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Temporal and spatial variation in hydrogen sulfide (H_2S) emissions during holopelagic *Sargassum* spp. decomposition on beaches

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ABSTRACT

Background: Since 2011, over 30 tropical Atlantic nations have experienced substantial landings of holopelagic *Sargassum* spp. Its decomposition results in the production of hydrogen sulfide (H_2S), which, in elevated concentrations, can pose a threat to human health. This study aims to enhance our understanding of the temporal and spatial variability in H_2S emissions during the decomposition of *Sargassum* on beaches. The primary objective is to assess potential exposure risks for local populations, tourists, and cleanup workers.
Methods: H_2S levels were monitored using a SENKO sensor (SGTP-H_2S; limit of detection 0.1–100 ppm; resolution 0.1 ppm) at four distances from *Sargassum* accumulation points of (0, 10, 30, and 40 m) in Puerto Morelos, Mexico, during 2022 and 2023.
Results: Elevated concentrations of H_2S were detected beneath the *Sargassum* piles, with 23.5% of readings exceeding 5 ppm and occasional spikes above 100 ppm. Above the piles, 87.3% of the measurements remained below 2 ppm, and the remainder fell between 2.1 and 5.2 ppm. At 10 m from the shoreline, 90% of measurements registered below 0.1 ppm, and the remaining 10% were below 2 ppm. Readings at 30 and 40 m consistently recorded levels below 0.1 ppm. H_2S concentrations positively correlated with *Sargassum* pile height, the temperature beneath the piles, and wind speed.
Conclusions: Our findings suggest no immediate and significant exposure risk for residents or tourists. However, *Sargassum* cleanup workers face a higher exposure risk, potentially encountering concentrations above 5 ppm for nearly one-fourth of the working time.

1. Introduction

In recent decades, macroalgae blooms have proliferated, posing significant threats to human health, biodiversity, and economies (Smetacek and Zingone, 2013; Xiao et al., 2020). Particularly noteworthy are the holopelagic *Sargassum* species (*S. fluitans* and *S. natans*), which experienced a surge in the Atlantic Ocean in 2011, currently impacting over 30 tropical Atlantic nations in America, Africa, and the Caribbean (Gower et al., 2013; Wang et al., 2019). These blooms are linked to increased nitrogen availability and shifts in ocean currents resulting from climate change (Lapointe et al., 2021; Marsh et al., 2023). *Sargassum*'s substantial landings, sometimes in the order of thousands of cubic meters per kilometer of shoreline annually (Rodríguez-Martínez et al., 2022), pose formidable management challenges, with annual cleanup costs ranging from US$0.3 to 1.5 million per kilometer in Mexico alone (Rodríguez-Martínez et al., 2023a). Unfortunately, many affected countries lack the resources for comprehensive cleanup efforts, resulting in neglected shorelines.

As dense *Sargassum* piles decay on coastlines, they release leachates and gases, including methane, ammonia, and the toxic and flammable hydrogen sulfide (H_2S) produced by sulfur-reducing bacteria (Hac Ko et al., 2015). Recognizable by its "rotten eggs" odor, H_2S can lead to various health effects, depending on the concentration and exposure duration (Supplementary Table 1). Even at low concentrations, H_2S can cause mild irritation of the eyes, nose, and throat, while prolonged exposure may result in symptoms such as headache, fatigue, dizziness,

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and nausea (WHO, 2003). This can occur in open, low-lying outdoor environments since H_2S is heavier than air (Williamson, 2010).

The NE Yucatan began being affected by extensive pelagic *Sargassum* landings in 2014 (Rodríguez-Martínez et al., 2016). These events lead to beach erosion and a decline in seawater quality, affecting seagrass beds, coral reefs, inlets, bays, and mangroves (Rodríguez-Martínez et al., 2016, 2019; van Tussenbroek et al., 2017). Improper disposal also affects adjacent jungles and aquifers (Chávez et al., 2020). *Sargassum* events have recurred annually since 2018, with substantial stranding lasting from five to seven months, particularly during spring and summer when east and southeast winds dominate (Rodríguez-Martínez et al., 2022). The quantity of beached *Sargassum* per kilometer during peak landing months in the northern section of this coast escalated from an average of 2360 m^3 in 2015 (Rodríguez-Martínez et al., 2016) to 6565 m^3 in 2019 (Rodríguez-Martínez et al., 2022). Residents of coastal areas have reported detecting the odor emitted by decomposing *Sargassum* up to several hundred meters inland (Chávez et al., 2020). Additionally, H_2S has been identified as a cause of corrosion of copper cables, electronic equipment, and hotel and household appliances near the shoreline.

