San Blas recorded a total of 3,451 GI cases allegedly related to the consumption of contaminated water; these events may be derived from the presence of fecal bacteria (Jáuregui Medina et al. 2010). For this reason, the risk assessed in this research has epidemiological relevance to link water as a source of infection with the occurrence of GI registered in the locality.

The acquisition of GI by operators is enhanced by fecal contamination of water from discharges of water without prior treatment from surrounding towns. In addition, the Santiago River, whose mouth is located 21 km northwest of the town of San Blas, has previously been diagnosed with questionable water quality for EC and ENT (CONAGUA 2018). Therefore, the use of water with anthropogenic fecal remnants and warm-blooded animals have been identified as important risk factors (Yajima and Kurokura 2008).

The basis for recommending criteria that use bacterial indicators of fecal contamination is that pathogens often coexist with indicators of contamination (USEPA 2012). Although, the use of fecal indicator bacteria data has been reported to underestimate the risks associated with other pathogens (Yajima and Kurokura 2008). Pathogen-specific risk assessments are necessary to protect vulnerable populations from exposure to fecal pathogens. However, in the context of pathogen dose calculation, there is a scarcity of pathogen data due to the difficulties and costs of regular monitoring of pathogen contamination (Federigi et al. 2020). Instead, surrogate data are used to infer the presence of the latter in environmental samples (Sklar et al. 2023).

Importantly, the estimated burden of disease exceeded international benchmarks. The risk values obtained for ENT (up to 5.96×10^{-1} per exposure event; 588 cases per 1000 workers) and for EC (1.16 cases per 10,000 workers) surpassed USEPA (3.6 cases per 100 people) and WHO (1 case per 10,000 people) reference levels. Such exceedances demonstrate that shrimp farm workers in San Blas face occupational health risks beyond internationally accepted safety thresholds. While previous studies have highlighted waterborne exposure in aquaculture and recreational contexts (Yajima and Kurokura 2008; Abia et al. 2016), this study provides one of the first quantitative assessments of microbial risk for shrimp farm workers, filling a gap in the occupational health literature.

Finally, this QMRA model provided a useful scientific tool to evaluate risks associated with aquaculture activities including INM and HMC exposure scenarios, and to project human capital health risk under different climatic conditions. Information on the influence of fecal indicator bacteria use statistics on potential risk in a particular seawater body may be useful to policy makers in planning health campaigns and prioritizing future interventions. The QMRA model presented in this study can be refined to adapt to potential pathogens present in aquaculture water. This QMRA approach can also be applied to tropical waters if comprehensive water quality data are collected in the future.

5. CONCLUSION

Understanding the origin of fecal contamination of water as a vital resource for shrimp production is essential to evaluate health risks, as well as to determine the necessary actions to remedy the problem. Here we examined the presence of EC and ENT in the estuary water of San Blas, Nayarit, Mexico, and it was possible to determine for the first time the risk of infection probabilistically for shrimp farm workers. This study highlights the pronounced seasonal variability of *Escherichia coli* (EC) and *Enterococci* (ENT) in coastal waters, with EC peaking in the dry season and ENT in the rainy season, resulting in a substantial proportion of samples exceeding microbial quality standards. QMRA demonstrates that occupational exposure during aquaculture activities, particularly through immersion and hand-to-mouth contact, poses a significant risk of gastrointestinal illness that varies seasonally. These findings have important implications for both worker safety and the sustainability of shrimp farming. Preventive measures such as seasonal monitoring of microbial indicators, use of protective equipment during immersion, and improved management of agricultural and urban discharges are recommended to reduce exposure risks. In addition, training workers on safe handling practices and promoting policies that integrate occupational health into aquaculture management could further mitigate risks. Despite inherent uncertainties in QMRA related to ingestion volume estimates and spatial variability of contamination, the consistency of the results across scenarios strengthens their relevance. Future research should integrate epidemiological monitoring of aquaculture workers and explore interventions tailored to local hydrological and occupational contexts.

