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RESEARCH ARTICLE

Influence of an anthropogenic disturbance gradient on the abundance and biochemical characteristics of heterotrophic bacteria on beaches of the central coastal zone of Veracruz

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Abstract

Before the increase in anthropogenic activities, the global coastal ocean was a net autotrophic system. From human activity and the evolution of the earth, changes have been generated in its continents, oceans, atmosphere and life. Transport of sediments and bioelements to the coastal zone has been drastically altered, and there is debate about whether this zone is autotrophic or heterotrophic. This work carried out an exploratory study of five sandy beaches in the central coastal area of the state of Veracruz, three urban beaches on a gradient of anthropogenic activities in the Metropolitan Zone of Veracruz (ZMV) and two natural, non-urbanized beaches far from the ZMV to determine the concentrations and biochemical characteristics of the heterotrophic bacterial groups found in samples of surface marine sediments during two contrasting seasons in the region: dry season and rainy season. The presence of heterotrophic bacteria reflected the degree of anthropogenic disturbance that each beach presents, with a tendency to concentrate mainly on those close to urban centers. On the other hand, the anthropogenic disturbance gradient did not influence the diversity of biochemical characteristics of heterotrophic bacteria.

Keywords Heterotrophic bacteria · Biochemistry · Beaches · Coastal zone · Anthropogenic pollution

Introduction

Coastal regions are spaces with variable physical, geomorphological, biotic and climatic characteristics that provide multiple ecosystem services, which is why they are preferred as recreational and housing sites (Martínez et al. 2007; Ruiz-Fernández 2014). Population growth and current urban and industrial developments are precursors of impacts that lead to environmental deterioration and alter spatial and structural patterns, affecting the value of the coastal ecosystem (Murray et al. 2019; Yan et al. 2020; Bushra et al. 2021).

Coastal areas have become a reservoir of pollutants that can be dangerous for biota and human health (Herrera and Suárez 2005) and can change environmental and hydrological conditions such as temperature, pH and salinity (Aguilar 2010). Wastewater is constantly discharged from urban areas and from agricultural and industrial activities, causing pollution in coastal systems (Yu et al. 2021) and generating conflicts due to the use of available resources (Ruiz-Fernández 2014).

Within the coastal zone, sandy beaches provide ecosystem services that generate economic development produced by tourist activities for leisure and recreation. However, these activities are also related to environmental pollution (Herrera and Suárez 2005) and the deterioration of the habitat of the different species of birds and invertebrates that develop there (Ruiz-Fernández 2014; Yan et al. 2020), including microorganisms. The latter are particularly

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important because certain groups can survive despite these drastic changes (Martínez-Alonso and Gaju 2005) and acquire ecological relevance by being capable of degrading polluting compounds, forming a front against deterioration (Kieft et al. 1997; Boschker et al. 2001; Pucci et al. 2009).

Bacteria, as regulators of the flow of contaminating material within an environmental system, can detect external changes and respond accordingly, adapt their behavior to specific signals such as alterations in temperature and nutrient limitation, or modify their local environment to facilitate growth, metabolic versatility and adaptability to varying conditions (Semenov 2023). Heterotrophic bacteria are relevant because they present resistance to toxic compounds and environmental changes as well as a significant degrading capacity (Abalos et al. 2004). They obtain energy from the oxidation of carbohydrates, lipids and proteins; they require organic compounds containing carbon and nitrogen as growth substrates, which are used aerobically and anaerobically (Jurtshuk 1996).

In the sea, heterotrophic bacteria are distributed throughout the water column (Cifuentes et al. 2003) in greater concentration in coastal areas because of the contribution of runoff and rivers (Seoánez 2000). They are an important group due to their degrading and mineralizing activity, they promote the self-purification capacity of the marine ecosystem, and they make nutritional elements available to primary producers to transform the substrate used into microbial biomass (Azam et al. 1983; Montes Cardona et al. 2021).

In several countries, heterotrophic bacteria have been used to understand changes in the state of an environment with anthropogenic pressure. The variations in the concentration of these bacteria and the increase in the rate of mineralization are indicators of a gradual change in environmental conditions and are reflected in the environmental impact (Seoánez 2000). It is important to know the diversity of microorganisms that inhabit pressured coastal environments and to evaluate their resistance to anthropogenic disturbances and their ability to degrade polluting materials using them as a source of energy (Martínez-Alonso and Gaju 2005; Gómez et al. 2006).