Despite *Sargassum* landings becoming annual events in Mexico and many other Atlantic countries, minimal attention has been given to its impact on human health, with limited data on day-to-day variations and potential health effects. To our knowledge, only the Regional Health Agency (ARS) in Martinique has monitored H_2S production associated with *Sargassum* decomposition since 2015, issuing advisories and implementing evacuations when concentrations exceed safe levels (>5 ppm). During the 2018 *Sargassum* episode, neurologic and respiratory complaints were reported on this island (Resiere et al., 2021), emphasizing the substantial public health hazard posed by elevated H_2S.

This study seeks to enhance our understanding of the temporal and spatial variability in hydrogen sulfide (H_2S) emissions during the decomposition of *Sargassum* on beaches. The primary objective is to assess potential exposure concentrations for local populations, tourists, and cleanup workers. The investigation explores the relationship between H_2S concentrations and critical attributes of *Sargassum* piles, such as height and width, as well as environmental factors, including air temperature, temperature beneath the pile, wind speed, and wind

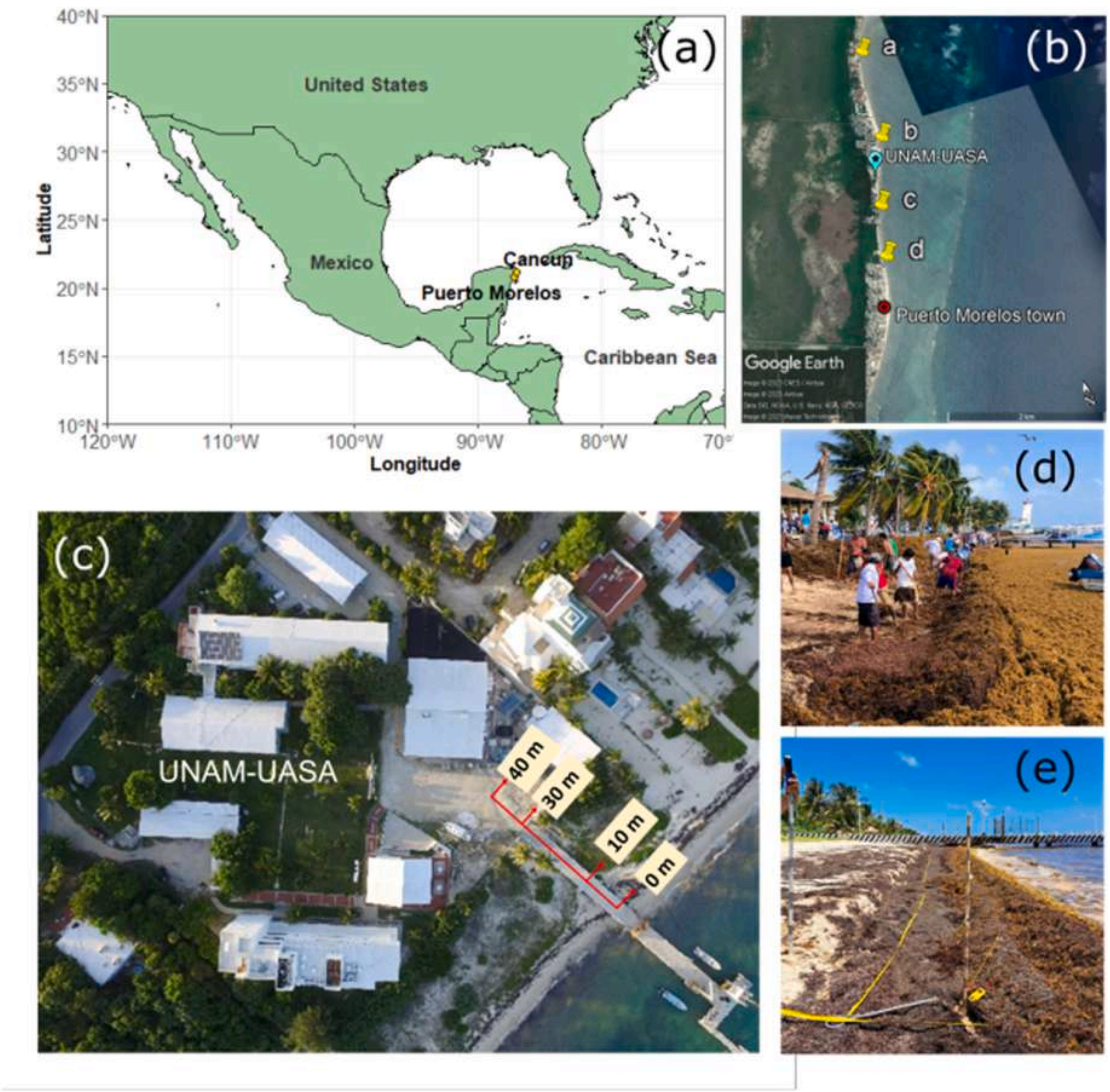

Fig. 1. (a) Map showing the location of Puerto Morelos, Mexico. (b) Google Earth image indicating the location of UNAM-UASA, where H_2S concentration measurements were conducted from July to September 2022 and February to August 2023. It also delineates four beaches within a 1.5 km radius on either side of UNAM-UASA, where hotels tracked monthly *Sargassum* landing volumes. (c) The drone image of the study site shows the four distances where H_2S concentrations were measured. (d) Beach cast *Sargassum* in Puerto Morelos. (e) Transect illustrating the shoreline path where H_2S measurements were taken.

direction.

2. Methods

2.1. Study area

The study was conducted in Puerto Morelos, located on the northeastern coast of the Yucatan Peninsula, 30 km south of Cancun (Fig. 1a). Puerto Morelos thrives on tourism, boasting 68 hotels with 7199 rooms; in 2022, the municipality hosted nearly one million tourists (SEDETUR, 2023). It has a population of 26,921 inhabitants (INEGI, 2023). The coastline is flanked by a 4 km long coral reef, forming a lagoon with widths ranging from 550 to 1500 m and depths from 3 to 8 m (Ruíz-Rentería et al., 1998).