ACKNOWLEDGMENTS

This research was supported by the Universidad Autónoma de Nayarit and the Universidad Autónoma de Sinaloa. Scholarship was awarded to one of the authors by the Consejo Nacional de Humanidades Ciencia y Tecnología (CONAHCYT). The authors wish to express their gratitude to the Comité Estatal de Sanidad Acuícola de Nayarit (CESANAY) for their collaboration.

FUNDING

A scholarship was awarded to one of the authors by the Consejo Nacional de Humanidades Ciencia y Tecnología (CONAHCYT).

REFERENCES

Abia, A.L.K., E. Ubomba-Jaswa, B. Genthe, and M.N.B. Momba. 2016. “Quantitative microbial risk assessment (QMRA) shows increased public health risk associated with exposure to river water under conditions of riverbed sediment resuspension.” *Science of the Total Environment* 566–567, 1143–1151. http://dx.doi.org/10.1016/j.scitotenv.2016.05.155

Ahmad, A., S.R.S. Abdullah, H.A. Hasan, A.R. Othman, and N.I. Ismail. 2021. “Aquaculture industry: Supply and demand, best practices, effluent and its current issues and treatment technology.” *Journal of Environmental Management* 287, 112271. https://doi.org/10.1016/j.jenvman.2021.112271

Akita, L.G., J. Laudien, C. Biney, and M.O. Akrong. 2021. “A baseline study of spatial variability of bacteria (total coliform, *E. coli,* and *Enterococcus spp*.) as biomarkers of pollution in ten tropical Atlantic beaches: concern for environmental and public health.” *Environmental Science and Pollution Research* 28, 50941–50965. https://doi.org/10.1007/s11356-021-15432-x

Bortagaray, V., P. Gamazo, S. Castro, M. Grilli, R. Colina, and M. Victoria. 2022. “Comparison of the risk of infection of human rotavirus and astrovirus according to fishing and swimming activities at Las Cañas beach, Uruguay." *Journal of Applied Microbiology* 133 (6): 3523–3533. https://doi.org/10.1111/jam.15785

Comisión Nacional Del Agua (CONAGUA). 2018. "Diagnóstico de la calidad del agua en el Río Santiago, desde el Lago de Chapala hasta el puente Arcediano y de los municipios de Juanacatlán y el Salto, en Jalisco. México." In Spanish. Available at: https://files.conagua.gob.mx/conagua/generico/calidad_del_agua/diagnostico_rio_santiago_2012-2018.pdf

Comité Estatal de Sanidad Acuícola de Nayarit (CESANAY). 2023. "Producción en instalaciones acuícolas que cultivan camarón en el Estado de Nayarit." In Spanish. Available at: https://cesanay.mx/

Cortés, A., R. Casillas-Hernández, C. Cambeses-Franco, R. Bórquez-López, F. Magallón-Barajas, W. Quadros-Seiffert, G. Feijoo, et al. 2021. "Eco-efficiency assessment of shrimp aquaculture production in Mexico." *Aquaculture* 544, 737145. https://doi.org/10.1016/j.aquaculture.2021.737145

Denissen, J., B. Reyneke, T. Barnard, S. Khan, and W. Khan. 2023. "Risk assessment of *Enterococcus faecium, Klebsiella pneumoniae,* and *Pseudomonas aeruginosa* in environmental water sources: Development of surrogate models for antibiotic resistance genes." *Science of the Total Environment* 901, 166217. https://doi.org/10.1016/j.scitotenv.2023.166217

Diario Oficial de la Federación (DOF). 2016. "Norma Mexicana, NMX-AA-120-SCFI-2016 Que establece los requisitos y especificaciones de sustentabilidad de calidad de playas." In Spanish. Available at: http://www.economia-nmx.gob.mx/normas/nmx/2010/nmx-aa-120-scfi-2016.pdf