On the coast in front of the Metropolitan Zone of Veracruz (ZMV), there is growing anthropic development where port, fishing, urban and tourist activities come together that puts pressure on the natural coastal systems, especially the sandy beaches adjoining the urban structures (Bernal-Ramírez and Granados-Barba 2008; Valadéz-Rocha 2013; Cataneo-Nieto et al. 2019); they are the most visited beaches on the Gulf of Mexico because of the tourist and recreational attractions they offer (Gallegos-Jiménez 2008). Likewise, they provide the opportunity to investigate the role played by heterotrophic bacteria on these beaches with specific problems of organic and inorganic pollution; however, there are no studies to our knowledge that consider the biochemical characteristics of these bacteria contained in the sediments. Based on the above, this research studied the spatial and temporal variation of heterotrophic bacteria in the ZMV, a region pressured by urban growth whose activities and waste influence the concentrations and capacities of the bacteria. It seeks to generate a baseline of previous information for future research that contemplates the deterioration of the coastal zone from a microbiological approach and for the implementation of a subsequent environmental monitoring program.

Materials and methods

Selection of sampling sites

The sampling sites on the beaches of the Veracruz coast were selected according to the historical urban-coastal growth from the port of Veracruz proposed by Siemens et al. (2006); the loss of coastal dunes was considered. Three beaches in the central urban area of the state were chosen, Antepuerto, Villa del Mar and Mocambo, in addition to two contrasting rural beaches located outside the urban center: Playa Farallón, approximately 71 km northwest of the port of Veracruz, and Arroyo Giote, 27 km to the southeast (Table 1, Fig. 1).

Description of the study sites

With the arrival of human settlements and disorderly urban-port growth, important changes were generated in the coastal zone, giving rise to environmental conflicts that put the beaches at risk and increased their deterioration (Cataneo-Nieto et al. 2019). This was considered, in addition to the human intensity (and incidence), location and border with the urban core. Table 2 summarizes the differences between each of the beaches studied. In Fig. 2, the morphological and structural differences that accompany each of the beaches studied are observed.

Table 1 Coordinates of the study sites

Beaches	Coordinates	
Farallón	19° 38′ 29.87″ N	96° 23′ 39.73″ O
Antepuerto	19° 11′ 53.57″ N	96° 07′ 47.74″ O
Villa del mar	19° 11′ 04.11″ N	96° 07′ 26.00″ O
Mocambo	19° 07′ 58.14″ N	96° 06′ 08.01″ O
Arroyo Giote	19° 04′ 57.77″ N	96° 05′ 03.30″ O

Fig. 1 Location of beaches oandsampling sites

Sampling

The samples were collected during the two contrasting seasons in the region, dry (May) and rainy (September), during low tide, on the days with the least tidal variation. According to Schlacher et al. (2008), during low tide there is a greater retention of organisms in the sediment, they are buried and are less mobile, and the structural characteristics of the beach are more evident.

The collection of samples on the selected beaches was carried out at nine stations located on three transects perpendicular to the coastline with a separation of 5 m between each one. Three tidal levels were considered within the intertidal zone (high, medium and low) and the morphology of the beach (Fig. 3). At each station, three samples of 60 cm^3 surface sand were collected with a 60-ml plastic syringe with the tip cut off and used as a nucleator, which was inserted vertically over the sediment. The samples collected were placed in sterile Nasco Whirl-Pak plastic bags, which were protected within a temperature-controlled container (approximately 4 °C), during transport to the laboratory for analysis (APHA 1989).

Table 2 Differences between the beaches studied based on their anthropogenic incidences

	Farallón	Antepuerto	Villa del Mar	Mocambo	Arroyo Giote
Adjacent to the urban center	Away	Directly	Directly	No Directly	Away
Protective structures	Non-existent	Breakwaters	Breakwaters	Breakwaters	Non-existent
Uses	Natural presence of dunes	Presence of boats	Restaurants, tourist palapas, fishing and tourism boats	Restaurants, tourist palapas, fishing and tourism boats	Fishing boats
Tourist and recreational influence	Minimum (small groups for periods)	Moderate (small groups for periods)	Massive (throughout the year)	Moderate massive (per periods)	Minimum (small groups for periods)
Others factors that influence the state of the beaches	Nearby agricultural and livestock activities	Port activity, urban and hotel development, stormwater discharge and garbage	Wastewater discharge, port activity and organic waste	Increase in population rate, wastewater discharge, fishing activity and habitat destruction	Construction of residential areas, mouth of the Giote stream and surrounding livestock activities

Fig. 2 Beaches studied. **A** Farallón, **B** Antepuerto, **C** Villa del Mar, **D** Mocambo, **E** Arroyo Giote

