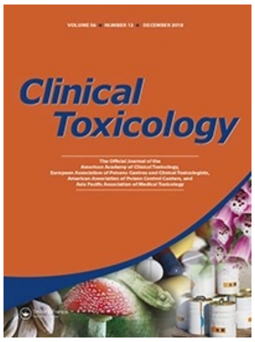

Clinical Toxicology

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ictx20

Sargassum seaweed health menace in the Caribbean: clinical characteristics of a population exposed to hydrogen sulfide during the 2018 massive stranding

Dabor Resiere , Hossein Mehdaoui , Jonathan Florentin , Papa Gueye , Thierry Lebrun , Alain Blateau , Jerome Viguier , Ruddy Valentino , Yannick Brouste , Hatem Kallel , Bruno Megarbane , André Cabie , Rishika Banydeen & Remi Neviere

CLINICAL TOXICOLOGY
https://doi.org/10.1080/15563650.2020.1789162

Taylor & Francis
Taylor & Francis Group

CLINICAL RESEARCH

Check for updates

Sargassum seaweed health menace in the Caribbean: clinical characteristics of a population exposed to hydrogen sulfide during the 2018 massive stranding

Dabor Resiere[a,b,c], Hossein Mehdaoui[b,c], Jonathan Florentin[a,d], Papa Gueye[d], Thierry Lebrun[e], Alain Blateau[f], Jerome Viguier[f], Ruddy Valentino[b], Yannick Brouste[d], Hatem Kallel[g], Bruno Megarbane[h,i], André Cabie[j,k], Rishika Banydeen[c,l] and Remi Neviere[c,m]

[a]Department of Toxicology, CHU Martinique (University Hospital of Martinique), Fort-de-France, France; [b]Department of Critical Care Medicine, CHU Martinique (University Hospital of Martinique), Fort-de-France, France; [c]Cardiovascular Research Team EA7525, Université des Antilles (University of the French West Indies), Fort de France, France ; [d]Emergency Unit, CHU Martinique (University Hospital of Martinique), Fort-de-France, France; [e]Department of Anesthesiology, CHU Martinique (University Hospital of Martinique), Fort-de-France, France; [f]Regional Health Agency of Martinique (ARS), Fort-de-France, France; [g]Department of Critical Care Medicine, General Hospital of Cayenne, Cayenne, France; [h]Department of Medical and Toxicological Critical Care, Assistance Publique des Hôpitaux de Paris (AP-HP), Lariboisière Hospital, Paris, France; [i]Federation of Toxicology APHP, Paris-Diderot University, Paris, France; [j]Department of Infectious Diseases, CHU Martinique (University Hospital of Martinique), Fort-de-France, France; [k]EA4537; INSERM CIC1424, Université des Antilles (University of the French West Indies), Fort-de-France, France; [l]Department of Clinical Research, CHU Martinique (University Hospital of Martinique), Fort-de-France, France; [m]Department of Cardiology, CHU Martinique (University Hospital of Martinique), Fort-de-France, France

ABSTRACT

Background: Since 2011, there have been ongoing massive unexplained increases of sargassum seaweed strandings along the coastlines of Caribbean countries. The objective of our study was to describe the clinical characteristics of patients exposed to noxious emissions of decomposing sargassum seaweed.

Methods: This observational study included patients from January 2018 to December 2018 for complaints attributed to decomposing sargassum seaweed. History and geographical characteristics of sargassum seaweed strandings as well as detection of ambient air hydrogen sulfide (H_2S) levels were documented during the inclusion period.

Findings: A total of 154 patients were included. Mean exposure period was 3 months. Neurological (80%), digestive (77%) and respiratory (69%) disorders were the most frequent reasons for medical visit. Temporal distribution of medical visits was related to history of strandings. Geographical origins of patients were consistent with the most impacted areas of strandings as well as the most elevated ambient air H_2S levels.

Interpretation: The toxicological syndrome induced by sargassum seaweed exposure is close to the toxidrome associated with acute H_2S exposure in the range of 0–10 ppm. Our study suggests that patients living in massive stranding areas may be exposed to $H_2S > 5$ ppm for 50 days per year.

ARTICLE HISTORY
Received 12 April 2020
Revised 20 June 2020
Accepted 23 June 2020

KEYWORDS
Sargassum seaweed; caribbean; hydrogen sulfide; toxicological syndrome

Introduction

Coastlines of Caribbean islands, Florida and Mexico have witnessed deposition of successive and massive waves of sargassum seaweed, i.e., *sargassum fluitans* and *sargassum natans* depending on the geographical area [1]. French Caribbean overseas departments, especially Martinique and Guadeloupe, have also been affected by strandings of sargassum seaweed since 2011 [2]. Pelagic deposition of sargassum seaweed on Martinique and Guadeloupe beaches has never been as extensive as it was in 2018 [3,4], while prediction models indicate that massive strandings are likely to repeat in the coming years [5]. Despite constant cleaning, beach accumulation and compaction of large amounts of sargassum seaweed result in anaerobic degradation and release of nonvolatile and volatile compounds, which have not been fully characterized [3,4]. Among the many toxic gases produced by decomposing sargassum seaweed, hydrogen sulfide (H_2S) and ammonia are known to elicit deleterious consequences on human health [6].

H_2S is a colorless gas that inhibits cytochrome oxidase, an important mitochondrial enzyme in the electron transport chain involved in ATP production [6]. H_2S is irritating to mucous membranes and its foul smell of rotten eggs can be detected at a level as low as 0.02 ppm [6–9]. Depending on H_2S doses, effects of acute exposure are ranging from mucosal irritation such as eyes, nose and throat prickling, coughing, sneezing and tear production (10–50 ppm) to neurological, pulmonary and cardiac symptoms (100–500 ppm) [6–9]. Severity of the toxicological syndrome increases with H_2S concentration, potentially leading to pulmonary edema, coma and cardiopulmonary arrest (>500 ppm) [6–9]. Although, the acute H_2S syndrome is

CONTACT Remi Neviere remi.neviere@chu-martinique.fr Department of Cardiology, CHU Martinique (University Hospital of Martinique), CS 90632, Fort de France 97261, France.

reasonably well described, deleterious consequences of prolonged and repeated exposure to low H_2S doses (<10 ppm) have been much less investigated. Studies in industrial and geothermal areas have previously reported associations between day-to-day variations in H_2S levels and health outcomes among both normal subjects and patients with chronic diseases [10–16]. In these studies, other ambient pollutants have precluded definitive conclusion regarding health outcomes related with H_2S chronic exposure [10–16]. In the context of sargassum seaweed strandings, it is expected that the toxicological syndrome would resemble the H_2S exposure toxic syndrome, yet no previous studies has been reported.