Diario Oficial de la Federación (DOF). 2021. "Norma Oficial Mexicana NOM-001-SEMARNAT-2021 Que establece los límites máximos permisibles de contaminantes en las descargas de aguas residuales en aguas y bienes nacionales." México: Secretaría de medio Ambiente, Recursos Naturales y Pesca. In Spanish. Available at: https://www.dof.gob.mx/nota_detalle.php?codigo=5645374&fecha=11/03/2022#gsc.tab=0

Dirección General de Epidemiología (DGE). 2025. "Anuario de Morbilidad 1984–2024." Gobierno de Mexico. In Spanish. Available at: https://epidemiologia.salud.gob.mx/anuario/htmL/index.htmL

Dorevitch, S., M.S. Dworkin, S.A. DeFlorio, W.M. Janda, J. Wuellner, and R.C. Hershow. 2012. "Enteric pathogens in stool samples of Chicago-area water recreators with new-onset gastrointestinal symptoms." *Water Research* 46 (16): 4961–4972. http://dx.doi.org/10.1016/j.watres.2012.06.030

Federigi, I., L. Bonadonna, G.B. Ferraro, R. Briancesco, L. Cioni, A.M. Coccia, S.D. Libera, et al. 2020. "Quantitative Microbial Risk Assessment as support for bathing waters profiling." *Marine Pollution Bulletin* 157, 111318. https://doi.org/10.1016/j.marpolbul.2020.111318

Food and Agriculture Organization of the United Nations/World Health Organization (FAO/WHO). 2002. "Risk assessment of *Campylobacter spp.* in broilers chickens and *Vibrio spp*. in seafood. Report of the joint FAO/WHO expert consultation." FAO Regional Office for Asia and the Pacific, Bangkok, Thailand. Available at: https://www.fao.org/4/y8145e/y8145e00.htm

Gupta, B., A.K. Gupta, P.S. Ghosal, S. Lal, D. Saidulu, A. Srivastava, and M. Upadhyay. 2022. "Recent advances in application of moving bed biofilm reactor for wastewater treatment: Insights into critical operational parameters, modifications, field-scale performance, and sustainable aspects." *Journal of Environmental Chemical Engineering* 10 (3): 107742. https://doi.org/10.1016/j.jece.2022.107742

Gyraite, G., M. Kataržyte, D. Overlinge, D. Vaičiuté, E. Jonikaitè, and G. Schernewski. 2020. "Skip the dip—Avoid the risk? Integrated microbiological water quality assessment in the South-Eastern Baltic Sea coastal waters." *Water* 12 (11): 3146. https://doi.org/10.3390/w12113146

Gyraite, G., M. Katarzytea, and G. Schernewskia. 2019. "First findings of potentially human pathogenic bacteria *Vibrio* in the southeastern Baltic Sea coastal and transitional bathing waters." *Marine Pollution Bulletin* 149, 110546. https://doi.org/10.1016/j.marpolbul.2019.110546

Haas, C., J. Rose, and C. Gerba. 2014. *Quantitative Microbial Risk Assessment. 2nd edition.* John Wiley & Sons Inc., New York, NY.

Hernández-Díaz, L.D.J., N. Leon-Sicairos, J. Velazquez-Roman, H. Flores-Villaseñor, A.M. Guadron-Llanos, J.J. Martinez-Garcia, J.E. Vidal, and A. Canizalez-Roman. 2015. "A pandemic *Vibrio parahaemolyticus* O3:K6 clone causing most associated diarrhea cases in the Pacific Northwest coast of Mexico." *Frontiers in Microbiology* 6, 221. https://doi.org/10.3389/fmicb.2015.00221

Huang, Y.S., C.A. Hwang, L. Huang, V.C.H. Wu, and H.I. Hsiao. 2017. "The risk of *Vibrio parahaemolyticus* infections associated with consumption of raw oysters as affected by processing and distribution conditions in Taiwan." *Food Control* 86, 101–109. https://doi.org/10.1016/j.foodcont.2017.10.022