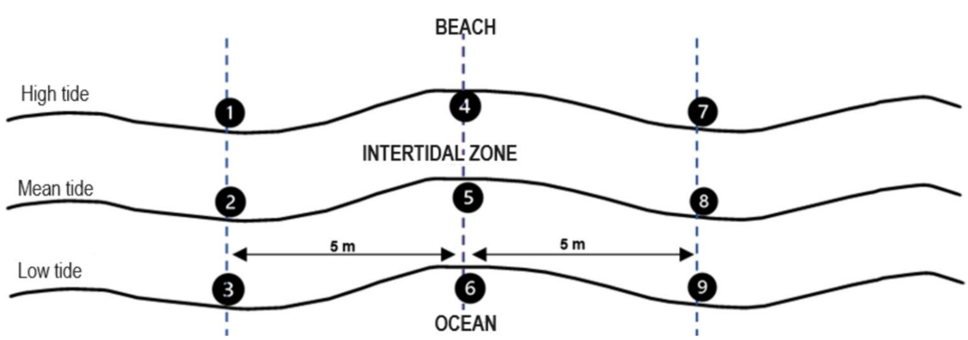

Fig. 3 Location of transects and collection stations

Sample processing

Prior to the analysis, the samples were processed for controlled use throughout the experimental phase using the microcosm technique, a prolonged incubation test that consists of subjecting the samples to the conditions they would have naturally through an artificial simulation of their habitat on a laboratory scale (Sánchez et al. 1987). Each sample was prepared and sterilized (121 °C × 15 min, AESA autoclave) with a solution of 90 ml distilled water with 3% NaCl, the salt concentration of sea water (Ramírez et al. 2004); 10 g of the sampled sediment was added. The jars were sealed and stored in coolers at ambient conditions.

Sample pre-enrichment

Diluted phosphate buffer solution (9 ml) was placed in medium-sized test tubes, which were sterilized at 121 °C in the autoclave for 15 min. After this, they were cooled, and 1 ml of sample was added to each one. The flasks in microcosms were labeled and incubated (Memmerk incubator) for 24 h at 35 °C. Isotonic diluents such as saline or phosphate-buffered saline solutions are systematically used in the preparation of microbial cell suspensions, where the salts contained in these liquids provide an isotonic medium capable of maintaining the integrity and viability of the cells (SOPs 2008).

Bacterial quantification

The number of viable aerobic microorganisms in the samples was estimated by plate counting, according to the NOM-092-SSA1-1994. For samples with very high bacterial loads it was necessary to carry out a series of dilutions, so the first step in this analysis was to determine the optimal dilution to use for each beach; it was selected with a growth range between 25 and 250 colonies. The plates were incubated for 48 h at 35 °C–37 °C (Fig. 4).

Biochemical characterization

Bacterial seeding was carried out in TSA (casein-soy agar), a non-selective culture medium, with incubation for 24 h at 35 °C. According to Winn et al. (2008), colonies that shared similar morphological traits were separated from those different from the rest. The following characteristics were considered: size (small: < 1 mm, medium: 1–3 mm and large: > 3 mm), shape (point-shaped, circular, oval or indefinite shape), color (cream, whitish and yellowish), surface (flat, filled and/or transparent or opaque) and texture (dry or viscous). With this classification, pure cultures were isolated in TSA; the plates were incubated under the same conditions as for the seeding (Fig. 5).

Biochemical tests

With the isolated pure cultures, a battery of tests was carried out to determine the biochemical and enzymatic characteristics, temperature and resistance to different concentrations of salt of the bacteria in the different sampling sites. This could be examined biotechnologically and studied with greater emphasis in future research. The investigated characteristics are shown in Table 3.