2.2. Temporal variation in H_2S concentrations at four distances from the shoreline

The H_2S measurements were conducted utilizing a SENKO sensor (SGTP-H2S) with a resolution of 0.1 ppm and a detection limit of 0.1–100 ppm. These measurements occurred on average twice a week at four distances from the shoreline in front of the Unidad Académica de Sistemas Arrecifales, Instituto de Ciencias del Mar y Limnología, UASA-UNAM (Fig. 1b), spanning from July to September 2022 and February to August 2023. *Sargassum* landings were minimal between the two sampling periods, and no H_2S measurements were taken. No beach cleanup activities were undertaken during the study period.

The selected distances from the shore included 0m (corresponding to *Sargassum* piles), 10m (designated tourist area), and 30m and 40m (representing the populated area), all at the height of 1.5 m above ground (Fig. 1c). Ground-level measurements were also taken at 0 and 10 m. A supplemental reading was obtained after excavating within the *Sargassum* piles undergoing decomposition until reaching the sand to estimate potential exposure to cleanup workers (Fig. 1d). On each sampling day, two measurements were taken at the shoreline and one at each of the other three distances. The total number of measurements was 774.

Sargassum landing volumes for the study period were provided by four hotels within a 1.5 km radius on both sides of the study site (Fig. 1b). Collectively, these locations encompassed a sampling distance of 1.3 km. During our investigation, *Sargassum* beach cast volumes ranged from 3 to 975 cubic meters per 100 m of shoreline (Supplementary Fig. 1). The highest median volume was recorded in April 2022 (Median: 338 m^3 per 100m), while the lowest was observed in September 2023 (Median: 24 m^3 per 100m).

During H_2S measurements, wind speed, direction, and air temperature were sourced from UNAM-UASA's Oceanographic and Meteorology Monitoring Service in Puerto Morelos, which boasts an ISO 9001:2015 certification (SAMMO, 2023)—sampling hours ranged from 8 a.m. to 7 p.m. During the study period, air temperature fluctuated between 26.2 and 31.6 °C in the study area, with wind direction from 27° to 336°, while wind speeds ranged from calm conditions (0 m/s) to brisk 11.3 m/s (Supplementary Fig. 1).

