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ORIGINAL PAPER

Evaluation of climate, water and peloid of the Pink Lagoon of Torrevieja and its possible use in thalassotherapy

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Abstract
The Pink Lagoon in Torrevieja is found in the Bajo Segura region of the province of Alicante (Spain). This exorheic lake of marine sedimentary origin was connected to the Mediterranean Sea up until Quaternary times. Today it acts as a salt flat, receiving water from its neighbouring Lagoon La Mata and brine from washing of the El Pinoso quarry. The purpose of the work is to study its environmental resources: the factors of the climate, the physicochemical properties and the composition of the waters, the thermal and textural characteristics of the natural peloid, and assess their possible use as thalassotherapeutic agents. The results obtained: marine climate; hypothermal water of strong mineralization (390 g/l), hypersaline, rich in magnesium sodium chloride and extremely hard; and lime muds of mineral sediment mainly organic with a low water content and scarce hardness and adhesiveness. They allow their application in thalassotherapy, obtaining the best results in musculoskeletal and skin disorders.

Keywords Climate · Salt Water · Peloid · Climatotherapy · Thalassotherapy · Mud Therapy · Pink Lagoon of Torrevieja

Introduction

The Pink Lagoon in Torrevieja (PLT) and neighbouring lagoon La Mata are found in the Bajo Segura within a basin whose surrounding relief is the consequence of local tectonic activity. Into this basin drain small streams and gullies of sporadic activity. The lagoons are included in the Parque Natural de las Lagunas de La Mata-Torrevieja, which covers 3,700 Ha in the municipalities of Torrevieja, Guardamar del Segura and Los Montesinos, in the Alicante province (Fig. 1).

From a climate perspective, the PLT belongs to the southern coastal sector of Orihuela, south of the Betic Ranges and east of the climate sector of Villena, which is the most arid of the Valencia Community. Its dry period lasts six months centred in the summer. Average yearly temperatures are elevated due to mild winters, and mean yearly rainfall, sometimes below 300 mm, varies scarcely in autumn and spring.

These exorheic lakes arising from marine sediments were, up until the Quaternary, naturally connected to the sea. They communicate with the Mediterranean Sea via both channels and are connected to each other by the Canal de Las Salinas. This canal functions according to the needs of the salt industry such that, during the dry season, adequate levels are maintained in the Torrevieja lagoon through water transfer from La Mata lagoon. The PLT has more homogenous concentrations of dissolved substances and serves as a salt crystallizer receiving water from La Mata lagoon and brine from the washing of salts at the El Pinoso quarry (Martí 2010).

Since time immemorial it has been known that the waters and natural muds of the PLT are topically used to treat certain conditions (Martí 2010).

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Fig. 1 Maps showing the location on the eastern Spanish coast of the PLT

Coastal environments offer a wide variety of natural resources that, in addition to being ecologically unique, have significant therapeutic applications and health benefits. Among these resources are the climate, seawater, and mud generated in saline environments (Munteanu and Munteanu 2019; Gomes et al. 2021; Antonelli and Donelli 2024).

The climate of coastal areas is characterized by milder temperatures, high levels of humidity, and clean air, all of which have positive effects on physical and mental health. In regions like Torrevieja, the Mediterranean climate, with more than 300 days of sunshine per year, enhances vitamin D synthesis thanks to moderate sun exposure, improving bone health and the immune system. Along with the sea breeze, rich in saline aerosols, it also helps improve respiratory airways and resolves various conditions, including skin disorders (Maraver et al. 2011; Antonelli and Donelli 2024; Nordgren and Duvetorp 2024; Weather Spark 2024).

Seawater, especially the hypersaline water found in PLT with a salt concentration far higher than conventional seawater, inhibits the proliferation of microorganisms and is useful for cleaning and healing minor wounds, as well as addressing physiological oxidation and silent inflammation processes (Harel et. 2023; Cegolon et al. 2024). Hypersaline waters contain halophilic microorganisms that produce substances with antimicrobial and antioxidant properties, which could have therapeutic applications in preventing skin infections (Carbajo and Maraver 2018; Sánchez-Porro 2023).

Its high density facilitates flotation, reducing joint stress and providing relief for rheumatic and muscular conditions (therapeutic flotation therapy) while stimulating blood flow, helping to reduce inflammation, and improving cellular metabolism (Zijlstra et al. 2005; de Andrade 2008; Kim et al. 2020; Gomes et al. 2021; Bekaryssova et al. 2024; Cegolon et al. 2024; Costanzo et al. 2024).

Finally, the mud generated in these saline environments, known as silt, sludge, or marine mud, is rich in minerals such as magnesium, calcium, potassium, and sulfates. When applied directly to the skin, it has numerous detoxifying and anti-inflammatory benefits, particularly for joint ailments such as arthritis or rheumatism (Kim et al. 2010; Abu-Shakra et al. 2014; Gálvez et al. 2020), as well as for skin exfoliation and cosmetic processes related to skin aging (Mourelle et al. 2024). Its minerals and osmotic abrasive effects help remove dead skin cells, resulting in softer and rejuvenated skin (Carbajo et al. 2024). Additionally, it can alleviate dermatological issues such as psoriasis, eczema, or acne (Munteanu and Munteanu 2019; Carretero 2020; Antonelli and Donelli 2024; Harari 2024).

The purpose of the work is to study the climate, water and peloid of the PLT and its possible use in thalassotherapy.

Materials and methods

Climate

The temperature of a given region is usually directly related to the sunlight it receives and the quality of its soil. This is, in turn, dependent on altitude, latitude, season, month, day, time, relative humidity and air velocity. Historic data related to the climate of PLT can be found in records of the Spanish Meteorological Agency (WeatherSpark 2024).

Variations in maximum, minimum and average temperatures were examined, along with mean temperatures of the different seasons and special circumstances. Similarly, we compiled monthly: Daylight hours, Clear Sky percentage, Shortwave solar energy, Rainy days (means), Average Wind speed, Relative humidity and Temperature.

For the set of components characterizing atmospheric weather, we compiled data obtained for the period 2015–2023 and prepared the corresponding figures.

Water

The sample was taken from the central part of the lagoon (geographic coordinates 37°59′29.5"N; 0°43′12.2″ W) on July 1, 2021, a surface sample in an area equidistant from its shores. For analysis and sampling of the lagoon's waters, we followed the Standard Methods for the Examination of Water and Wastewater 23rd edition (Baird and Eaton 2017) and the US EPA norm (EPA 1986), using two-liter polymeric flasks suitable for sampling, we employed two samples.