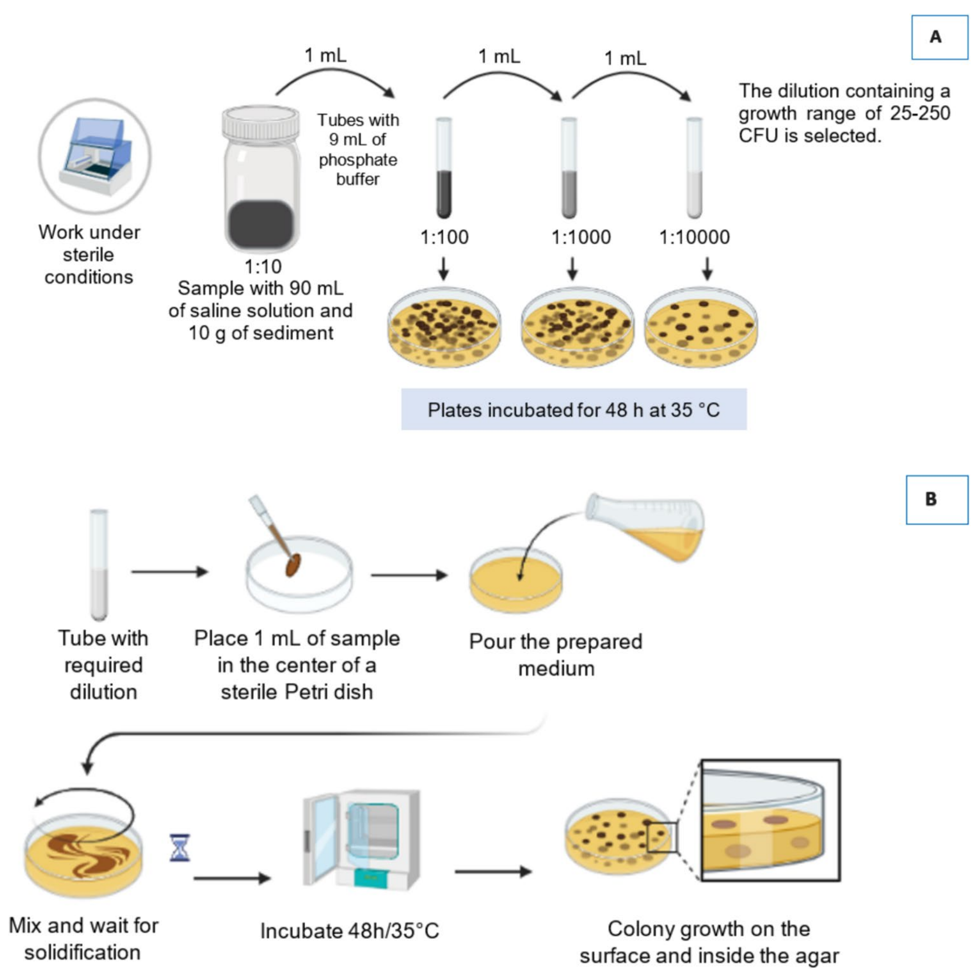

Fig. 4 Plate account. **A** Procedure for choosing the optimal dilution, **B** execution of the technique for counting colonies

Statistical analysis

The statistical analyses and correlation of the response variables, climatic seasons and sampled sites, in addition to the construction of the graphs, were carried out in the Statistica program of StatSoft; the variance test was carried out using Kruskal-Wallis.

Results

Concentration of heterotrophic bacteria

Table 4 shows the average concentrations of heterotrophs found on each beach during both climatic seasons.

High loads of heterotrophic bacteria were found on the beaches Antepuerto (2.0E + 06 CFU/10 g), Villa del Mar and Arroyo Giote (1.8E + 06 CFU/10 g each) during the dry season and on Villa del Mar and Mocambo (2.6E + 06 CFU/10 g and 2.9E + 06 CFU/10 g, respectively) during rainy season. The lowest concentrations were presented by Farallón during the two study seasons (9.3E + 05 CFU/10 g in dry season and 2.4E + 05 CFU/10 g in rainy season) (Fig. 6).

Identification of factors influencing the concentrations of heterotrophic bacteria

Two factors were considered that may influence the concentration of heterotrophic bacteria in the sampled sites: the climatic temporality and the site according to

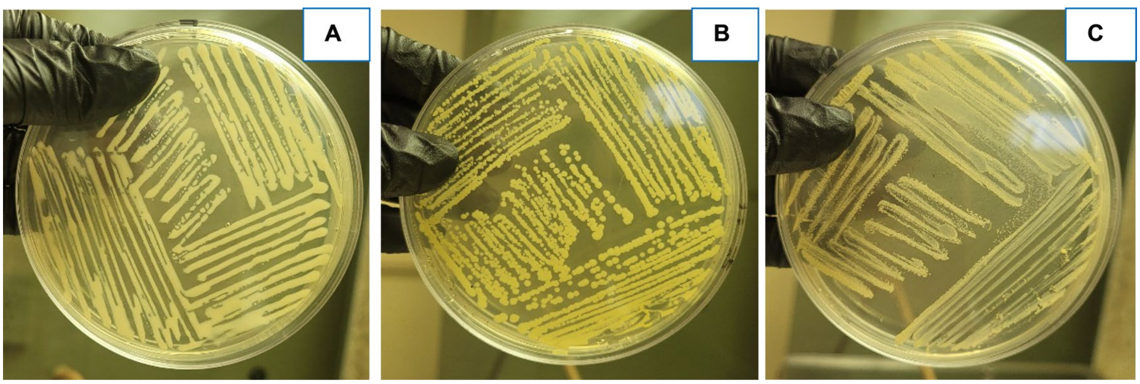

Fig. 5 Growth and isolation of pure cultures in petri dishes. **A** Cream-colored colony with viscous texture, **B** yellowish-colored colony with a viscous texture, **C** cream-colored colony with dry texture (color figure online)

Table 3 Battery of tests for the biochemical characterization of the study sites

Analysis	Name of products and reagents used	Method used
Oxidase	Oxidase test strips	MacFaddin (2003)
Catalase	H_2O_2-(hydrogen peroxide)	
Citrate as the only carbon source	Simmons citrate agar	
Carbohydrate fermentation	Difco™ triple sugar iron agar (TSI)	
Ornithine decarboxylation and bacterial mobility	Difco™ MIO medium	
Lysine decarboxylation	Iron and lysine agar (LIA)	Fernández-Olmos et al. (2010)
Temperature tests	Trypticasein soy agar (TSA)	APHA (1989)
Salinity tests	Trypticasein soy agar (TSA) Sodium chloride (NaCl)	