2.2.1. Spatial variation in H_2S concentration within decomposing *Sargassum* piles

To assess the potential exposure to H_2S of *Sargassum* cleanup workers, we positioned nine 15-m-long transects in a random configuration, running parallel to the shoreline within the central region of decomposing *Sargassum* piles (Fig. 1e). This data collection was carried out from 11 August to September 14, 2023. For each meter along the transect, the following data were recorded: 1) H_2S concentration levels beneath *Sargassum* piles, measured using a SENKO SGTP-H2S sensor with a resolution of 0.1 ppm and a limit of detection from 0.1 to 100 ppm; 2) the width and height of *Sargassum* piles, measured in centimeters with a resolution of 5 cm; 3) the temperature of the sand beneath the algae, assessed with a calibrated thermometer, accurate to 0.1 °C; and 4) wind speed at the height of 1 m above ground level, measured using a portable anemometer AIOMEST AI-100-WM. Air temperature and wind direction data were sourced from UNAM-UASA's Oceanographic and Meteorology Monitoring Service in Puerto Morelos. The total number of measurements for each variable was 135.

2.3. Statistical analysis

The temporal and spatial data were consolidated to determine the percentage of measurements falling within specific concentration ranges (ppm): <0.1, 0.1–2, 2.1–5, 5.1–10, 10–50, and >50. A Principal Component Analysis (PCA) was conducted to investigate the relationship between H_2S concentration and the following variables: a) air temperature, b) the temperature beneath *Sargassum* piles, c) *Sargassum* pile width, d) *Sargassum* pile height, e) wind speed, and f) wind direction. The Spearman rank correlation was used to determine the association level between the various parameters.

All analyses were conducted in R (R Core Team, 2023) using packages: ggpubr (Kassambara, 2020), plyr (Wickham, 2014), tidyr (Wickham, 2021), vegan (Oksanen, 2011), and ggbiplot (Vu, 2011). The significance level (α) for all analyses was set at 0.05. A reproducible record of all statistical analyses and the underlying data can be found on GitHub (https://github.com/rerodriguezmtz/Sargassum_H2S_emission).

3. Results

3.1. Temporal variability in H_2S concentrations at four distances from the shoreline

Throughout the study, hydrogen sulfide (H_2S) concentrations ranged from less than 0.1 to over 100 ppm. Fig. 2 illustrates that concentrations surpassing 5 ppm were almost exclusively recorded underneath the *Sargassum* piles, with only two instances (out of 142 measurements) where such levels were observed on the shoreline above the piles. Among the 277 measurements underneath *Sargassum* piles, 59.5% were below 2 ppm, 17.0% ranged from 2.1 to 5 ppm, 9.7% fell within the 5.1–10 ppm range, 11.2% went from 10.1 to 50 ppm, and 2.5% exceeded 50 ppm (Fig. 2a); the median was 1.2 ppm [interquartile range {IQR}: <0.1–4.6].

H_2S concentrations just above the *Sargassum* piles varied from less than 0.1–5.2 ppm (Fig. 2b); 62.7% of the recorded measurements remained below 0.1 ppm, 24.6% ranged from 0.1 to 2 ppm, and 12.7% fell between 2.1 and 5.2 ppm. The median was <0.1 ppm [IQR: 0.0–1.5]. At 10 m from the shoreline, at the ground level, H_2S concentrations ranged from <0.1 to 2.0 ppm, with 90.1% falling below the 0.1 ppm threshold (Fig. 2c). The median and IQR were <0.1 ppm. In H_2S measurements obtained at 1.5 m above ground, the highest observed concentrations were 0.9 ppm, a reading consistent above the *Sargassum* piles and 10 m from the shore, with a median and IQR <0.1 ppm (Fig. 2d–e). All measurements taken at 30 and 40 m from the shoreline consistently registered less than the sensor's detection limit (0.1 ppm) (Fig. 2f).

3.2. Spatial variation in H_2S concentration within decomposing *Sargassum* piles

Hydrogen sulfide concentration within the nine randomly positioned, 15-m-long transects parallel to the shoreline, located within the central area of decomposing *Sargassum* piles, exhibited a range <0.01–94.2 ppm, with a median of 0.6 ppm [IQR: <0.1–3.2]. At the time of the measurements, the *Sargassum* piles' heights varied from 5 to 30 cm, with widths spanning 70–300 cm, air temperature ranged from 28.9 to 31.1 °C, while temperatures beneath the *Sargassum* piles ranged from 29.4 to 36.4 °C (Table 1). Wind direction varied from 31.4° to 210°, with wind speeds ranging from 0 to 6.2 m/s (Table 1).