Peloid

The peloid sample was collected from the lagoon bottom some two meters from the shore (geographic coordinates 38º01′00'' N; 0º42′26'' W) into a polymer recipient and kept refrigerated until analysis.

The following variables were determined: instrumental texture (Hardness in g, Adhesiveness in g.s, Cohesion dimensionless determination) (Armijo et al. 2015), particle size en μm, heat capacity in J/kg K, thermal conductivity in W/mK, heat retention capacity in 10^4 s/m^2, cooling curve and relaxation time in s of peloids following the methods described in a recent article (Armijo et al. 2016; Maraver et al. 2021).

Results

Climate

The results of PLT climate are represented in Fig. 2 and Table 1. The different climatic variables are characterized by: (A) Daylight hours range from 14.8 h in June to 9.6 h in December; (B) Clear Sky percentage, in July 90% of the days are clear, unlike 57% in October; (C) Shortwave solar energy presents a maximum of 7.9 kW/h in June and a minimum of 2.4 kW/h in December; (D) Rainy days (means), the highest number of rainy days occurs in October, with a monthly average of 4.5 days, while July is the least rainy month with only 0.7 days; (E) Monthly average rainfall, the rainiest month is October with an average of 31.9 mm and the least rainy is July with an average of 2.7 mm; (F) Average Wind speed. February is the month with the highest wind speed, with 16.6 km/h and the lowest is August with 13.7 km/h; (G) Relative humidity. October and December obtained the maximum monthly average with 68% and the minimum in June 58%; (H) Temperature. The highest monthly average is obtained in August 26 ºC and the lowest average in January 11 ºC.

Water

Table 2 shows the analytical results of the PLT water sample taken from the surface of the central lagoon area. The water can be described as hypothermal, of strong mineralization, hypersaline, rich in magnesium sodium chloride and extremely hard.

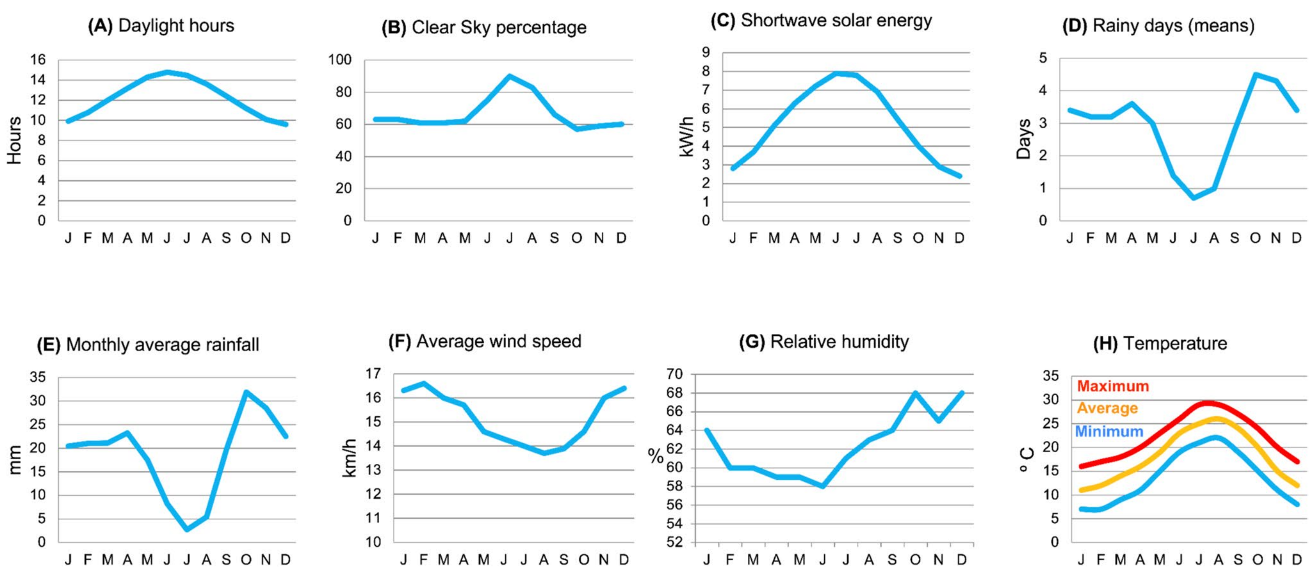


Fig. 2 Images with PLT climate factors (years 2015–2023): (**A**) Daylight hours by month; (**B**) Average percentage clear days per month (means); (**C**) Average daily incident shortwave solar energy (means); (**D**) Rainy days by month (means); (**E**) Monthly average rainfall (mm); (**F**) Average wind speed by month; (**G**) Variations in mean relative humidity by month; (**H**) Average, maximum and minimum ambient temperatures (means)

Table 1 Average monthly and annual values of PLT climate variables during 2015–2023 period

	J	F	M	A	M	J	J	A	S	O	N	D	Ann
Daylight hours (h)	9.9	10.8	12.0	13.2	14.3	14.8	14.5	13.6	12.4	11.2	10.1	9.6	12.2
Clear Sky percentage (%)	63	63	61	61	62	75	90	83	66	57	59	60	66.6
Shortware solar energy(kW/h)	2.8	3.7	5.1	6.3	7.2	7.9	7.8	6.9	5.4	4.0	2.9	2.4	5.2
Rainy days (number)	3.4	3.2	3.2	3.6	3.0	1.4	0.7	1.0	2.8	4.5	4.3	3.4	2.8
Monthly average rainfall (mm)	20.5	21.0	21.1	23.2	17.5	8.2	2.7	5.4	19.9	31.9	28.5	22.5	18.6
Average wind speed (km/h)	16.3	16.6	16	15,7	14.6	14.3	14	13.7	13.9	14.6	16	16.4	15.1
Relative humidity (%)	64	60	60	59	59	58	61	63	64	68	65	68	62.4
Temperature (ºC)	11	12	14	16	19	23	25	26	24	20	15	12	18.1

Table 2 Physicochemical composition of water from the PLT

Type of water	Strong mineralization Sodium, Chloride		
Organoleptic properties	Smell: Marine Colour: Colourless Flavour: Salty		
Physicochemical properties			
Temperature	26.3 ºC		
Conductivity to 25 °C	757,000 µS.cm^{-1}		
pH value	7.9		
TDS to 180 °C	389,720 mg/L		
Alkalinity	356.4 mg/L $CaCO_3$		
Anions	mg/L	mEq/L	% mEq
Cl^-	216,687.6	6,112.758	90.04
F^-	12.3	0.648	0.01
HCO_3^-	434.8	7.127	0.10
Br^-	1,018.8	12.756	0.19
NO_3^-	16.6	0.268	0.00
SO_4^{2-}	31,461.4	655.026	9.65
Cations	mg/L	mEq/L	% mEq
Na^+	106,467.8	4,631.347	69.55
K^+	7,758.6	201.569	3.03
Li^+	39.3	5.667	0.09
Ca^{2+}	4,858.2	242.424	3.64
Mg^{2+}	19,176.8	1,578.055	23.70
Dissolved Gases	mg/L		
CO_2 dissolved	17.8		

Peloid

Centesimal composition

In Table 3, we provide the peloid composition analysis results and compare them to those of other latitudes.