Table 4 Average of the CFU/10 g response variable per beach during the dry and rainy seasons

Season	Sites				
	Antepuerto	Villa del Mar	Mocambo	Arroyo Giote	Farallón
Dry season	2.0E + 06	1.8E + 06	8.9E + 05	1.8E + 06	9.3E + 05
Rainy season	3.8E + 05	2.6E + 06	2.9E + 06	1.3E + 06	2.4E + 05

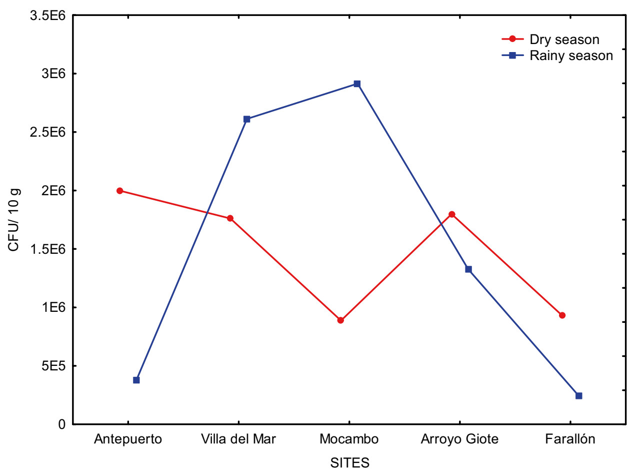

Fig. 6 Concentration of heterotrophic aerobic bacteria during the dry and rainy seasons

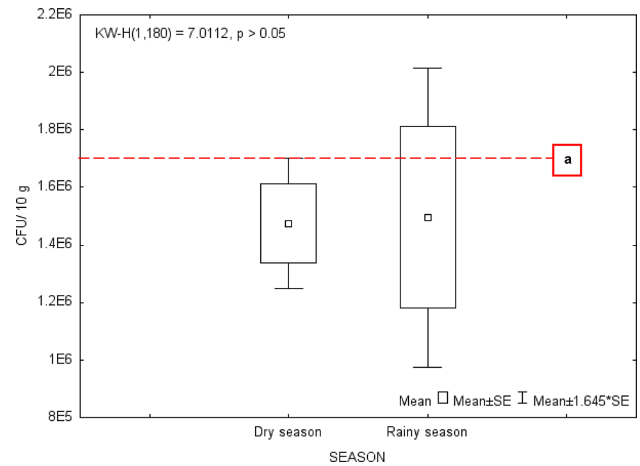

Fig. 7 Box plot of the concentration relationship of heterotrophic bacteria as a function of the season where "a" represents similarity between the data. Graph given by the equation: KW-H (1–180) = 7.0112, with $p > 0.05$, with a confidence percentage of 95%

Table 5 Descriptive statistics of the concentration of heterotrophic bacteria (CFU/10 g) during two climatic seasons

Dry season	Rainy season
1.5E + 06 ± 1.3E + 06[a]	1.5E + 06 ± 3.0E + 06[a]

[a]Mean no significant difference

There are no significant statistical differences between the two groups $p > 0.05$

its proximity to the urban center. A statistical analysis of the concentrations was carried out using CFU/10 g as the response variable and the sites and climatic seasons as independent variables.

When analyzing the climatic seasons as the only variable, and when comparing the variances between dryness and rainfall, no significant statistical differences were found (Table 5), so the data were grouped into a single group ([a]), with their means being very similar. Hence, this factor did not exert any pressure on the concentrations of heterotrophic bacteria on the beaches.

Regarding the sites, three groupings were found, denoted as [a], [b] and [ab]. The loads of heterotrophic bacteria presented on the beaches of Antepuerto (1.2E + 06 ± 9.6E + 05 CFU/10 g), Villa del Mar (2.2E + 06 ± 3.3E + 06 CFU /10 g) and Mocambo (1.9E + 06 ± 2.3E + 06 CFU/10 g) did not show significant statistical differences. Farallón beach presented the lowest load in both climatic seasons, having significant statistical differences compared with the other three beaches. Arroyo Giote did not present significant statistical differences compared with any of the beaches (Table 6). Therefore, it was concluded that the site factor has a greater effect on the concentrations of heterotrophic bacteria than the season factor.

The box plots in Figs. 7 and 8 show the variations of each factor.

Determination of the biochemical characteristics of heterotrophic bacterial groups

The sites with the most isolated heterotrophic groups were Antepuerto and Mocambo: during the dry season 27 and 26 groups and in the rainy season 26 and 27, respectively, with a lower presence on Farallón beach with 16 isolated during dry season and Arroyo Giote beach with 19 during rainy season (Table 7).