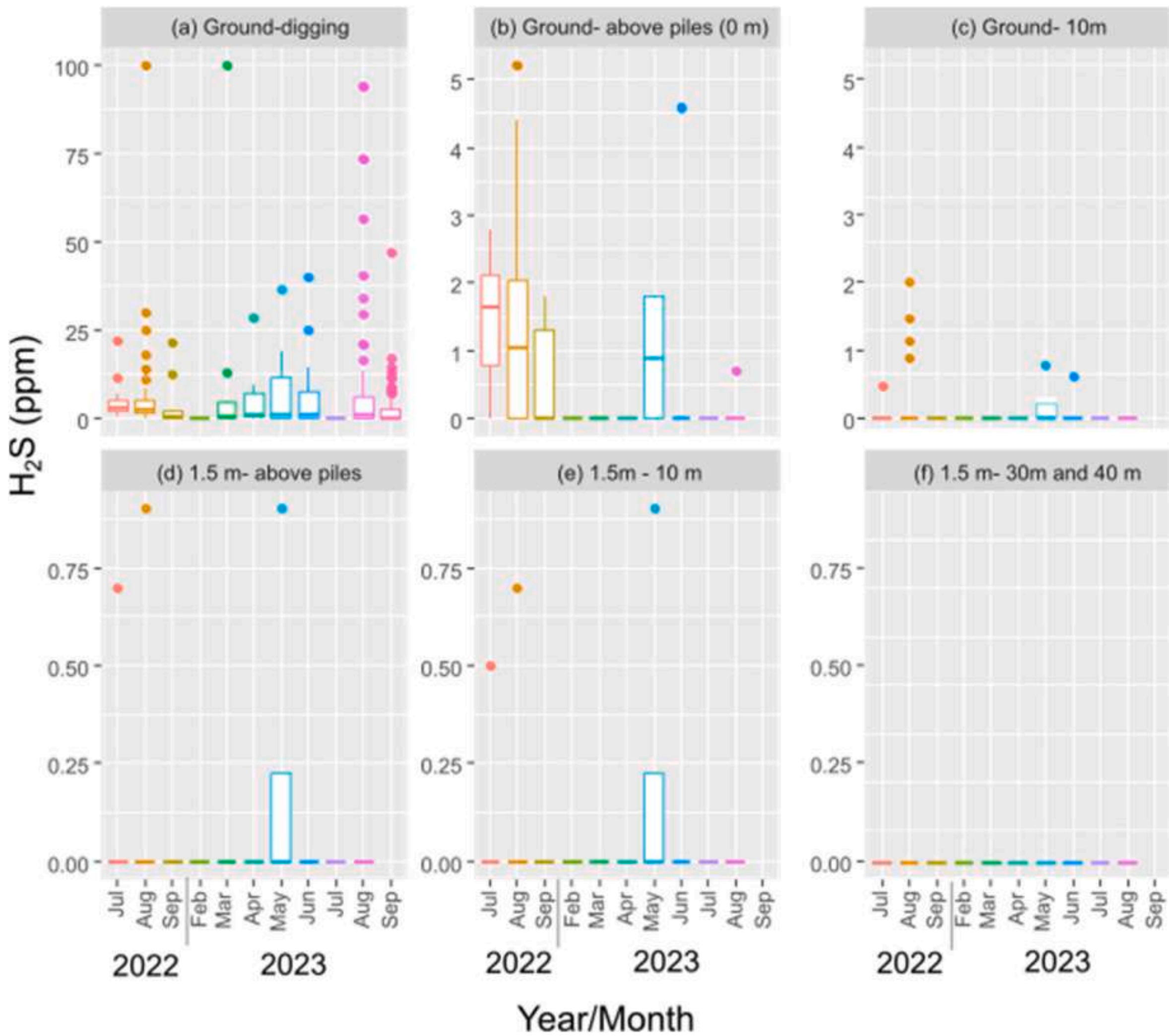

Fig. 2. Hydrogen Sulfide (H_2S) concentration (ppm) measured at various distances from the shoreline and heights: (a) underneath *Sargassum* piles, (b) above *Sargassum* piles, (c) ground level at 10 m from the shore, (d) 1.5 m above *Sargassum* piles, (e) 1.5 m height at 10 m from the shore, and (f) 1.5 m height at 30 and 40 m from the shore. The sensor's detection range was 0.1–100 ppm, with a resolution of 0.1 ppm. In each plot, the bottom and top of the box correspond to the first and third quartiles, while the horizontal line within the box represents the median. The whiskers extend to the lowest datum within 1.5 times the lower quartile and the highest datum within 1.5 the upper quartile. Filled circles denote outliers.