To determine the peloids solid phase, we examined their ash/solids ratio. The higher this value is, the lower the content of volatile and organic substances eliminated through high temperatures; that is, the solid phase is of the inorganic type.

Table 3 Other peloids of low water content obtained from lagoons of high dry-residue waters classified according to their water content

Peloid	% Water	% Ash	Ash/Solids
Torrevieja (Spain)	21.8	57.5	0.74
Hakisor (Kazakhstan)*	23.1	76.9	0.99
Inder (Kazakhstan)*	26.1	72.7	0.98
Sorkol (Kazakhstan)*	27.9	69.9	0.96
Dead Sea (Israel)**	30.1	54.2	0.77
Lo Pagan (Spain)**	34.3	56.2	0.85
Aralsor (Kazakhstan)*	35.2	63.9	0.98

* Data from Akhmedenov & Khalelova 2021; ** Maraver et al. 2021

The product obtained from the PLT shores was found to have a low water content and an ash/solids ratio of 0.74 (Table 3), indicating a solid phase mainly composed of inorganic materials at a similar concentration to those of the Dead Sea and mud flats of Lo Pagan (Spain).

Particle size

Figure 5 (A) shows a histogram of peloid particle size distributions and the attached table provides percentages for the different size ranges. The k-th percentile was defined as the size measurement equivalent or lower than k/100 of observations. Accordingly, Dv50 would be the maximum particle diameter below which would represent 50% of the sample volume, also known as the median volume. The most commonly reported percentiles are Dv10, Dv50 and Dv90.

Thermal parameters

In Table 4, we present the thermal parameters calculated for the Torrevieja peloid: heat capacity, thermal conductivity and heat retention capacity shows the same parameters compared to those of other hypersaline waters with specific heats similar to that of the PLT. Heat retention capacity is defined as the heat transmission velocity from the peloid to the patient. These results are completed with those displayed in Fig. 5 (B) which provides curves of temperature variations with time. Relaxation times in these curves indicate rapid heat release of the product.

Instrumental texture

The instrumental texture of peloids is important as their hardness, adhesiveness and cohesion offer information regarding their possible uses and method of application. Figure 5 (C) show the texture results of the Torrevieja peloid. With a Hardness 52.2 g, Cohesiveness of 0.88, and

Table 4 Thermal parameters of the PLT peloid compared to those of similar salt concentration

Peloid	Heat capacity (J/kg K)	Thermal conductivity (W/mK)	Thermal retention (10^4 s/m^2)
Torrevieja (Spain)	1.6	0.488	5.49
Hakisor (Kazakhstan)*	1.6	0.604	4.51
Inder (Kazakhstan)*	1.7	0.578	4.89
Sorkol (Kazakhstan)*	1.7	0.561	5.13
Lo Pagan (Spain)**	2.0	0.489	6.21
Aralsor (Kazakhstan)*	2.0	0.529	5.81

* Data from Akhmedenov & Khalelova 2021; ** Maraver et al. 2021

an Adhesiveness of 510.56 g.s. Based on our experience, we consider the hardness value of 300 g as a reference (Maraver et al. 2021).

Discussion

Once the results of PLT thalassotherapy factors have been described, we proceed to the analysis of the climatic variables and characteristics of water and peloid:

Climate

Day length varies considerably over the year. Figure 2 (A) shows hours of *daylight* over the months of the year. The earliest sunrise is at 6:39 h on June 14 and the latest is 1 h and 44 min later at 8:23 h on October 28.

Cloudy skies occur in varying measure throughout the year, the least overcast period starting in mid-June and finishing at the start of September. Figure 2 (B) shows the proportion of *clear sky percentage* in the year which are essential for heliotherapy procedures. The clearest month of the year is July, during which the sky is clear 90% of the time.

Figure 2 (C) shows average daily *shortwave solar energy* falling on the Earth's surface including visible light and ultraviolet radiation, which shows high seasonal variation throughout the year. The brightest period of the year spans from May 5 to August 17, with an average daily incident shortwave energy greater than 6.9 kWh/m^2. The thermal effect of the solar radiation is mainly dependent on infrared radiation and to a lesser extent on wavelengths of light in the visible region. This effect can be more or less damaging to the skin from the corneal epidermal layer to the papillary dermis and manifests in the form of a rash caused by ultraviolet radiation.

Rainy days, depending on the season, in winter (December, January and February) the average rainfall is 78.1 l/m^2 and the average temperature is 13.2 °C, which contrasts with the average rainfall and temperatures in summer (June, July and August), of 17.1 l/m^2 and 25.4 ºC. Autumn (September, October and November) is rainier (107.6 l/m^2) and warmer (20.3 ºC) than spring (March, April and May), with 62.1 l/m^2 and 17.1 ºC, respectively. A rainy day is defined as one receiving at least 1 mm of rainfall. The rainiest period occurs from September 12 to May 24 when the likelihood is more than 8% of rainy days. The month with most rainy days is October with a mean of 4.5 days. Figure 2 (D) shows the days of rain for each month of the year. It is important to consider monthly rainfall. Torrevieja only shows slight variation in rainfall, the rainy season lasting 8.8 months from September to May. The rainfall regimen is described as minimum for a Mediterranean summer given the influence of the Azores Maximum which reaches the Mediterranean and shows two peaks: one in autumn and the other at the end of spring.

About *monthly rainfall*, the rainiest month is October with an average rainfall of 32 mm and July is the least rainy at only 3 mm. Figure 2 (E) shows the monthly millimetres of rain received. Autumn rains are provoked by low pressure areas from the Gulf of León, or via the Gibraltar straits causing an abrupt rise in rainfall between August and September. Mean annual precipitation (MAP) in Torrevieja is 288 mm.