Table 6 Descriptive statistics of the concentration of heterotrophic bacteria (CFU/10 g) of the sampled sites

Antepuerto	Villa del Mar	Mocambo	Arroyo Giote	Farallón
1.2E + 06 ± 9.6E + 05[b]	2.2E + 06 ± 3.3E + 06[b]	1.9E + 06 ± 2.3E + 06[b]	1.6E + 06 ± 2.8E + 06[ab]	5.9E + 05 ± 7.4E + 05[a]

[a, b]Mean no significant difference

[ab]Means significant differences

Mean values with different subscripts show significant statistical differences

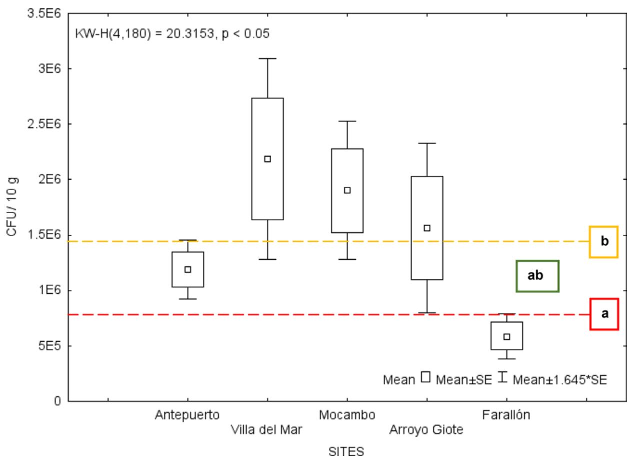

Fig. 8 Concentration relationship of heterotrophic bacteria depending on the site, where "a" groups the boxes with similar data and "b" groups the boxes with similar data that differ from "a". Graph given by the equation: KW-H $(4,180)=20.3153$, with $p<0.05$, with a confidence percentage of 95%

Table 7 Number of isolates in the different study sites during the dry and rainy season

Sites	Dry season	Rainy season
Antepuerto	27	26
Villa del Mar	20	20
Mocambo	26	27
Arroyo Giote	20	19
Farallón	16	24

During the dry season, the bacteria isolated in Villa del Mar were positive in the seven analyses carried out with a minimum response of 45% (Fig. 9). When considering this same percentage for the rainy season (Fig. 10), three beaches presented a similar response; Antepuerto and Mocambo are two urban beaches, and Farallón is a rural beach where there are no records of possible direct anthropogenic pressure. The bacteria isolated in Arroyo Giote were able to use citrate as the only carbon source, degrade carbohydrates, develop at 42 °C and grow in a medium without salts; however, the percentage of carbohydrate degradation they showed was low during both seasons.

The biochemical characteristics with the greatest presence in heterotrophic bacteria were their ability to oxidase and catalase enzymes, metabolize citrate and grow in media with 0 and 10% salt concentrations in addition to growth at 42 °C. Temperature testing at 7 °C was considered at the beginning of the study; however, it did not show a growth response from the bacteria, so it was discarded from the biochemical battery; the fermentation capacity of the bacteria was variable between seasons (Table 8).

Discussion

Influence of the anthropogenic gradient of ZMV beaches on the concentrations of heterotrophic bacteria

High loads of heterotrophic bacteria were found on the Antepuerto and Villa del Mar beaches (2.0E+06 CFU/10 g and 1.8E+06 CFU/10 g, respectively) during the dry season and from Villa del Mar and Mocambo (2.6E+06 CFU/10 g and 2.9E+06 CFU/10 g, respectively) during rainy season. The lowest concentrations were presented by Farallón during the two study seasons (9.3E+05 CFU/10 g in dry season and 2.4E+05 CFU/10 g in rainy season). From a general perspective, these values allowed us to visualize how a space with growing urban development presents