Instituto Nacional de Estadística y Geografía (INEGI). 2021. “Censos Económicos 2019 Pesca y acuicultura.” Instituto Nacional de Estadística y Geografía (INEGI). México, c2021. In Spanish. Available at: https://www.inegi.org.mx/contenidos/productos/prod_serv/contenidos/espanol/bvinegi/productos/nueva_estruc/702825198978.pdf

Jáuregui Medina, C., I. Rodríguez Castañeda, L. Coronel Sandoval, S. Ramírez Hernández, and R. Noriega Padilla. 2010. “Calidad sanitaria del agua potable en San Blas, México.” *Ambientalia* 1 (1): 108–117. In Spanish. http://hdl.handle.net/10481/20503

Lee, D., J.M. Gibson, J. Brown, J. Habtewold, and H.M. Murphy. 2023. “Burden of disease from contaminated drinking water in countries with high access to safely managed water: A systematic review.” *Water Research* 242, 120244. https://doi.org/10.1016/j.watres.2023.120244

Malcolm, T.T.H., Y.K. Cheah, C.W.J.W.M. Radzi, H.K. Kantilal, J. Martinez-Urtaza, M. Nishibuchif, and R. Son. 2016. “Microbial risk assessment of *Vibrio parahaemolyticus* in bloody clams in Malaysia: A preliminary model from retail to consumption.” *Microbial Risk Analysis* 4, 43–51. http://dx.doi.org/10.1016/j.mran.2016.07.002

Mustafa, A., M. Paena, A. Athirah, E. Ratnawati, R. Asaf, H.S. Suwoyo, S. Sahabuddin, et al. 2022. “Temporal and spatial analysis of coastal water quality to support application of whiteleg shrimp *Litopenaeus vannamei* intensive pond technology.” *Sustainability* 14 (5): 2659. https://doi.org/10.3390/su14052659

Noman, E., A. Al-Gheethi, R.M.S.R. Mohamed, B. Talip, M. Al-Sahari, and M. Al-Shaibani. 2021. “Quantitative microbiological risk assessment of complex microbial community in prawn farm wastewater and applicability of nanoparticles and probiotics for eliminating of antibiotic-resistant bacteria.” *Journal of Hazardous Materials* 419, 126418. https://doi.org/10.1016/j.jhazmat.2021.126418

Poma, H.R., A. Kundu, S. Wuertz, and V.B. Rajal. 2019. “Data fitting approach more critical than exposure scenarios and treatment of censored data for quantitative microbial risk assessment.” *Water Research* 154, 45–53. https://doi.org/10.1016/j.watres.2019.01.041

Ponce Palafox, J.T., E. Soto Ceja, E. Meza Ramos, and F.J. Robles Zepeda. 2018. “La etapa de crecimiento lento de la acuicultura en Nayarit: Aspectos económicos y sostenibilidad.” *Revista Mexicana Sobre Desarrollo Local.* Autonomous University of Nayarit, Mexico. In Spanish. http://dspace.uan.mx:8080/jspui/bitstream/123456789/2106/1/la%20etapa%20de

%20crecimiento%20lento%20de%20la%20acuicultura%20en%20nayarit%20aspectos%20economicos%20y%20sostenibilidad.pdf

Priya, T., A. Tarafdar, B. Gupta, and B.K. Mishra. 2018 "Effect of bioflocculants on the coagulation activity of alum for removal of trihalomethane precursors from low turbid water." *Journal of Environmental Sciences* 70, 1–10. https://doi.org/10.1016/j.jes.2017.09.019

Rivas-Montaño, A.M., I.E. Luis-Villaseñor, P. Piña-Valdez, B. Gómez-Gil, and M.L. Lizárraga-Partida. 2018. "Spatiotemporal distribution of *Vibrio parahaemolyticus* in relation to environmental parameters in a coastal lagoon on the Pacific coast of northwestern Mexico." *Ciencias Marinas* 44 (3): 141–153. http://dx.doi.org/10.7773/cm.v44i3.2772