In terms of water evaporation, it is interesting to consider *wind speed*. Figure 2 (F) shows wind velocity in km/h over the year. This variable shows little variation over the period examined. In general, anticyclone weather conditions predominate in winter, at times involving strong winds from the east. As Torrevieja is a coastal region, there are scarce atmospheric pressure variations over the year, especially from spring to autumn, when it fluctuates between 1022 and 1005 mbar within a range that has no effect on organic functions. The predominant wind is the easterly Levant from the sea, and its closeness to the sea means that humidity is high over most of the year such that the sensation of heat is generally intense and sticky.

Atmospheric pressure, winds and temperature all markedly affect environmental *relative humidity* which has an impact on a person's sensation of wellbeing. Figure 2 (G) shows the variation in relative humidity produced over the months of the year. Mean relative humidity varies from 68 to 58%, being highest in October (68.06%) and lowest in June (57.59%).

Climate at the PLT typically consists of warm dry summers with *temperatures* rarely exceeding 40 ºC and few days hotter than 35 ºC. Winters are mild with temperatures very infrequently falling below 2 ºC. Climate classifications are based on temperature. Torrevieja is described as having a climate typical of intermediate latitudes with well-defined summer and winter periods. Over the period 2015 to 2023, mean yearly temperature was 19.0 ºC. The warmest month is August, with a mean temperature of 26.9 ºC and the coldest is January with one of 12.8 ºC. The rainiest month is September with a mean rainfall of 44.3 l/m^2 and the driest is July at 1.1 l/m^2. Figure 2 (H) shows the distributions of maximum, minimum and mean temperatures of Torrevieja. The hottest period spans three months from June 21 to September 22, when the average maximum daily temperature is above 27 °C. The hottest month of the year is August with an average maximum temperature of 29 °C and minimum of 22 °C. The cool period lasts four months, from November 23 to March 22, when the average daily maximum temperature is 19 °C. The coldest month of the year in Torrevieja is January, with a mean minimum temperature of 7 °C and maximum of 16 °C, giving rise to a mean annual temperature (MAT) of 18.4 ºC.

According to Koppen classification (Peel et al. 2007), in 2015–23 period, the climate of Torrevieja can be described as BWh, that is, arid, desert and hot. Its classification as *Arid or dry* is based on the fact that its MAP of 222 mm is lower than 10 $\times P_{threshold}$ (500 mm). The $P_{threshold}$, when 70% of MAP occurs neither in winter nor in summer, is equal to (2 $\times$MAT + 14) in this case 50.

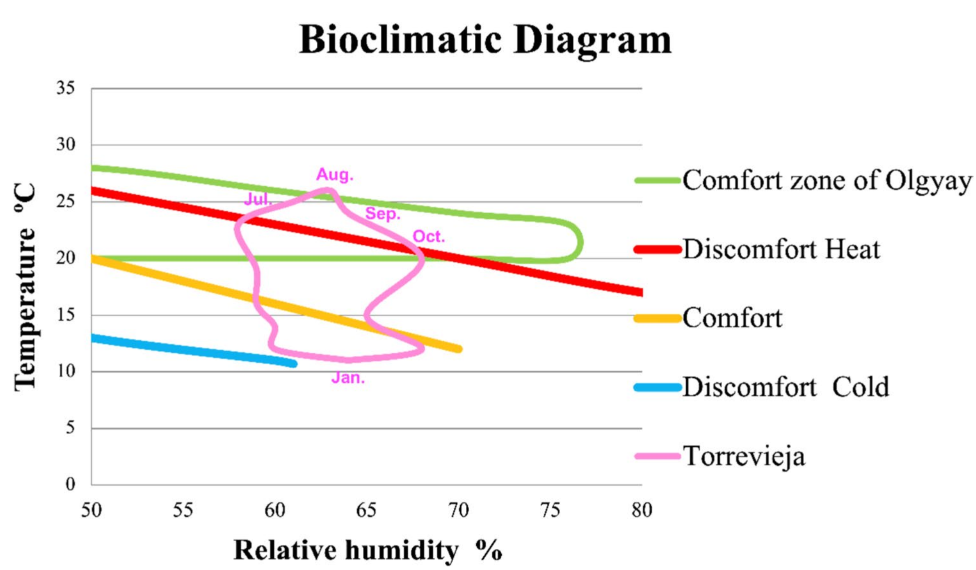
In this context, evaporation exceeds mean annual precipitation, providing adequate conditions for the appearance of salt pans with no remains of water and precluding the existence of permanent water currents. In Torrevieja the climate classification of *Steppe* “S”, is moderate because of its closeness to the sea and is consequently never severe.

Figure 3 shows the zone of temperature and relative humidity values in which the human body normally experiences a feeling of personal wellbeing or comfort (Honjo 2009). This zone appears between the boundaries of discomfort due to heat (red line) or cold (blue line). The pink line designated “Torrevieja” indicates mean monthly values of relative humidity and temperature, showing their behaviour month by month from January to December. The months January to June, November and December have relative humidity and temperature means that fall within the limits of wellbeing. Under these conditions, the region is also ascribed to the zone of wellbeing or comfort in the human comfort climate diagram of Olgyay. That is, for a person at rest and in the shade, the ideal ambient temperature should be between 22 ºC and 27 ºC, and relative humidity in the range 20% to 80%. These months thus comply with the limits defining an acceptable thermal sensation (Lyndon et al. 2015). Outside the limits of comfort due to heat or cold are the months of July, August, September and October, although only August falls outside the human comfort climate zone of Olgyay (Nikolopoulou 2011).