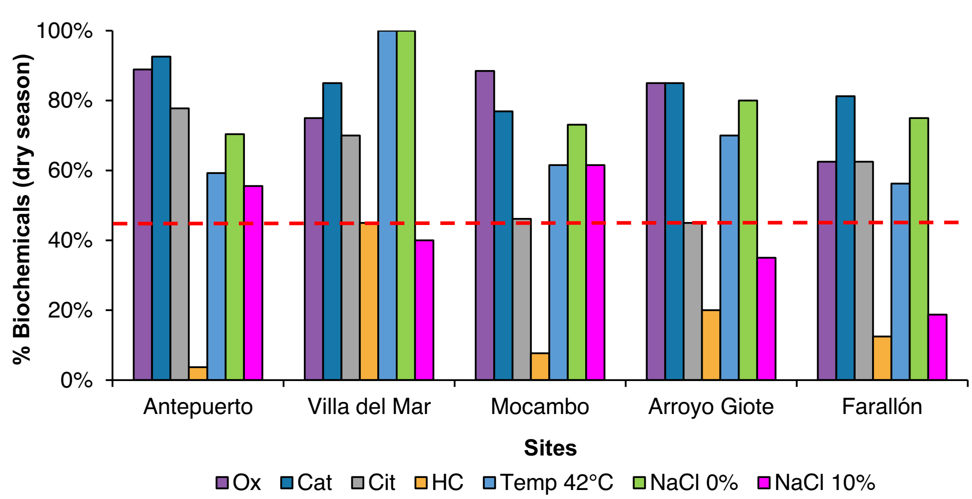

Fig. 9 Percentage variation of biochemicals during the dry climatic season. *Ox* oxidase, *Cat* catalase, *Cit* citrate, *HC* carbohydrates, *Temp* temperature

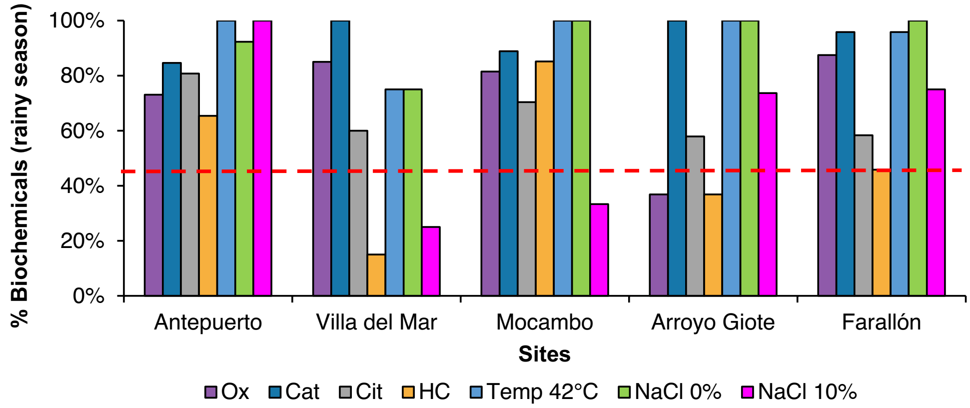

Fig. 10 Percentage variation of biochemicals during the rainy climatic season. *Ox* oxidase, *Cat* catalase, *Cit* citrate, *HC* carbohydrates, *Temp* temperature

greater pressure on those that still conserve their natural characteristics. According to Montes Cardona et al. (2021), the concentration of heterotrophic bacteria could be affected by the availability of organic matter at the site; in addition, these values are usually higher in coastal areas due to the contributions of runoff and rivers.

Farallón was selected as a contrast beach because it is an exposed beach, considered natural, with little anthropogenic contribution of organic matter and far from an urban center. In fact, Pérez-Ruiz (2012) proposes it as a reference beach to evaluate natural and induced disturbances. Therefore, it is not surprising that the lowest concentration of heterotrophic bacteria was recorded there (Bertasi et al. 2007). Likewise, Rodil et al., (2007) found that the concentrations of organic matter were significantly different when comparing protected and exposed beaches, since the low hydrodynamic conditions of protected beaches favor the settlement of fine sediments rich in organic matter.

Antepuerto is a narrow beach that has the greatest anthropogenic influence. In addition to having a rainy discharge, close movement of small boats and the presence of tourists, it is adjacent to the tourist area of the boardwalk and the urban/hotel development. The highest rate of heterotrophs was recorded during the dry season. The Navy statistics (de Marina 2022) were consulted on the monthly movement of cargo on ships for the months in which the sampling was carried out. This showed that in September, during the rainy season, the port activity was lower than that in May in the dry season. Also, the waste generated by vessels is mainly contaminants in the form of organic matter (Cifuentes et al. 2003; Cataneo-Nieto et al. 2019).

Villa del Mar and Mocambo are very similar beaches, exposed to various anthropogenic activities, close to the urban center, with a high presence of tourists and high concentrations of organic matter and coliforms (Pérez-Ruiz 2012; Sánchez-Domínguez et al. 2015; Hidalgo-Rodríguez 2017) as well as the presence of breakwaters that dissipate wave energy but promote the deposit of fine materials and organic matter (Bernal-Ramírez and Granados-Barba 2008). High rates of organic material are not direct indications of the degree of site deterioration (Brown and McLachlan 1990). Particularly in Villa del Mar the coastal current reflects a strong sedimentation of fine materials and organic matter (Lizárraga-Arciniega et al. 2007; Pérez-Ruiz 2012). On the other hand, Trojanowski and Bigus (2013) explain that precipitation favors the increase in vegetation and this, in turn, increases organic matter in coastal areas that arrives through river discharge. Therefore, another factor explaining why higher concentrations of heterotrophs were obtained in the rainy season could be that these beaches had been affected by the contribution of terrigenous sediments from the Papaloapan, La Antigua and Jamapa Rivers (Ortiz-Lozano and Bello-Pineda 2012; García-Fuentes et al. 2014; Pérez-Jiménez et al. 2023). Pérez-España and Vargas-Hernández (2008) indicate that the average annual sedimentation rate is 250 g m^{-2} day^{-1}, which is indicative of a greater presence of organic matter on beaches located near the urban center.