Rodríguez-Camacho, J.C., E. Méndez-Gómez, A.M. Rivas-Montaño, and J.A. Cortés-Ruiz. 2014. "Evaluación de la presencia de *Vibrio parahaemolyticus* en camarón blanco (*Litopenaeus vannamei*) silvestre estuarino en el sur de Sinaloa y norte de Nayarit, mediante análisis microbiológico y PCR." *Revista Bio Ciencias* 2 (4): 282–292. In Spanish. http://dx.doi.org/10.15741/revbio.02.04.06

Sklar, R., A.E. Chabrelie, R.S. Carreira, P.L. Gurian, and J. Mitchell. 2023. "Health Risks to Communities and Athletes Associated with Swimming, Wading, and Sailing in Water Bodies of Brazil's Guanabara Bay Basin." *Water* 15 (14): 2509. https://doi.org/10.3390/w15142509

Sunger, N. and C. Haas. 2015. "Quantitative microbial risk assessment for recreational exposure to water bodies in Philadelphia." *Water Environment Research* 87 (3): 211–222. https://doi.org/10.2175/106143015x14212658613073

Turcios, A.E., R. Miglio, R. Vela, G. Sanchez, T. Bergier, A. Włodyka-Bergier, J.I. Cifuentes, et al. 2021. "From natural habitats to successful application – Role of halophytes in the treatment of saline wastewater in constructed wetlands with a focus on Latin America." *Environmental and Experimental Botany* 190,104583. https://doi.org/10.1016/j.envexpbot.2021.104583

U.S. Environment Protection Agency (USEPA). 2012. "2012 Recreational Water Quality Criteria (RWQC) for Bacterial Indicators of Fecal Contamination." Office of Water, United States Environmental Protection Agency, Washington, DC, (EPA-820-F-12-058). Available at: https://www.epa.gov/wqc/recreational-water-quality-criteria-and-methods#rec1

U.S. Food and Drug Administration (USFDA). 2005. "Quantitative Risk Assessment on the Public Health Impact of Pathogenic *Vibrio parahaemolyticus* in Raw Oysters." Available at: https://www.fda.gov/food/risk-and-safety-assessments-food/quantitative-risk-assessment-public-health-impact-pathogenic-vibrio-parahaemolyticus-raw-oysters

Vieira, C.B., I.T. Araújo, F.C. Ferreira, J. Liu, R.C. Feitosa, and M.P. Miagostovich. 2022. “Fast screening of enteropathogens in marine water samples.” *Brazilian Journal of Microbiology* 53, 1439–1446. https://doi.org/10.1007/s42770-022-00770-w

World Health Organization (WHO). 2006. “Wastewater and excreta use in aquaculture.” In: WHO/United Nations Environmental Programme (UNEP) (ed.). WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater, Vol 3. World Health Organization, Geneva. pp 39–45. Available at: https://www.who.int/publications/i/item/9241546840

World Health Organization (WHO). 2014. “Preventing diarrhea through better water, sanitation, and hygiene: Exposures and impacts in low and middle-income countries.” World Health Organization, Geneva, Switzerland. Available at: https://www.who.int/publications/i/item/9789241564823

World Health Organization (WHO). 2016. “Quantitative microbial risk assessment: application for Water Safety Management.” World Health Organization, Geneva, Switzerland, pp 204. Available at: https://www.who.int/publications/i/item/9789241565370

Yajima, A. and H. Kurokura. 2008. “Microbial risk assessment of livestock-integrated aquaculture and fish handling in Vietnam Aya.” *Fisheries Science* 74, 1062–1068. https://doi.org/10.1111/j.1444-2906.2008.01625.x

Zhang, Q., J. Gallar, B. Wu, V.J. Harwood, M.J. Sadowsky, K.A. Hamilton, and W. Ahmed. 2019. “Synergy between quantitative microbial source tracking (qMST) and quantitative microbial risk assessment (QMRA): A review and prospectus.” *Environment International* 130, 104703. https://doi.org/10.1016/j.envint.2019.03.051