Martinique is an insular region of France located in Lesser Antilles of the West Indies in the eastern Caribbean Sea. Martinique has an area of 1128 square kilometers and a population of approximately 380,000. Back to the 1980s, the regional health agencies (ARS) in Martinique island have created a sentinel network of referral doctors (general practitioners) working in their private clinics in order to collect health information such as epidemic-prone infectious diseases and pollution-related illness. During the most recent massive sargassum seaweed stranding episode in 2018, physicians of the sentinel ARS network in Martinique reported 8525 visits by people living or working in the affected areas for complaints that the patient related to exposure to gaseous emissions of decomposing sargassum seaweed. Due to marine Atlantic current and maritime trade winds, sargassum seaweed strandings preferentially impacted cities located on the Atlantic coast of Martinique, i.e., Le Robert, Le Vauclin and Le François, which have a population of 23,000, 17,000 and 9000 of inhabitants, respectively. Daily ambient H_2S levels measured by gas sensors deployed on impacted coastlines since January 2016 were used by the ARS to inform the population on air quality and launch evacuation warnings if necessary. Ambient ammonia (NH_3) sensors were however only operational on the island as from September 2018.

During the massive 2018 stranding episode in Martinique, all patients presenting to general physicians of the ARS sentinel network benefited from a classical clinical examination. If the patients' signs and symptoms were deemed by the physician as being consistent with exposure to gaseous emissions from decomposing sargassum, they were systematically directed to the specialist toxicological outpatient care service (toxicological unit) of the University Hospital of Martinique. At the same time, symptomatic patients directly presenting at the hospital's emergency department with self-declared sargassum exposure were also seen at the toxicological unit where completed medical records were systematically collected by experienced clinical toxicologists.

The present study's main objective is to describe the clinical characteristics of patients seen at the toxicological unit of the University Hospital of Martinique in 2018 and complaining for health effects potentially related to exposure to gases produced by decomposing sargassum seaweed. Second, we attempt to describe the relationship between temporal and geographical patterns of sargassum seaweed stranding and observed clinical characteristics in the exposed population.

Patients and methods

Ethics statement

Institutional Review Board approvals for the study procedures were obtained from the University of West Indies. Written informed consent was obtained from all participants before participation. The patients were informed of the collection of data that were processed anonymously using Microsoft Excel following the ethical standards of the declaration of Helsinki and French laws applicable to retrospective studies.

Participants

Patients were included from January 2018 to December 2018. The population for this analysis was restricted to persons who attended the toxicological unit at the University Hospital of Martinique. These patients were directed towards the toxicological unit either from the hospital's emergency department or upon recommendation from referral doctors (general practitioners) of the sentinel network. Patients were included if they reported exposure to sargassum seaweed stranding for at least a week near to their home and/or working place, and if they presented signs and symptoms consistent with exposure to gas emissions produced by decomposing sargassum.

Data collection and processing

Patient health data were collected using the Emergency DX Care software (Medasys, Dedalus, France) on presentation. Clinical examinations were performed by senior physicians (emergency physician, intensivist and anesthesiologist) or general practitioner. Paper copies of the medical data were referenced, and the variables of interest were predefined in the study protocol written by the medical staff. Epidemiological data were collected and processed using Microsoft Excel software.

H_2S exposure estimation

During the study period, H_2S levels were measured by gas sensors in different areas located in regularly impacted areas of the Atlantic coasts of Martinique. H_2S sensors have been deployed by Madininair (https://www.madininair.fr/), an air pollution network certified by the French Ministry of Ecology, Energy and Sustainable Development. We used raw data hourly recorded from the 16 ambient H_2S sensors deployed across the Martinique Atlantic coast to calculate day-by-day average of H_2S concentrations at each location of interest.

Temporal and geographical distribution of sargassum seaweed stranding in Martinique

Monthly occurrence of sargassum seaweed stranding risk was documented through the Sargassum Watch System (SAWS) of the University of South Florida (https://optics.marine.usf.edu/ projects/SaWS.html). Raw satellite data are provided by the U.S. NASA processed through to provide customized data products including the floating algae index to detect floating algae. The prediction of strandings by satellite analysis was computed to risk, such none = 0, Mild = 1, Moderate = 2, high = 3, very high = 4, extremely high = 5. Actual sargassum seaweed stranding were confirmed by *via* air sight and ground observations by Direction de l'Environnement, de l'Aménagement et du Logement, DEAL Martinique, France (http://www.martinique.developpement-durable.gouv.fr/les-bulletins-de-prevision-des-echouages-r414.html). Squares of 1 km × 1 km were encoded to semi-quantitative data in regards to sargassum stranding using a visual analog scale as follows: null intensity (no stranding) = 0; mild intensity (small sargassum clusters scattered on the beach and floating near the coastline) = 1–2; moderate intensity (large compacted sargassum piles (forming thin layers) stranded on the beach, with sargassum rafts floating near the coastline) = 3–5; high intensity (large dense sargassum piles (forming thick layers) stranded on the beach, with extensive sargassum rafts (1 to 5 m wide) floating near the coastline) = 6–8; very high intensity (large dense sargassum piles (forming thick layers) stranded on the beach, with extensive sargassum rafts (5 to 10 m wide) floating near the coastline) = 9–10; extremely high intensity (large dense sargassum piles (forming thick layers) stranded on the beach, with extensive sargassum rafts (>10 m wide) floating near the coastline) = 11–12.

Weather

Maximum, minimum, mean daily temperatures, rainfall, barometric pressure, wind speed data were measured at Trinité, the closest meteorological station of impacted cities of the Atlantic coasts (https://www.infoclimat.fr/climatologie-mensuelle/DT727/mai/2018/trinite-caravelle-martinique.html).

Trinité meteorological station is 7, 16 and 24 km far from Le Robert, le Francois and Le Vauclin, respectively. We used raw data daily recorded to compute week-by-week aggregated means.

Pollution

Among air pollutants, levels of ozone (O_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and particulate matter 10 micrometers or less in diameter (PM10) were available at Le Robert, the main city of the Atlantic coast (https://www.madininair.fr/Mesures-fixes). We used raw data hourly recorded to compute day-by-day aggregated means.

Statistical analysis

A complete descriptive analysis was performed using the statistical software SAS 9.4 version (Cary Inc, North Carolina, USA). Normal distribution of quantitative data was first verified by the Shapiro–Wilk test. Mean and standard deviation were reported for continuous normally distributed data, whereas median, interquartile and min–max ranges were described for non-normally distributed data. Categorical variables were presented as frequencies or percentages.

The following tests were used for group comparisons when appropriate: Student's *t*-test or Wilcoxon–Mann–Whitney tests for continuous variables and $\chi 2$ or Fisher's exact tests for categorical variables. All inferential analyses were performed by means of a 2-sided test, with a level of significance set at 5%.

Table 1. Baseline characteristics of patients seen at the University Hospital of Martinique.