As described, the Pink Lagoon offers exceptional climatic conditions no comparable to other environmental resources, such as the Dead Sea and Kazakhstan's saline lakes Hakisor, Inder, Sorkol, and Aralsor. Despite their geographical and altitudinal differences, both locations stand out for their beneficial health properties and distinctive climatic environments. The Dead Sea, located approximately 430 m below sea level, is the lowest point on Earth's surface. This altitude contributes to a unique atmosphere, with higher air density and increased filtration of ultraviolet rays. This allows for longer and safer sun exposure, which is beneficial for individuals with skin conditions like psoriasis (Emmanuel et al. 2020, 2022; Harari 2024). On the other hand, the Pink Lagoon is situated at sea level, resulting in more direct solar incidence and a less dense atmosphere. However, its location on the Mediterranean coast provides a mild, sunny climate for most of the year, with over 300 sunny days annually. Other hypersaline lagoons or lakes, such as Kazakhstan's saline lakes Hakisor, Inder, Sorkol, and Aralsor, are situated at varying altitudes and experience less direct solar incidence due to their more northerly location (Akhmedenov 2020; Akhmedenov and Khalelova 2021). This affects temperature and the duration of sunny seasons, making them shorter than in Torrevieja and the Dead Sea. The lakes in Kazakhstan, such as Sorkol, Inder, Hakisor, and Aralsor, have more extreme climates. Winters are often cold, with subzero temperatures, while summers are warm, with peaks exceeding 30 °C (Akhmedenov 2020; Akhmedenov and Khalelova 2021). These thermal fluctuations and the limited duration of warm seasons make their therapeutic use more seasonal compared to Torrevieja and the Dead Sea (Antonelli and Donelli 2024).

At the Dead Sea, winds are typically gentle and consistent, contributing to the stability of its atmosphere. In the

Fig. 3 Bioclimatic diagram for Torrevieja



Pink Lagoon, prevailing winds are Mediterranean, fresh, and saline, enhancing the air quality in the area and boosting the therapeutic benefits of the environment. The absence of strong currents in both locations also ensures the safety and comfort of users. In Kazakhstan's saline lakes, such as Inder and Hakisor, winds can be stronger, and climatic conditions may become harsher at certain times of the year, which can hinder accessibility and therapeutic experiences.

Water temperature may be another determinant for skin application (Cegolon et al. 2024). The Dead Sea exhibits elevated temperatures year-round, with averages ranging from 20 °C to 40 °C depending on the season. Its relative humidity is low, which, combined with the high salinity of the water, creates a unique environment for relaxation, respiratory health, and suitable conditions for exfoliative skin processes (Emmanuel et al. 2020). In contrast, Torrevieja's Pink Lagoon offers very comfortable annual average temperatures, ranging from 18 °C to 28 °C, with moderate humidity due to its proximity to the Mediterranean. This balance makes the climate pleasant in both summer and winter. Other environmental resources using seawater, such as those in coastal regions like in Brittany (France), Lo Pagán (Spain), or the Canary Islands (Spain), also harness the benefits of saline water, mild climates, and air rich in salinity. However, both the Pink Lagoon and the Dead Sea offer a distinguishing factor: their hypersaline waters (Emmanuel et al. 2022). The Pink Lagoon, with its characteristic colour due to microorganisms such as halobacteria and the alga *Dunaliella salina*, provides exfoliating and revitalizing properties like those of the Dead Sea, where the high concentration of minerals also delivers highly therapeutic and anti-inflammatory effects (Martínez et al. 2022; Cegolon et al. 2024).

In summary, both the Pink Lagoon and the Dead Sea share natural resources with health-beneficial properties that make them unique locations for health and wellness care. While the Dead Sea benefits from its significant depth below sea level, the Pink Lagoon stands out for its Mediterranean climate and scenic uniqueness. Compared to other thalassotherapy establishments, such as Lo Pagán, Spain, or Kazakhstan's lakes, both offer exceptional conditions that position them as privileged destinations for those seeking treatments based on the properties of the natural environment.

Water

As previously referred to in Table 2 the PLT water is described as hypothermal, of strong mineralization, hypersaline, rich in magnesium sodium chloride and extremely hard.

Sodium chloride waters of comparable mineralization to that shown by the PLT (390 g/l) can be found in Alzhansor (Kazakhstan) 152 g/l, lakisor (Kazakhstan) 160 g/l, Ursu (Rumania) 256 g/l, Salies de Béarn (France) 260 g/l, Kreuznach Salinen (Germany) 310 g/l, Droitwich (UK), 318 g/l, Salies du Salat (France) 322 g/l, Dead Sea (Israel) 340 g/l, Elgorriaga (Spain) 341 g/l, and Elton (Russia) 500 g/l (Portugal-Cohen et al. 2019; Akhmedenov 2020; Akhmedenov and Khalelova 2021; Gomes et al. 2021; Armijo and Maraver 2022).

The microbial load of salt waters has not always been considered important. For a long time, it was even thought that life in hypersaline environments was unlikely and that these were inadequate for any physiological activity (Martínez et al. 2022).

This concept has changed dramatically. Hypersaline environments are common on our planet. In the presence of brine, the fauna is dominated by halotolerant microorganisms, preventing the life of conventional microscopic water organisms. This means that only moderately halophilic organisms (up to 150 g/kg of salinity) and extremely halophilic organisms (salt concentrations exceeding 250 g/kg) remain, which is probably the case of the PLT (Martí 2010).

Microorganisms capable of living in brine, depending on the characteristics of temperature, salt concentration and luminosity are generally made up of phyto- and zooplankton, bacteria, archaea, fungi and yeasts. A recent study has examined the microbiome of the LRT (Martínez et al. 2022). We should also consider the microbial load of the PLT. In natural brines, there exists a specific population of microorganisms that is highly resistant to hyperosmotic conditions as is the microalga *Dunaliella salina*, which is able to release to the environment, substances with useful applications in cosmetics and dermatology (Apone et al. 2019).

The phytoplankton consists of prokaryotes (cyanobacteria protozoa) and eukaryotes like some diatoms and *Dunaliella* spp., especially *Dunaliella salina* (Oren 2002). In natural brines, the existence has been reported of a population of microorganisms that are highly resistant to hyperosmotic environments, as is the microalga *D. salina*, capable of releasing substances useful for the skin (Monte et al. 2020).

Dunaliella salina is a unicellular green microalga with known antioxidant properties arising from its contents including polar lipids, betacarotenes, carotenoids and vitamin B_{12} (Monte et al. 2020). It also has humidifying properties owing to its glycerol content, and antiageing properties because of its antioxidant capacity, possibly influenced by its vitamin B_{12} content (Kumudha and Sarada 2016). Further, this alga has been found to show a marked antimicrobial action (Bahador et al. 2019).

In such hypersaline settings, it is common to find halotolerant bacteria such as oxygen-dependent phototrophs (cyanobacteria) and anorexigenic organisms; or chemoautotrophs: sulphur-oxidizing bacteria, anaerobic and aerobic heterotrophs, and sulphur-reducing bacteria (SRB) able to convert sulphate ions into hydrogen sulphide (Gheorghievici et al. 2023).