Table 1
Summary of variables recorded in nine 15-m transects surveyed on *Sargassum* piles. N = 135. IQR: interquartile range.

Variable	Min-Max	Median (IQR)
H_2S beneath piles (ppm)	<0.1–94.2	0.6 (0–3.2)
Pile height (cm)	5.0–30.0	15.0 (10–20)
Pile width (cm)	70.0–300.0	130 (100–190)
Temperature below piles (°C)	29.4–36.4	30.9 (30.3–32.3)
Air Temperature (°C)	28.9–31.1	30.4 (30.4–30.8)
Wind speed (m/s)	0.1–6.2	2.5 (2.0–3.5)
Wind direction (°)	31.4–210.0	51.0 (31.4–91.8)

3.3. *Relation between H2S concentration and other variables*

Principal Component Analysis (PCA) revealed that H_2S concentration showed dependency on the height of *Sargassum* piles and the temperature beneath these piles. At the same time, wind speed exerted a comparatively milder influence (Fig. 3). No discernible relationship was observed between H_2S concentration and air temperature, pile width, or wind direction. These trends align with the results of the Spearman rank correlation analysis (Table 2).

4. Discussion

The hydrogen sulfide (H_2S) concentrations resulting from the decomposition of *Sargassum* on the beach exhibited significant variability in time and distance from the shoreline, ranging from less than 0.01 to over 100 ppm. As expected, the highest concentrations were consistently observed beneath the *Sargassum* piles, decreasing with increasing distance from the coastline, with 90% of measurements at ≥10 m registering below 0.1 ppm.

The observed H_2S concentrations suggest no immediate and significant exposure risk for residents or tourists. Occasional exposure to low H_2S concentrations (0.3–1 ppm) has been associated with minor irritation of the eyes, nose, and throat, as well as symptoms like headache, fatigue, dizziness, and nausea, particularly with prolonged exposure. These effects are likely temporary and pose minimal risk to human health (Higashi et al., 1983; Bhambhani and Sing, 1991; Lewis and Copley, 2015). However, it is uncertain whether long-term chronic exposure to low concentrations of H_2S could be as harmful to human health as short-term high exposure.

Residents in coastlines affected by substantial *Sargassum* landings may experience exposure to low H_2S concentrations for five to seven months. Studies in New Zealand, with the world's largest population

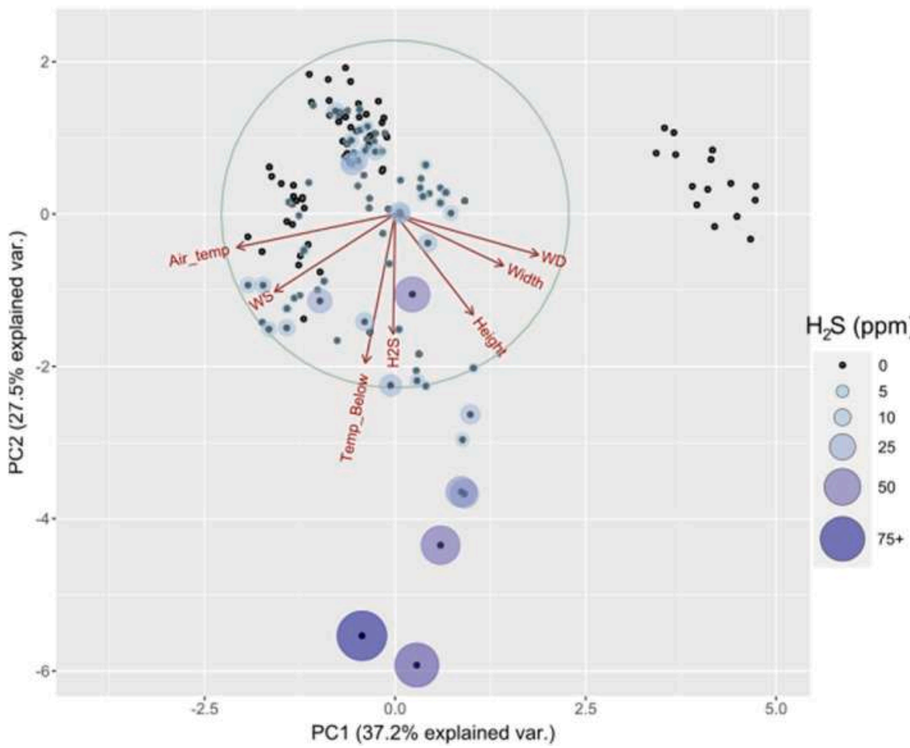

Fig. 3. Principal component analysis plot that examines the impact of several variables, including air temperature (Air_Temp), temperature beneath *Sargassum* piles (Temp_Below), pile height and width, wind speed (WS), and wind direction (WD) on the levels of H_2S concentration. The x and y axes correspond to the first two principal components, jointly responsible for elucidating 65% of the total data variability. Larger circle sizes (representing samples) and a deeper shade of blue indicate a higher concentration of H_2S.