Baseline characteristics	Parameters
Socio-demographics	
Female gender, *n* (%)	117 (76.0)
Median age, years [min–max]	51.5 [5.0–96.0]
Vulnerable groups	
Children (age <16 years), *n* (%)	19 (12.3)
Mean age, years (±*SD*)	9.7 ± 3.2
Pregnant women, *n* (%)	2 (1.3)
Mean age, years (±*SD*)	27 ± 1.4
Elderly people (>70 years), *n* (%)	21 (13.6)
Median age, years [min–max]	76.0 [71.0–96.0]
Personal and Medical history	
Current smoking	2 (1.3)
Hypertension, *n* (%)	23 (14.9)
Atopy, *n* (%)	14 (9.1)
Asthma, *n* (%)	20 (13.0)
Diabetes, *n* (%)	10 (6.5)
Hypothyroidism, *n* (%)	5 (3.2)
Hyperthyroidism, *n* (%)	2 (1.3)
Glaucoma, *n* (%)	2 (1.3)
Migraine, *n* (%)	3 (1.9)
GERD & gastric ulcer, *n* (%)	3 (1.9)
Obstructive Sleep Apnea, *n* (%)	5 (3.2)
Chronic Obstructive Pulmonary Disease, *n* (%)	2 (1.3)
Heart failure & Congestive Cardiac Failure, *n* (%)	3 (1.9)
Stroke, *n* (%)	1 (0.6)
Patient orientation and management	
Referral Doctor (sentinel network), *n* (%)	82 (53.2)
Emergency consultation, *n* (%)	72 (46.8)
Exposure data	
Geographical origin, *n* (%) $^{N=153}$	
North Atlantic	4 (2.6)
Center Atlantic	88 (57.5)
South Atlantic	53 (34.6)
Center	5 (3.3)
South Caribbean	3 (2.0)
North Caribbean	0 (0.0)
Mean exposure period, months (±*SD*)$^{N=140}$	3.1 ± 2.6
Median exposure period, months (min–max; IQR)$^{N=140}$	2.9 (0.03–12.0; 1.1–4.0]

January 2018–December 2018 ($N = 154$).
SD: Standard Deviation; GERD: Gastro esophageal Reflux Disease; min: minimal value; max: maximal value; IQR: Inter-Quartile Range. « Atopy » includes conditions such atopic dermatitis and allergic rhinitis. Emergency room toxicology consultation includes medical visits to the Emergency service, Emergency room consultation, as well as Emergency Medical Services Transport to the Emergency service. "Referral Doctor (sentinel network)" referrers to general practitioners working in their private clinics in order to collect health information such as epidemic-prone infectious diseases and pollution-related illness.

Table 2. Clinical symptomatology of patients seen at the University Hospital of Martinique.

Clinical characteristics	Overall ($N = 154$)	Exposure period* <1 month ($N = 30$)	Exposure period* ≥ 1 month ($N = 110$)	p Value**
Neurological disorders, *n* (%)	123 (79.9)	26 (86.7)	90 (81.8)	.53
Headache	106 (68.8)	23 (76.7)	76 (69.1)	.42
Dizziness	72 (46.8)	14 (46.7)	54 (49.1)	.81
Malaise	29 (18.8)	9 (30.0)	18 (16.4)	.09
Sleep disorders	7 (4.6)	2 (6.7)	4 (3.6)	.61
Loss of consciousness	4 (2.6)	3 (10.0)	1 (0.9)	.03
Convulsions	2 (1.3)	0 (0.0)	2 (1.8)	1.00
Coma	1 (0.7)	0 (0.0)	1 (0.9)	1.00
Digestive disorders, *n* (%)	119 (77.3)	22 (73.3)	91 (82.7)	.25
Abdominal pain	118 (76.6)	22 (73.3)	91 (82.7)	.25
Vomiting	35 (22.7)	5 (16.7)	26 (23.6)	.42
Respiratory disorders, *n* (%)	106 (68.8)	17 (56.7)	81 (73.6)	.07
Dyspnea	75 (48.7)	13 (43.3)	58 (52.7)	.36
Cough	62 (40.3)	10 (33.3)	48 (43.6)	.31
Chest discomfort	27 (17.5)	3 (10.0)	23 (20.9)	.17
Wheeze	14 (9.1)	5 (16.7)	9 (8.2)	.18
Ophthalmological disorders, *n* (%)	99 (64.3)	12 (40.0)	81 (73.6)	<.01
Conjunctivitis	96 (62.3)	11 (36.7)	79 (71.8)	<.01
Eyelid pruritus	44 (28.6)	6 (20.0)	37 (33.6)	.15
ENT disorders, *n* (%)	82 (53.3)	13 (43.3)	64 (58.2)	.15
Rhinitis	65 (42.2)	8 (26.7)	55 (50.0)	.02
Oral mucous membrane irritation	35 (22.7)	8 (26.7)	24 (21.8)	.58
General & Psychological state, *n* (%)	50 (32.5)	7 (23.3)	41 (37.3)	.15
Asthenia	47 (30.5)	7 (23.3)	38 (34.6)	.24
Anxiety	7 (4.6)	1 (3.3)	6 (5.5)	1.00
Irritability	2 (1.3)	1 (3.3)	1 (0.9)	.38
Skin eruption, *n* (%)	40 (26.0)	7 (23.3)	30 (27.3)	.66
Cardiovascular disorders, *n* (%)	32 (20.8)	4 (13.3)	28 (25.5)	.16
Tachycardia	30 (19.5)	3 (10.0)	27 (24.6)	.09
Palpitations	5 (3.3)	2 (6.7)	3 (2.7)	.29
Hospitalization, *n* (%)	4 (2.6)	1 (3.3)	3 (2.7)	1.00

January 2018–December 2018 ($N = 154$ patients).
Abbreviations: *SD*: Standard deviation; ENT: Ear, Nose, Throat.
*Exposure period was undetermined for 14 patients.
**Statistical significance set at $p < .05$.

Results

Population for this analysis was restricted to persons who were seen at the toxicological outpatient unit from January 2018 to December 2018 at the University Hospital Martinique because of symptoms associated with sargassum seaweed exposure. Population characteristics are described in Table 1. The mean age was just above 50 years. Approximately three quarters of the patients were female. Hypertension, asthma and diabetes were the most frequent personal medical history, whereas few patients had chronic obstructive pulmonary disease. At the time of patients' visit at the hospital's toxicological unit, mean exposure period to sargassum seaweed stranding was 3 months (Table 1). The main clinical pictures of all patients are summarized in Table 2. Neurological (79.9%), digestive (77.3%) and respiratory (68.8%) disorders were the most frequent reasons for medical visit. Other frequent clinical manifestations included eye irritation (64.3%) and ENT complaints (53.3%). Exposure to noxious gases emitted by decomposing sargassum seaweed for up to one month increased the prevalence of airway, eye and ENT irritation (Table 2). For example, cases of conjunctivitis and rhinitis were significantly more frequent when patients were exposed for more than 1 month compared to a period <1 month (71.8% vs. 36.7%, $p < .01$ and 50.0% vs. 26.7%, $p = .02$, respectively). Four patients required intensive treatment for asthma attack and one patient died during the study period. Temporal distribution of medical visits and the geographical origin of patients are, respectively, described in Figure 1(A,B). Similar clinical sign distributions were found in young (<18 years), middle age (18–70 years) and elderly (>70 years) patients (Figure 2).