Arroyo Giote beach, in both dry and rainy seasons, presented average concentrations, with very little difference between them; like Farallón, it is an unmodified rural beach. The difference between their concentrations could be because fishing predominates as an economic activity in Arroyo Giote and livestock activities are carried out in neighboring areas. It has little direct influence from the urban center; however, it is closer than Farallón and receives intermittent input from a stream with the same name. The interaction of the southern currents, near where this site is located, generates a cyclonic gyre, whose vertical movement produces resuspension of sediments, increasing the amount of material near the surface (Salas-Monreal et al. 2009).

Characteristics of the ZMV beaches influence the biochemical capacities of heterotrophic bacteria

Baisre (2008) and Castañeda-Chávez et al. (2018) explain that, due to the nature of the sources and transport routes, most pollutants that enter the marine environment from land-based sources are released near the coast where they are

Table 8 Response of heterotrophic bacteria to the battery of tests

Beach	Antepuerto	Villa del Mar	Mocambo	Arroyo Giote	Farallón	Antepuerto	Villa del Mar	Mocambo	Arroyo Giote	Farallón
Test	Dry season					Rainy season				
Oxidase	24	15	23	17	10	19	17	22	7	21
Catalase	25	17	20	17	13	22	20	24	19	23
Citrate	21	14	12	9	10	21	12	19	11	14
Fermentation	1	9	2	4	2	17	3	23	7	11
Temperature 42 °C	16	20	16	14	9	26	15	27	19	23
NaCl 0%	19	20	19	16	12	24	15	27	19	24
NaCl 10%	15	8	16	7	3	26	5	9	14	18

Numbers indicate the number of groups of heterotrophic bacteria with a positive response to each test

recycled and trapped. Therefore, the coastal zone represents a genetic reserve with potential use in sectors such as medicine and biotechnology (Martínez et al. 2007).

In spaces influenced by external forces, bacteria become more selective because of their adaptation to the environmental conditions (Celis-Bustos et al. 2017). Thus, it is inferred that dominant bacterial populations have developed on urban beaches such as Villa del Mar, Mocambo and Antepuerto because of the site characteristics. Pérez-Ruiz (2012) classifies Farallón as a site totally exposed to wind and waves that induce instability in the environment. The waves complicate the establishment of species not adapted to the environment. Therefore, a lower biochemical diversity of bacteria would be expected. However, this was not the case, and the responses shown by the heterotrophic groups allow us to see their ability to metabolize different substrates and adapt to different conditions.

Yannarell and Kent (2009) and García-Fuentes et al. (2014) state that seasonal patterns can govern and produce the flowering of great bacterial diversity, with changes in their communities causing species rotation. Based on the percentage differences in the biochemical capacities of the isolates during two seasons where the environmental conditions were different, as well as the human activities carried out in each site during the study period, the heterotrophic bacteria demonstrated their metabolic versatility and adaptability to different conditions.

Conclusions

Factors such as proximity to an urban center, activities related to various economic and recreational purposes that cause contaminating organic material and coastal protection structures, sediments are retained, and these factors influence the deterioration of the area. Other environmental factors include waves, currents, wind, weather events, beach hydrodynamics and runoff as carriers of external polluting material and/or as contributors to a spatial rearrangement of this substrate, which is essential for bacterial metabolism, having a greater influence on bacterial concentrations. The site factor demonstrated that the degree of anthropogenic disturbance presented by each beach was a reflection of the differences in their morphology, structure and use.

In terms of biochemical diversity, the isolates showed their ability to metabolize different substrates, present diverse enzymes and tolerate the ranges of temperature and concentration of salts to which they were exposed. This study provides valuable information for carrying out new research in the coastal area of Veracruz where heterotrophic bacteria will be studied. The importance of constant monitoring is highlighted, where climatic temporalities and the particular characteristics of each beach are considered to establish patterns of intertidal bacterial diversity.

The presence of heterotrophic bacteria is a reflection of the degree of anthropogenic disturbance that each beach presents, with a tendency to concentrate mainly on those within the ZMV. On the other hand, the gradient of anthropogenic disturbance did not influence the diversity of the biochemical characteristics of heterotrophic bacteria since they are distributed in both urban and natural beaches.

Author contributions Conceptualization, C.R.V. and M.R.C.CH.; Methodology, V.U.R. and C.R.V.; A.G.B Validation; formal analysis, C.R.V and M.R.C.CH.; research, A.G.B; and M.R.C.CH. All authors reviewed the manuscript.

Data availability The data are available.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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