In settings similar to those surrounding the PLT, the abundance of archaea should be highlighted. These unicellular organisms lack a nucleus, and while they resemble bacteria, they may be differentiated from them in that their cytoplasmic membranes are mainly composed of lipids bound to glycerol by an ether bond, while in bacteria this occurs via an ester bond.

Archaea produce exopolysaccharides, carotenoids and proteins as a way of adapting to extreme environmental conditions as well as some red pigments whose antioxidant capacity is much more active than that of betacarotenes. Interestingly, these pigments are what gives flamingos their intense pink colour when filtered during feeding (Yim et al. 2015).

The reddish pigment is due to the formation of carotenoids such as bacterioruberin and its derivatives such as mono- and bis anhydrobacterioruberin and bacteriorhodopsin (Oren 2002).

In addition, bacterioruberin, unlike betacarotenes which have 9 conjugated double bonds and no hydroxyl group, has a greater antioxidant capacity because of its 13 conjugated double bonds and four hydroxyl groups.

These reddish carotenoid pigments become embedded in the cell membranes of archaea and have some 50 carbon atoms. In some cases, this is accompanied by a reddish pigment called bacteriorhodopsin. This pigment contains fractions of retinal (retinaldehyde) with marked antiageing properties as a precursor, as is retinol (vitamin A), of cutaneous retinoic acid, responsible for skin cell renewal (Belyaeva et al. 2019).

In consequence, hypertonic saline settings have their own environment-dependent microbiota, and this microbiota has important properties for their use in dermatological and cosmetic formulations (Belyaeva et al. 2019).

Studies of halophilic microbiota in Mediterranean salt flats (including PLT) have recorded the presence of cyanobacteria in lower proportions than the aforementioned halobacteria and extremophilic archaea and halo-tolerant microalgae, with their proportion of toxins (such as microcystins) being very limited in this type of media, and no toxic influence has been described in animals or humans (Martínez et al. 2022).

Salt waters rich in sodium chloride have been used since ancient times as a therapeutic agent for skin conditions despite no knowledge then of their generation of a sensation of well-being through the release of endorphins (Portugal-Cohen et al. 2019).

According to our analysis of the water of PLT, salinity is exceptionally high at around 390 g/l and pH is mildly alkaline. These variables indicate its classification as a hypertonic water with clearly defined properties in the treatment of dermatological, respiratory and joint disorders (Gomes et al. 2021).

We would like to emphasize that, unlike other saline environments in the LTP, the proliferation of macroalgae is greatly hampered by the high salt concentration throughout the year. Although macroalgae are photosynthetic eukaryotic organisms, they are usually associated with stable marine environments, some species have developed mechanisms of tolerance to extreme salinity and are found in lagoons, salt flats, and hypersaline effluents, including waste brines from desalination plants, which is not the case in the LTP. These hypersaline environments are challenging due to their high osmotic pressure, low nutrient availability, and strong irradiation. However, certain species manage to survive, adapt, and even perform important ecological functions.

While the exact actions of electrolytes on skin remain unclear, direct chemical measurements have indicated that skin is a deposit of water and sodium chloride. Titze et al. (2002) reported that glycosaminoglycans in the skin become polymerized and facilitate the cutaneous storage of osmotically-inactive sodium without proportionally increasing the skin's water content.

In hypernatremia, as in the present case, there is displacement of water from the intracellular to the extracellular space, leaving the skin pasty and velvety smooth. Conversely, when there is hyponatremia, the skin loses turgidity and takes on a more wrinkled appearance, due mainly to displacement of extracellular water to the venous circulation.

This phenomenon is regulated by osmotic factors (Carbajo & Maraver 2018) because the cell plasma membrane is permeable to water and semipermeable to inorganic and organic solutes. To maintain their viability, epidermal keratinocytes have semipermeable membranes sensitive to external osmotic pressure. They regulate their hydration state and cell volume, adapting to the external osmotic pressure via the accumulation/elimination of low molecular weight inorganic ions and of organic molecules called osmolytes.

Changes in cell volume and hydration state are an essential process for life. Such changes regulate several vital cell functions like growth and differentiation, metabolism, epithelial transport, the release of hormones, excitability, migration and even cell death.

Cells in general and cutaneous cells in particular respond to changes in their volume mainly through two mechanisms. The process whereby cells swollen by a hypotonic medium recover their normal volume is called regulator volume decrease (RVD), while the opposite process, as in the present case whereby cells increase their volume to recover from shrinkage in a hypertonic medium like brine, is known as regulator volume increase (RVI) (Carbajo & Maraver 2018).

This phenomenon, regardless of accompanying processes, has a marked influence on the vitality and general state of the skin. When the skin is submerged in a hypertonic solution like the water and peloid of the PLT, an increase is produced in dermal glycosaminoglycan production (Agócs et al. 2020) probably due to a lethal osmotic shock for superficial cutaneous cells. In turn, this leads to the apoptotic death of these superficial keratinocytes and induces the basal keratinocyte to undertake its growth and renewal to replace the eliminated superficial apoptotic keratinocyte. This phenomenon is technically known as "saline peeling". It stimulates the cell renewal of the epidermis, as an ideal dermatological treatment for skin cell renewal and is essential to treat scaly skin conditions such as psoriasis, ichthyosis and atopic dermatitis, among others.

In general, it is recommended that the thalassotherapeutic treatment of the scaling dermatological condition psoriasis (Munteanu & Munteanu 2019; Harari 2024) should be carried out at regulated establishments and following a clinical protocol of action. It has even been observed that, sometimes in certain skin conditions, simple immersion in water is as effective as the standard habitual treatment.

Similarly, several clinical studies have shown the therapeutic benefits of bathing in salt waters for rheumatoid arthritis (Karagülle et al. 2017) and osteoarthritis conditions (Kim et al. 2020) and for chronic low back pain (Gomes et al. 2021).

While the intake of minerals is necessary for skin health, skin treatment in health resort medicine, balneotherapy or thalassotherapy depends considerably on the cutaneous actions of water's mineral elements (Morer et al. 2017) and the composition of its salts. Moreover, in pelotherapy this is the only mechanism for therapeutic activity. With the exception of some molecules present in peloids (Gomes et al. 2021), active thermal agents are hydrophilic molecules, and their detailed study will help us elucidate the efficacy of hydrothermal topical treatment.