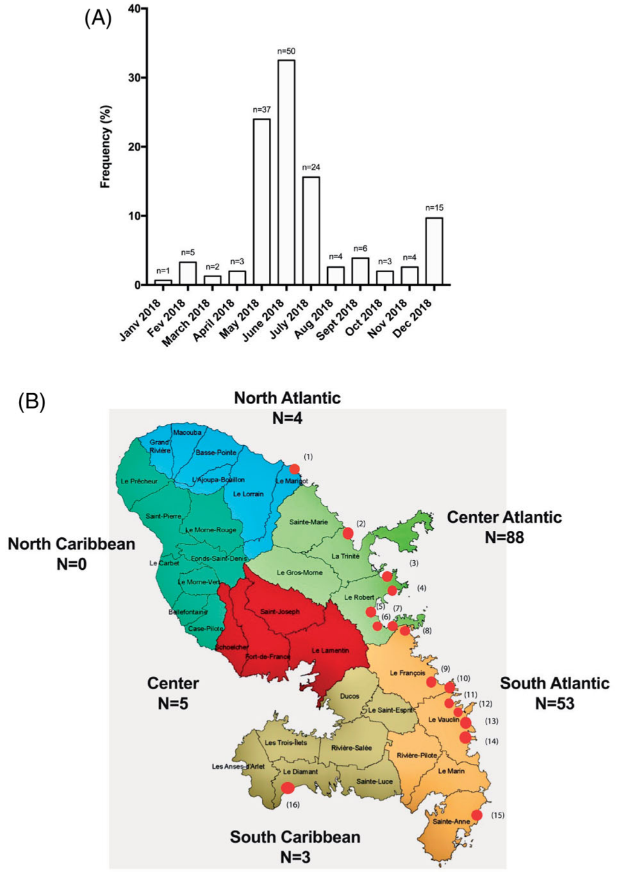

Figure 1. Frequency of medical visits ($N = 154$ patients) from January 2018 to December 2018. Data are presented as percent and absolute number of visits (A). Geographical origin of patients ($N = 153$ patients) attending the toxicological outpatient care service at University Hospital of Martinique (B). Grey dots on the figure indicate the localization of ambient H_2S sensors on the coastlines, detailed as such: (1) Marigot; (2) Trinité; (3) Pointe savane; (4) Robert bourg; (5) Robert - Pontaléry Nord; (6) Robert- Four à Chaux; (7) Robert - Pointe Hyacinthe Est; (8) Robert -Sable blanc; (9) François Presqu'île; (10) François - Frégate; (11) François - Dostaly; (12) François Cap Est (La Prairie); (13) François Cap Est (Pointe Jacob); (14) Vauclin - Château Paille; (15) Anse Michel - Sainte Anne; (16) Anse Cafard - Diamant.

Prediction of sargassum seaweed stranding risk provided by the Sargassum Watch System (SAWS) of the University of South Florida is shown in Figure 3(A). SAWS prediction was consistent with actual sargassum seaweed stranding as referenced by Direction de l'Environnement, de l'Aménagement et du Logement, DEAL Martinique. Sargassum strandings mainly occurred in Center and South Atlantic coastline regions of Martinique (Figure 3(B)). Recordings of H_2S levels are detailed in Figure 4. Ambient pollutant levels and climatic conditions are, respectively, presented in Figures 5 and 6. The number of days with hourly H_2S concentration above 5 ppm in specific Center and South Atlantic cities is

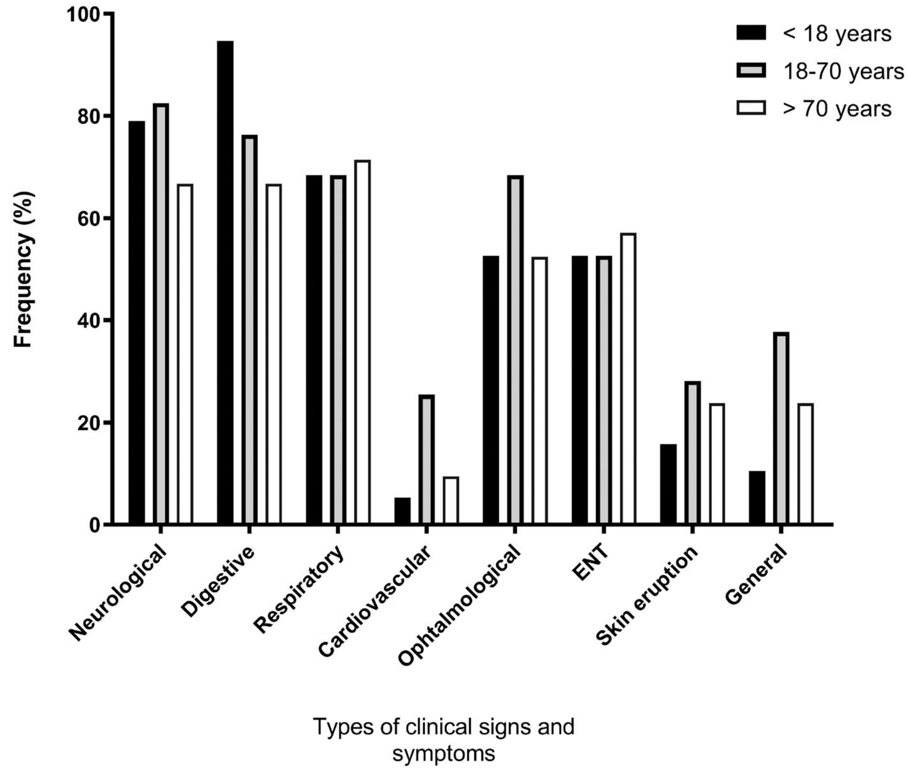

Figure 2. Age distribution of clinical signs and symptoms observed in patients seen at the University Hospital of Martinique, January 2018–December 2018. Abbreviation: ENT: Ears, Nose and Throat. General signs and symptoms include asthenia, irritability and anxiety. <18 years $N = 19$ patients, 18–70 years $N = 114$ patients, > 70 years $N = 21$ patients. No statistical difference was observed according to age ($p > .05$).

summarized in Table 3. The temporal distribution of medical visits was related to the history of sargassum seaweed strandings, while the geographical origin of patients was consistent with the most impacted coastlines as well as the most elevated H_2S recordings. The distribution of clinical signs and symptoms of patients living or working in areas with high H_2S levels did not differ from those of patients living or working in areas with low H_2S levels (Table 4).