Table 2
Results of Spearman rank correlation between H_2S concentrations underneath decomposing *Sargassum* piles and several variables.

Comparison	R	P
Temperature below pile	0.19	**<0.03**
Pile height	0.42	**<0.001**
Air temperature	0.084	0.33
Pile width	0.12	0.16
Wind speed	0.24	**0.0053**
Wind direction	−0.023	0.8

exposed to ambient H_2S, found that chronic exposure to low H_2S levels (<0.07 ppm) did not result in reductions in lung function or an increased risk of chronic obstructive pulmonary disease or asthma (Bates et al., 2013, 2015). There are reports of neurobehavioral and/or pulmonary impairments in people living near hog lagoons and exposed to average H_2S concentrations ranging from 0 to 0.03 ppm (Kilburn, 2012) and people exposed to H_2S from the sour gas/oil industry of New Mexico (Kilburn et al., 2010). However, the self-selected nature of the participants in those two studies does not exclude possible selection bias. Nonetheless, the risk to individuals chronically exposed to small quantities of H_2S remains uncertain, and the link between day-to-day variations in H_2S levels and their impact on health outcomes is not well understood. Further studies are necessary to determine the health effects of long-term exposure to low concentrations of H_2S produced during *Sargassum* decomposition. Until more research is conducted, it is wise to make efforts to limit long-term exposure, especially for vulnerable populations such as pregnant women, children, individuals with asthma and heart failure, and the elderly.

Additionally, residents and tourists near *Sargassum* piles could occasionally be exposed to concentrations ranging from 2.1 to 5.2 ppm, observed in 12.7% of cases. Such exposure could lead to mild symptoms, including eye irritation, headaches, fatigue, nausea, and dizziness; additionally, individuals with asthma may experience bronchial constriction (see Supplementary Table 1). Educating the public on strategies to limit H_2S exposure, including avoiding walking in affected areas and providing training and information to improve knowledge on H_2S toxicity, is essential.

Individuals involved in the manual cleanup of decomposed *Sargassum* face a higher exposure risk to H_2S, as they commonly spend 6–8 h daily, six days a week, for five to seven months per year shoveling through the piles and could be exposed to concentrations up to and exceeding 5 ppm 23.4% of the time. The effects of such chronic H_2S concentrations on workers' health are difficult to predict because although H_2S is heavier than air, it can be spread quickly by wind (Hussien et al., 2020). Thus, it is unlikely that H_2S will have the same health effects as those reported for exposure in closed environments, which vary depending on the concentration and exposure time. Resiere et al. (2021) have published the only study on the clinical characteristics of patients with long-term exposure to the repeated stranding of *Sargassum*. The authors documented respiratory, digestive, and neurological symptoms attributed to H_2S emissions during a substantial *Sargassum* event in Martinique from January to December 2018, where concentrations ranged from 0 to 11.1 ppm across the island. Nonetheless, clinical signs and symptoms distribution among individuals residing or working in areas with elevated H_2S levels did not markedly differ from those with lower H_2S concentrations. In a separate investigation, de Lanlay et al. (2022) associated H_2S exposure with a 65% elevated risk of early onset preeclampsia within a 2 km radius of strandings. However, no heightened risk gradient was identified for women closer to *Sargassum* decomposition sites. Additional research is needed to arrive at conclusive findings. Nonetheless, pregnant women residing or working in at-risk zones should undergo specialized surveillance, especially if they present other established risk factors of preeclampsia. It would be valuable to conduct studies similar to those of Resiere et al. (2021) and de Lanlay et al. (2022) in other countries affected by *Sargassum* invasions.