Accordingly, main indications for thalassotherapy are conditions affecting the respiratory tract (asthma, rhinitis and sinusitis) (Gomes et al. 2021); skin conditions (eczema, acne, rash, ichthyosis, psoriasis) (Munteanu & Munteanu 2019; Emmanuel et al. 2020; Emmanuel et al. 2022; Dai et al. 2023; Harari 2024); rheumatic disorders (arthritis, arthrosis, fibromyalgia, neuritis) (Zijlstra et al. 2005; de Andrade et al. 2008; Munteanu & Munteanu 2019; Gálvez et al. 2020; Kim et al. 2020; Cegolon et al. 2024); gynaecological diseases; fatigue; stress and depression; and oral hygiene involving both teeth and gums (Gomes et al. 2021; Antonelli & Donelli 2024).

Osmotic changes are promoted if the sea water temperature approaches normal human body temperature (35–37 °C). It may therefore be concluded that the success of thalassotherapy is improved the greater are both the salinity and temperature of the waters employed.

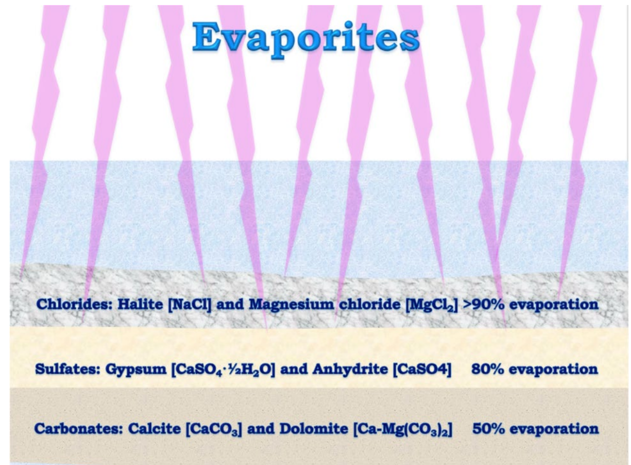


Fig. 4 Precipitation of the saline PLT peloid according to percentage water evaporation

Peloid

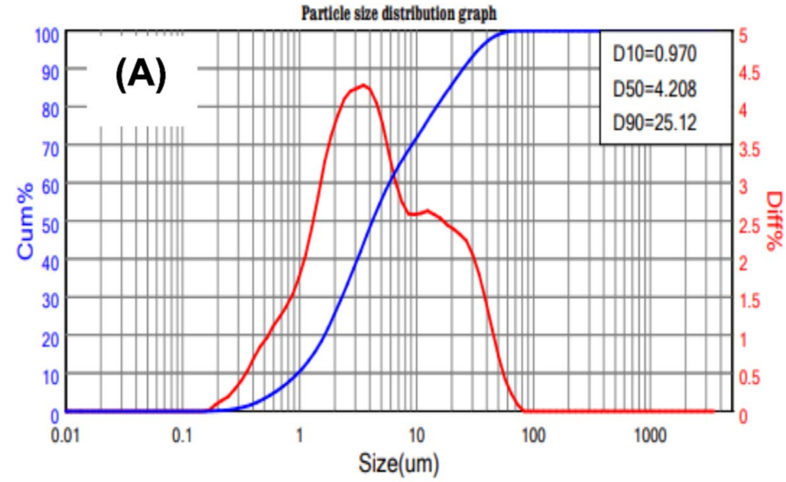
Salt water of marine or mineral origin is characterized by its high mineral ionic content, high density and chemical composition rich in chlorides and sodium, as well as magnesium, calcium, potassium and iodine (Antonelli & Donelli 2024).

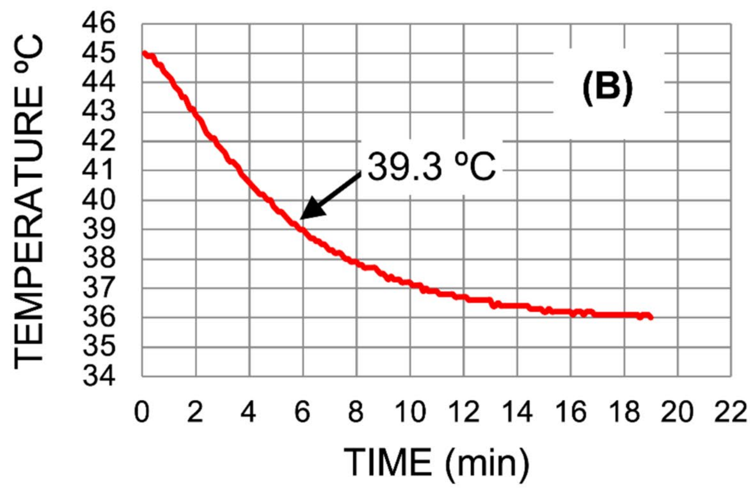
Besides their osmotic activity, the composition and characteristics of these salts offer some benefits for skin health. The saline PLT complex comprises a hypersaline wetland.

Some environmental factors described below cause an uncommon situation in the PLT: shallow brine layers receiving intense sunlight reaching high temperatures and salt concentrations, besides a relatively scarcely alkaline water pH (Revsbech et al. 1983). This scenario leads to a high evaporation rate of water that produces the concentration of brine and the ordered precipitation of its dissolved minerals. This precipitation is progressive as water evaporates and the brine becomes saturated with the different salts and these precipitate according to their water saturation index (Tamez 2009), which is the essential feature of a peloid.

In the climate setting of the PLT, the ordered precipitation of salts takes place, modifying the composition of the lagoon's waters. Salt precipitation is the outcome saturation caused by massive water evaporation.

The first salts precipitated are carbonates and bicarbonates in the form of calcite ($CaCO_3$) and dolomite (Ca-Mg$(CO_3)_2$), which under conditions of 50% water evaporation, become saturated and are decanted. When water evaporation reaches 80%, this time sulphates precipitate out in the form of gypsum ($CaSO_4 \cdot 1/2\ H_2O$) and anhydrite ($CaSO_4$). Finally, following more than 90% water evaporation of brine concentration, the salts precipitated are chlorides mainly in the form of halite (sodium chloride, NaCl) and in smaller proportion magnesium chloride (MgCl) (Martí 2010), Fig. 4.