Discussion

Main objective of this study was to evaluate human health effects related to noxious gases emitted by decomposing sargassum. The observations provide a description of the predominant clinical characteristics of patients exposed to outgassing of sargassum seaweed during the massive stranding episodes in 2018 in the French West Indies. The population for this analysis was restricted to persons who were seen at the toxicological outpatient unit because of symptoms associated with sargassum seaweed exposure. Mean exposure time to sargassum seaweed stranding, at the living or work place, was 3 months. Neurological, digestive and respiratory disorders were the most frequent reasons for medical visit. Other frequent clinical manifestations included eye and ear, nose and throat (ENT) complaints. Most importantly, results of our study will be used by the French national health care agency to provide public information and to design educational campaigns of prevention in Caribbean overseas territories.

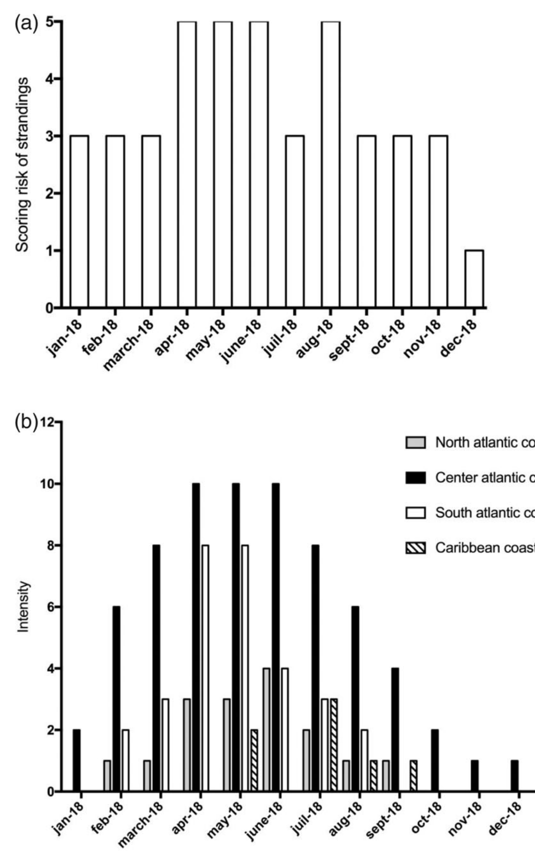

Figure 3. Risk of sargassum strandings on Martinique coasts evaluated by satellite prediction. Risk of stranding are scored as none = 0, mild = 1, moderate = 2, high = 3, very high = 4, extremely high = 5 (A). Actual visual intensity of sargassum seaweed accumulation on Martinique coastlines are scored as none = 0, mild = 1–2, moderate = 3–5, high = 6–8, very high = 9–10, extremely high = 11–12 (B). See Patients and Methods for details.

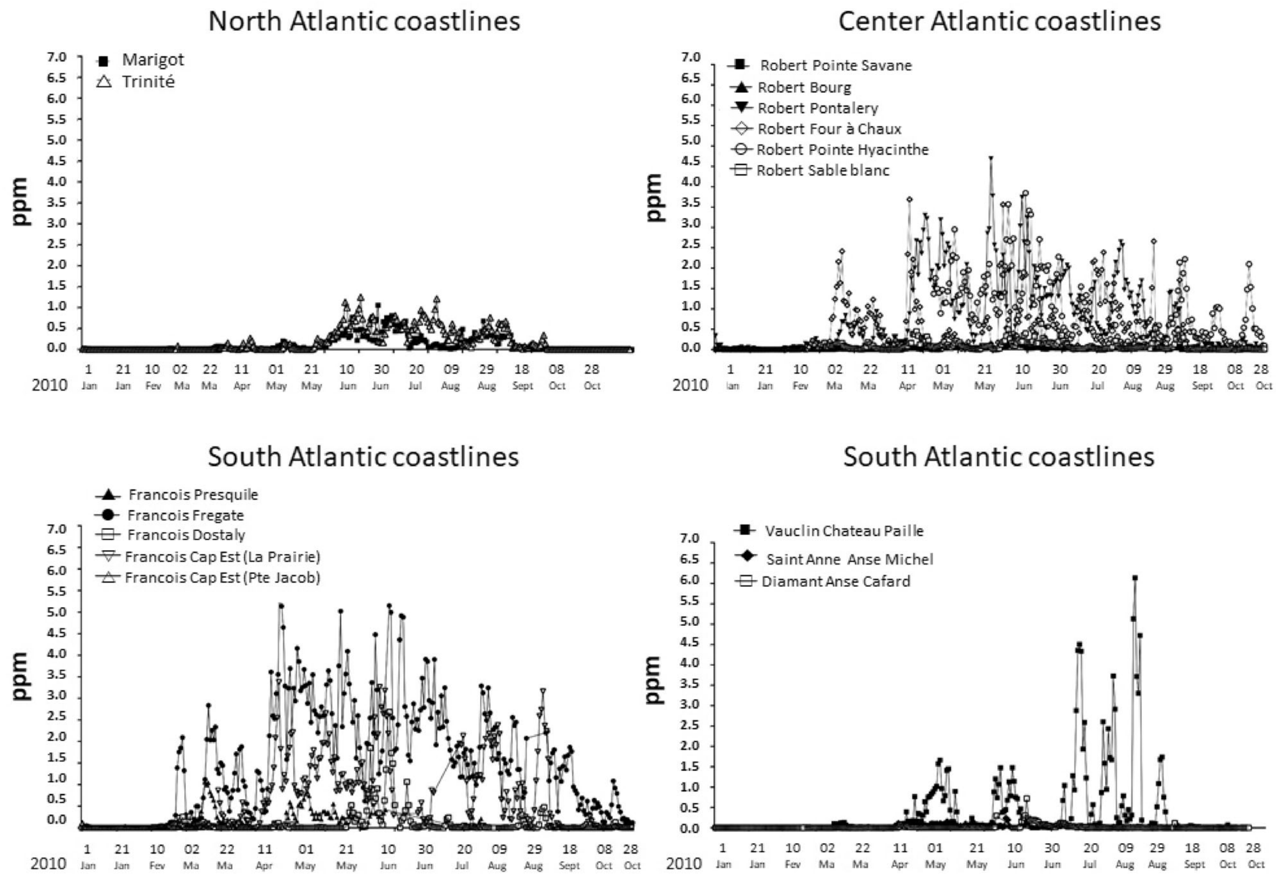

Figure 4. H_2S exposure measured by ambient sensors in 2018. Raw data were hourly recorded from ambient H_2S sensors deployed across Martinique coastlines to calculate day-by-day average of H_2S concentrations at each location of interest. Please see location of ambient H_2S sensors on the map displayed Figure 1(B).