Our study identified several factors influencing the spatial variability in H_2S concentration, including *Sargassum*'s pile height, the temperature beneath the piles, and wind speed. The higher the piles, the more compact they will become, and the heat and gases will become trapped and build up. (Bilkiewicz and Kowalski, 2020; Ajmal et al., 2021; Yang et al., 2023). The high temperatures can change the chemical equilibrium and solubility of gases, potentially favoring the release of H_2S and increasing its concentration levels (Ajmal et al., 2021; Yang et al., 2023). To mitigate the potential environmental and health impact, it is advisable to promptly remove *Sargassum* from the beach within 48 h of its arrival. Beyond this timeframe, the prolonged presence of *Sargassum* contributes to elevated microbial activity and organic decomposition, leading to an augmented formation of hydrogen sulfide (H_2S). Therefore, timely removal within the specified window minimizes these adverse effects.

While wind can spread H_2S quickly (Hussien et al., 2020), it may also lower the air's barrier to diffusion between the organic matter's interior and the surrounding atmosphere as it breaks down. This likely led to the H_2S being more easily released into the environment with increasing wind speed. Moreover, wind can create airflow patterns that result in temporary gas stagnation (Jiang et al., 2023). This could lead to the accumulation of H_2S in the pile of *Sargassum* before the release, increasing concentrations in specific areas during such stagnation periods. However, the measured variables do not fully explain all variability in H_2S concentration, suggesting other factors also influence sulfur-reducing bacterial microniches (Hao et al., 1996). Future studies should consider additional variables like pH, atmospheric pressure, and precipitation.

Until further research is conducted on this topic, adhering to the H_2S recommendations established by the High Public Health Council of Martinique (https://www.madininair.fr/Les-algues-Sargasses?lang=fr) is suggested as an interim guideline, restricting beach access for susceptible individuals when concentrations range from 1 to 5 ppm. Cleanup workers should have personal monitors with alarms set at 5 ppm. These guidelines were also incorporated into the Integral Strategy for the Management and Industrialization of *Sargassum* in Quintana Roo, Mexico (Rodríguez-Martínez et al., 2023b). Following these recommendations will help safeguard individuals in *Sargassum*-affected areas while awaiting further research into this complex issue.

4.1. Study limitations

In this study, hydrogen sulfide (H_2S) measurements were conducted at a singular site once daily, averaging a frequency of two times per week. To enhance the comprehensiveness of future investigations, it is advisable to expand sample sizes and include a diverse range of sites with varying environmental conditions. For the measurements, our team utilized commercial sensors from SENKO, proven effective within the concentration range of 0.1–100 ppm. However, to conduct thorough risk assessments across different population sectors, there is a pressing need for higher-resolution sensors (0.01 ppm). This is particularly crucial considering the potential adverse health effects of long-term chronic exposure to H_2S at concentrations below 0.1 ppm, which might be as harmful as short-term high exposure. Moreover, it is recommended that the sensors employed have an elevated detection limit, given that H_2S concentrations can exceed 100 ppm. Ideally, these sensors should allow for continuous data recording, enabling the assessment of day-to-day variability in H_2S concentrations. This improvement in sensor capabilities and the development of long-term monitoring programs will contribute to a more comprehensive understanding of the dynamics and potential risks associated with hydrogen sulfide exposure to humans and the environment.

5. Conclusions

The H_2S concentrations resulting from *Sargassum* decay (0 to > 100 ppm) varied greatly in time and distance from the shoreline. Concentrations of H_2S exceeding 5 ppm were exclusively documented below and above *Sargassum* piles. This observation suggests a substantial risk of exposure for cleanup workers, with nearly one-quarter of their working time characterized by H_2S levels surpassing the 5 ppm threshold. This underscores the importance of implementing safety measures and monitoring protocols to safeguard the well-being of workers engaged in cleanup activities. H_2S concentration decreased with distance from the shore, with 90% of the measurements at $\geq$10 m registering below 0.1 ppm, suggesting no significant anticipated immediate health risks for residents and tourists. More research is needed to properly determine *Sargassum*'s potential health risks to residents and tourists chronically exposed to low H_2S concentrations. High-quality, quantitative exposure data from an adequate sample size, with preferably continuous personal monitoring, are needed to assess concentration-response relationships, leading to appropriate safety measures. *Sargassum*'s pile's height was positively correlated with H_2S concentrations. Thus, it is advisable to remove it from the beach within 48 h of its arrival to minimize environmental and human health adverse effects.

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CRediT authorship contribution statement

Rosa E. Rodríguez-Martínez: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Miguel Ángel Gómez Reali:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Eduardo Gabriel Torres-Conde:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis. **Michael N. Bates:** Writing – review & editing, Writing – original draft, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data can be found at https://github.com/rerodriguezmtz/Sargassum_H2S_emission.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.118235.

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