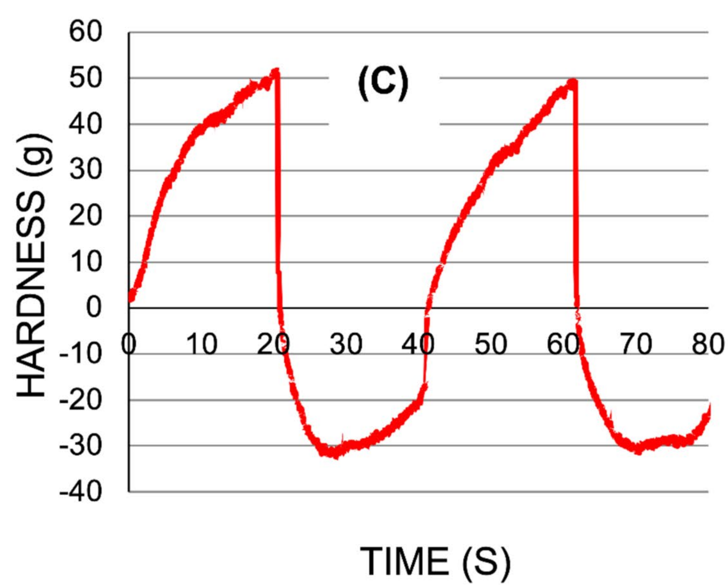


Fig. 5 Images of the properties of the natural peloid of PLT: (**a**) Histogram of particle size distributions (red line); (**b**) Cooling curve of the peloid; (**c**) Hardness profile of the peloid

Accordingly, at the bottom of this fordable lagoon forms a mud susceptible to the growth of halophilic microorganisms, both aerobic and anaerobic but mainly the latter. In effect, the mud surface is an ideal environment for the growth of aerobic microorganisms and its oxygen-free interior is ideal for the development of a saline anaerobic microbiota. Such anaerobes are usually found below the gypsum saturation layer, and they obtain nutrients and trace elements from the water above (Martí 2010).

These microorganisms generate active substances and under these conditions of light, temperature, saturation and pH, they can form these precipitates known as"evaporites"which give rise to an active clay with beneficial skin health properties (Singh & Singh 2017).

As observed in Table 3, the *centesimal composition* of the peloid obtained in PLT shows a low water content, similar to those of Hakisor, Inder and Sorkol (Kazakhstan). The ash/solids ratio of 0.74 is very similar to that of the Dead Sea and Lo Pagan thermal complexes, all of them with solid phases of the inorganic and organic type, which differentiates them from the mostly inorganic ones, with a value of this ratio close to one.

Our results indicate a similar *particle size* distribution for the Peruibe (Brazil) and differences with other saline Spanish peloids (Maraver et al. 2021). As can be seen in Fig. 5 (A), there are two particle sizes families, 50% of them between 1 to 10 µm with a maximum peak of 4.25 µm, while the second family (40% of the particles) between 10 and 100 µm with an approximate maximum peak of 12 µm.

In Table 4, we can see that the *specific heat* of the PLT peloid is very low, due to its low water content, and is comparable to those of Hakisor, Inder, and Sorkol (Kazakhstan). The *thermal conductivity* of the studied peloid is high, comparable to that of Lopagan (Spain). *Thermal retention* of the studied peloid has average values compared to those studied in the table, with the values for Sorkol and Aralsor being similar. From the curve Fig. 5 (B) showing the variation in temperature from 45 to 36 ºC from time, it can be deduced that the *relaxation time* up to 39.3 ºC is just under 6 min.

Figure 5 (C) show the *instrumental texture* of the Torrevieja peloid. With a *Hardness* 52.2 g, that defined as the compression force needed to produce a given deformation, is measured as the compression force peak in the first graphic cycle (g), which represents a low hardness. *Adhesiveness* of 510.56 g.s, defined as the work needed to extract the probe from the sample, is given by the area under the negative portion of the force peak in the first cycle, which represents a high adhesiveness value that allows it to be used in brushing. *Cohesiveness* of 0.88, is the ratio between the positive force during the second compression cycle and that of the positive force during the first compression Armijo et al. (2015). This is a high value, since the maximum is 1.

Organic matter comes from the remains of microorganisms, algae, or compounds derived from biological degradation. In the case of Pink Lagoon, halophilic microorganisms are of vital importance (Carretero 2021; Martínez et al. 2022).

They usually have a plastic and smooth texture that allows easy application on the skin. They possess a high capacity to retain and transmit heat, making them suitable for thermal therapies. They contain minerals and bioactive compounds that may have anti-inflammatory, analgesic, or regenerative effects (Maraver et al. 2021).

Peloids are highly valued for their therapeutic benefits, and their efficacy depends on the specific composition and characteristics of their place of origin. Water is a differentiating factor and generally determines their therapeutic activity (Gálvez et al. 2020). This is the case with Lake Techirghiol (Romania), Salies de Béarn (France), Morinje Bay (Croatia), and the lagoons of Kazakhstan (Morer et al. 2017; Akhmedenov 2020; Akhmedenov & Khalelova 2021; Bekaryssova et al. 2024).

Conclusions

The climatic characteristics of the PLT fulfil several requirements for for its health-beneficial activities. Similarly, the lagoon's waters, both in their natural state or diluted, are suitable for therapeutic use.

The hypersaline waters of PLT share numerous characteristics with those described for other spa medicine centres, which are used for their health benefits, although their health effects still need to be precisely defined through appropriate clinical trials.

Due to its physical characteristics (low water content, low hardness and adhesiveness, and rapid heat transfer), PLT peloid has properties for use as a thermotherapy agent. Due to its mineral composition (hypersaline), it has potential for health in musculoskeletal and dermatological disorders.

Abbreviations **MAP**: Mean annual precipitation; **MAT**: Mean annual temperature; **PLT**: Pink Lagoon in Torrevieja; **RVD**: Regulator volume decrease; **RVI**: Regulator volume increase

Authors contributions Conceptualization, F.M., F.A., J.-M.C. and M.-L.V.; methodology, F.M., F.A., J.-M.C. and M.-L.V.; investigation, F.M., F.A., J.-M.C., M.-L.V., L.A., M.A.F.-T., A.I.M.-M. and M.V.F.-G.; data curation, L.A., M.A.F.-T., A.I.M.-M. and M.V.F.-G.; writing—original draft preparation, F.M. J.-M.C. and M.-L.V.; writing—review and editing, F.M., F.A., J.-M.C. and M.-L.V.; visualization, F.M. and M.-L.V.; supervision, F.M. and M.-L.V.; All authors have read and agreed to the published version of the manuscript.

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Data availability All data supporting the findings of this study are available within the paper.

Declaration

Conflicts of interest The authors declare no conflicts of interest concerning this article.

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