During the study period, sargassum seaweed strandings were ascertained by both air sight and ground observations. Geographical origin of patients with complaints related to sargassum emissions coincided with the most severely affected coastlines with the majority of patients living and/or working in the Center and South Atlantic regions. Temporal frequency of medical visits also coincided with history of sargassum strandings on Martinique's coastlines. Likewise, temporal and geographical H_2S levels, a surrogate of noxious gases emitted by decomposing sargassum seaweed, were consistent with history of sargassum strandings. Clinical manifestations were related to both duration and intensity of exposure to gases emitted by decomposing sargassum seaweed. Exposure period $>$1 month increased the frequency of airway, eye and ENT irritation, compared with more acute exposure.

Exposure to high levels of H_2S is a well-documented and understood hazard. In contrast, sub-acute and chronic exposure to low levels of H_2S is not as well understood. Low-level exposure to H_2S is, however, not uncommon [15,16]. For example, studies in industrial and geothermal areas have previously reported associations between day-to-day variations in H_2S levels and health outcomes among both normal subjects and patients with chronic diseases [10–14]. The American Environmental Protection Agency (EPA) and the Agency for Toxic Substances and Disease Registry (ATSDR) have provided relevant recommendations for H_2S limit levels to community exposure [8,9]. The risk assessment process of EPA estimates levels safe for a lifetime exposure at 0.07 ppb, whereas ATSDR lists levels for acute at 70 ppb, and 30 ppb for chronic levels [8,9]. Although, there are no international guidelines for chronic H_2S exposure, the World Health Organization (WHO) has advised to use short term standards to predict chronic effects of H_2S on human health [17]. Consistently, the toxicological syndrome observed in our study is close to the toxidrome associated with acute H_2S exposure in the range of 0–10 ppm, which included signs of eye and ENT irritation, nausea and vomiting, headache and dizziness. Respiratory disorders were also frequently observed in our study, which is also consistent with previous study reporting respiratory symptoms, decreased lung function test results and increases in pulmonary diseases [12,18–21]

Limitation and strength of the study

The primary study limitation is the relatively small sample size, accounting for insufficient statistical power for comparisons between those with high and low exposure groups. Another main limitation was the collection of data from patients who presented voluntarily at a single study center. This may have biased the selection toward those who find it easy to travel. For example, few patients who resided in communities on the north Atlantic coast visited at the University Hospital of Martinique because of limited transportation facilities in these areas. A second probable source of selection bias is that patients with more severe symptoms

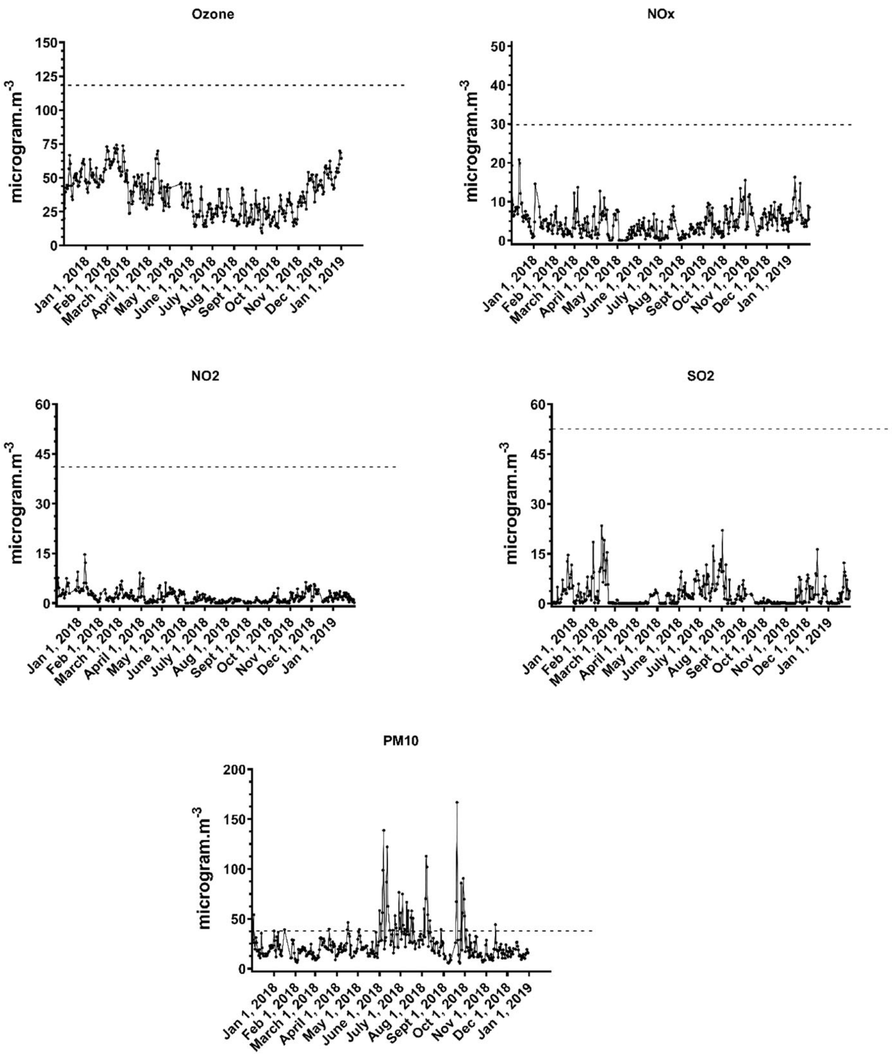

Figure 5. Air pollution Ozone O_3, NO_X, NO_2, SO_2, PM10 recordings, January 2018–December 2018. Dashed lines represent limits for good air quality ($<120\,\mu g.m^{-3}$; $<30\,\mu g.m^{-3}$; $<40\,\mu g.m^{-3}$; $<50\,\mu g.m^{-3}$; and $<30\,\mu g.m^{-3}$ for ambient O_3, NO_x, NO_2, SO_2 and PM10 levels, respectively).

might have more frequently resorted to primary care (general practitioners, emergency department) than paucisymptomatic ones. Furthermore, we found that the study population consisted of a higher proportion of women. This can be explained by the fact that most of these women were housewives and as such, they stayed in their homes for significantly longer periods of time. As a result, they might have been exposed for longer periods of time than the men in our study sample, and were, therefore, more symptomatic. However, while our study sample might not be representative of the overall population impacted by sargassum strandings on the island's coastlines, the present work does fulfill the aim of describing clinical characteristics of an exposed population exposed.

Moreover, in our study, only few objective clinical signs and symptoms were eligible for quantification. Whereas respiratory signs and asthma were frequently observed in our patients, pulmonary function testing was lacking. Complete pulmonary function testing including plethysmography, detection of nitric oxide in exhaled air and breath condensate analysis is now available for patients with suspected poisoning from decomposing sargassum seaweed gaseous emissions. Furthermore, detection of gas emitted by decomposing sargassum seaweed was solely limited to ambient H_2S, which may not reflect overall patient exposure to the multitude of gases contained in these emissions, including ammonia. Indeed, the lack of ambient ammonia sensor data before September 2018 does not allow us to reflect on the potential contribution of ammonia, a respiratory, skin and eye irritant.

It is also important to note that NO_x, NO_2 and SO_2 may be considered as potential confounding factors. In our study, we considered air pollutants such as ozone, NO_x, NO_2 and SO_2, which were under the thresholds defining optimal air quality set by the French Ministry of Ecology, Energy and Sustainable Development. In contrast, Saharan dust air pollution episodes could be considered as a potential confounding factor in our study, as ambient particulate matter PM10 concentrations reached the threshold of information and recommendations to reduce certain sources of polluting emissions ($50\,\mu g.m^{-3}$), as well as the alert threshold setting up measures of restriction or suspension of activities contributing to pollution, such as vehicle circulation ($80\,\mu g.m^{-3}$). Of note, these dust events were typically observed in June 2018

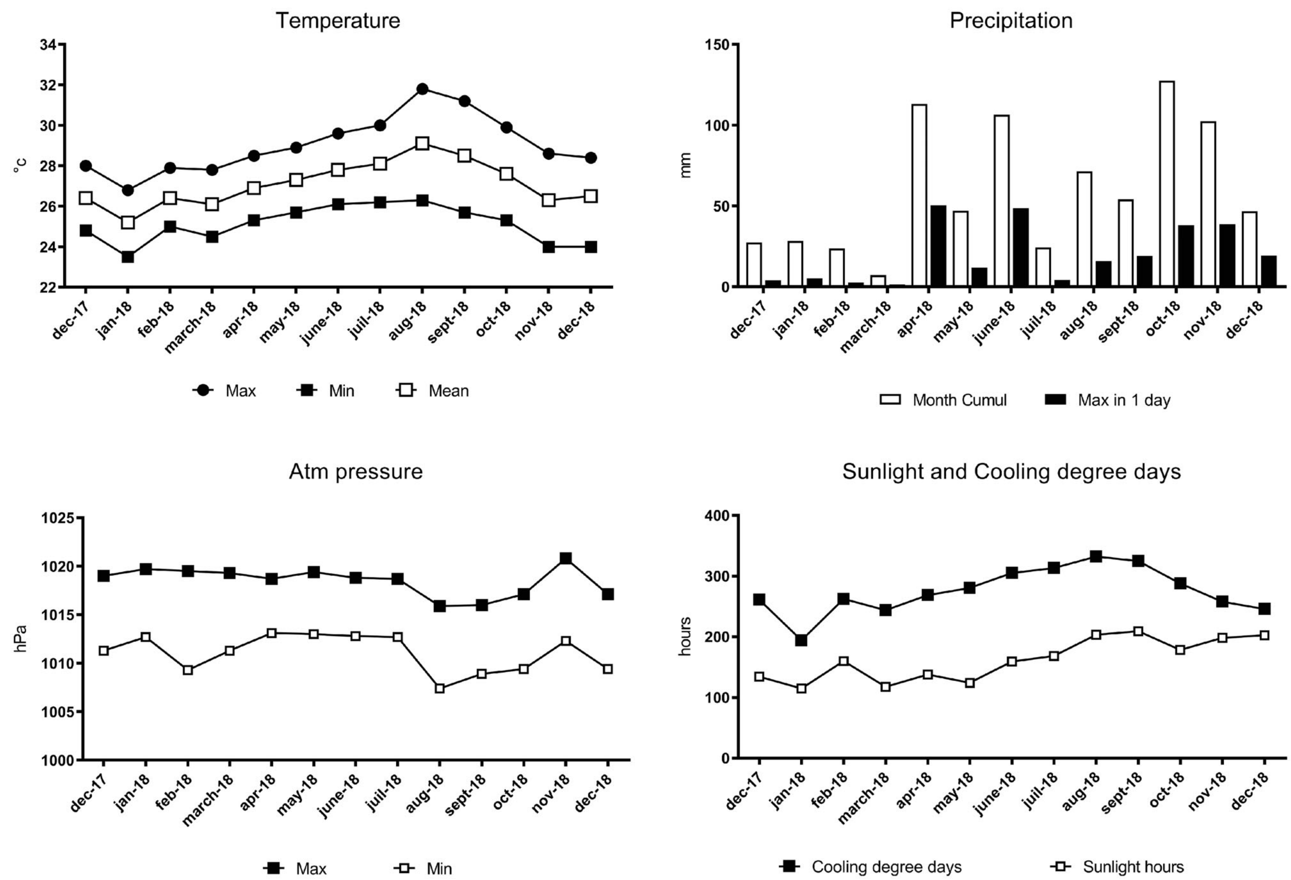

Figure 6. Weather in 2018 including recordings of temperature, precipitation (rain fall), atmospheric pressure, sunlight and cooling degree days.

Table 3. Analysis of hydrogen sulfide (H_2S) sensor data on the Central and Southern Atlantic coastlines of Martinique, January 2018–December 2018.

		Hourly H_2S concentration (ppm)		
Coastline	Geographical zone	Mean ± *SD*	Median [Min–Max]	No. of days >5 ppm (year)
Center Atlantic	Robert Pontalery Nord	0.7 ± 0.9	0.3 [0–7.3]	7
	Robert Four à Chaux	0.5 ± 0.8	0.1 [0–10.4]	10
	Robert Pte Hyacinthe Est	0.9 ± 0.9	0.6 [0.004–8.3]	6
South Atlantic	Francois Fregate EST 2	1.4 ± 1.5	1.0 [0–9.9]	50
	Francois Dostaly Sud	0.1 ± 0.4	0.0 [0.4–5.4]	1
	Francois Cap Est	0.8 ± 0.9	0.8 [0–6.2]	1
	Vauclin Chateau Paille	0.4 ± 1.0	0.0 [0–11.1]	14

H_2S: Hydrogen sulfide; *SD*: Standard deviation; Min: Minimal value; Max: Maximal value; ppm: parts per million .

Table 4. Clinical symptomatology of patients seen at the University Hospital of Martinique according to geographical zone of exposure to sargassum seaweed strandings.

Clinical signs & symptoms *n* (%)	Center-South Atlantic coastlines* ($n = 122$) High H_2S level	Other coastlines ($n = 31$) Low H_2S level	*p* Value**
Neurological	100 (82.0)	22 (71.0)	.17
Digestive	96 (78.7)	22 (71.0)	.36
Respiratory	82 (67.2)	23 (74.2)	.45
Ophthalmological	79 (64.8)	19 (61.3)	.72
Ear, Nose, Throat	67 (54.9)	15 (48.4)	.52
General & Psychological	40 (32.8)	10 (32.3)	.96
Dermatological	32 (26.2)	7 (22.6)	.68
Cardiovascular	26 (21.3)	6 (19.3)	.81

January 2018–December 2018 ($N = 154$).
*Center-South Atlantic coastlines: Robert, François, Vauclin.
**Statistical significance set at $p < .05$.

while the massive sargassum strandings episodes started early in March 2018.

Conclusion

Full characteristics of clinical signs and symptoms related to noxious gases emitted by decomposing sargassum have been made available during the massive stranding episodes in 2018 in the French West Indies. Overall, the toxicological syndrome induced by decomposing sargassum seaweed exposure resembles the one associated with acute H_2S exposure in the range of 0–10 ppm. Magnitude exposure was greater than previously expected with some patients living in massive stranding areas and exposed to H_2S levels $>$ 5 ppm for 50 days per year. A global plan addressing the enigma of sargassum invasion should be the subject of urgent international discussions, in order to encourage large-scale marine, scientific and medical research, pool resources and reconcile political priorities.

Author contributions

Dabor Resiere (DR); Hossein Mehdaoui (HM); Jonathan Florentin (JF); Papa Gueye (PG); Thierry Lebrun (TL); Alain Blateau (AB); Jerome Viguier (JV); Ruddy Valentino (RV); Yannick Brouste (YB); Bruno megarbane (BM); André Cabie(AC); Rishika banydeen (RB); Remi Neviere (RN)

- RN wrote the manuscript with support from RB, DR and HM.
- DR, HM, RB, RN contributed substantially to the conception and design of the study
- DB, HM, JF, PG, TL, AB, JV, RV, YB contributed substantially to the acquisition of data, analysis and interpretation.
- RB and HM performed statistical analyses.
- BM and AC contributed substantially to the interpretation of the data.
- All authors drafted or provided critical revision of the article.
- All authors provided final approval of the version to publish.

Disclosure statement

No potential conflict of interest was reported by the authors. The authors acknowledge no financial interest or benefit that has arisen from the direct applications of the present research.

Part of the present work has been previously published as a congress abstract at the 2020 congress of the French Intensive Care Society (Réanimation 2020, the French Intensive Care Society International Congress). The abstract was published (abstract number F-66) in the congress's proceedings in the Annals of Intensive Care journal (Resiere et al. Ann Intensive Care. 2020; 10 (Suppl 1); 16-F066).

Funding

The current research work has been supported by grants (2018) from the University Hospital of Martinique and the Regional Health Agency (ARS) of Martinique. They funded necessary human and logistical resources, which contributed towards data collection and analysis.

References

[1] Langin K. Seaweed masses assault Caribbean islands. Science. 2018;360:1157–1158.

[2] Resiere D, Valentino R, Neviere R, et al. Assault of sargassum seaweed in Caribbean islands: an emerging international public health concern. Lancet. 2018;392(10165):2691.

[3] Agence nationale de sécurité sanitaire alimentation, environnement, travail (ANSES). Guidelines 2017: expositions aux emanations d'algues sargasses en decomposition aux Antilles et en Guyane. 2017. Available from: https://www.anses.fr/fr/system/files/AIR2015SA0225Ra.pdf

[4] Haut conseil de la santé publique. Relatif à la définition de mesures de gestion concernant l'exposition des populations Antillaises à l'ammoniac et du sulfure d'hydrogène (H_2S) issus de la décomposition d'algues Sargasses. 2018. Available from: https://www.hcsp.fr/Explore.cgi/Telecharger?NomFichier=hcspa20180608_mesdegessuiladcodalgsarauxant.pd.pdf

[5] Wang M, Hu C, Barnes BB, et al. The great Atlantic Sargassum belt. Science. 2019;365(6448):83–87.

[6] Reiffenstein RJ, Hulbert WC, Roth SH. Toxicology of hydrogen sulfide. Annu Rev Pharmacol Toxicol. 1992;32:109–134.

[7] Guidotti TL. Hydrogen sulfide: advances in understanding human toxicity. Int J Toxicol. 2010;29(6):569–581.

[8] US EPA. 2003. Toxicological review of Hydrogen sulfide (CAS No. 7783-06-4). Washington, DC: U.S. Environmental Protection Agency. Available from: https://cfpub.epa.gov/ncea/iris/iris_documents/documents/toxreviews/0061tr.pdf

[9] ATSDR. 2014. Toxicological profile for Hydrogen Sulfide/Carbonyl Sulfide (Draft for Public Comment). Toxicological Profile for Hydrogen Sulfide/Carbonyl Sulfide. CAS#: Hydrogen Sulfide 7783-06-4; Carbonyl Sulfide 463-58-1. Available from: https://www.atsdr.cdc.gov/ToxProfiles/tp114.pdf

[10] Lim E, Mbowe O, Lee AS, et al. Effect of environmental exposure to hydrogen sulfide on central nervous system and respiratory function: a systematic review of human studies. Int J Occup Environ Health. 2016;22(1):80–90.

[11] Reed BR, Crane J, Garrett N, et al. Chronic ambient hydrogen sulfide exposure and cognitive function. Neurotoxicol Teratol. 2014;42:68–76.

[12] Richardson DB. Respiratory effects of chronic hydrogen sulfide exposure. Am J Ind Med. 1995;28(1):99–108.

[13] Bates MN, Garrett N, Crane J, et al. Associations of ambient hydrogen sulfide exposure with self-reported asthma and asthma symptoms. Environ Res. 2013;122:81–87.

[14] Bates MN, Crane J, Balmes JR, et al. Investigation of hydrogen sulfide exposure and lung function, asthma and chronic obstructive pulmonary disease in a geothermal area of New Zealand. PLoS One. 2015;10(3):e0122062.

[15] Lewis RJ, Copley GB. Chronic low-level hydrogen sulfide exposure and potential effects on human health: a review of the epidemiological evidence. Forensic Toxicol. 2000;31:172–179.

[16] Legator MS, Singleton CR, Morris DL, et al. Health effects from chronic low-level exposure to hydrogen sulfide. Arch Environ Health. 2001;56(2):123–131.

[17] Selene DC, Chou HJ. Hydrogen sulfide: human health aspects. Agency for Toxic Substances and Disease Registry. Atlanta, Georgia: World Health Organization Geneva; 2003. Available from: https://www.who.int/ipcs/publications/cicad/en/cicad53.pdf

[18] Jäppinen P, Vilkka V, Marttila O, et al. Exposure to hydrogen sulphide and respiratory function. Br J Ind Med. 1990;47(12):824–828.

[19] Hessel PA, Herbert FA, Melenka LS, et al. Lung health in relation to hydrogen sulfide exposure in oil and gas workers in Alberta, Canada. Am J Ind Med. 1997;31(5):554–557.

[20] Campagna D, Kathman SJ, Pierson R, et al. Ambient hydrogen sulfide, total reduced sulfur, and hospital visits for respiratory diseases in northeast Nebraska, 1998-2000. J Expo Sci Environ Epidemiol. 2004;14(2):180–187.

[21] Schinasi L, Horton RA, Guidry VT, et al. Air pollution, lung function, and physical symptoms in communities near concentrated Swine feeding operations. Epidemiology. 2011;22(2):208–215.