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Pelagic *Sargassum* cleanup cost in Mexico

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ABSTRACT

Pelagic *Sargassum* spp. (*Sargassum*) blooms in the tropical Atlantic began in 2011. Since then, frequent and significant beaching events have caused ecological, economic, and human-health-related problems in over 30 countries. On the Mexican Caribbean coast, massive beaching events began in late 2014 and, since 2018, have occurred annually, with high-volume landings lasting from five to seven months. This study analyzes data on *Sargassum* cleanup costs done by three municipalities (Puerto Morelos, Solidaridad, and Tulum) and five hotels between Tulum and Cancun. The annual harvested volumes ranged from 10,105–40,932 m^3 per kilometer, resulting in US$ 0.3–1.1 M cleanup costs per kilometer. The prices of cleaning one cubic meter of *Sargassum* ranged from US$: 19–85. The expenses were influenced by cleanup management strategies rather than beach cast volumes. Hotels were more cost-effective than municipalities. For the city of Puerto Morelos, we additionally calculated the yearly and monthly cleanup costs using the mean per-unit price obtained from hotels within this municipality (US$ 27 per m^3) and the *Sargassum* volumes removed monthly from the beach by 14 hotels during 2018, 2019, 2021, and 2022. The costs per kilometer for this municipality ranged from 0.8 to 1.5 M in years (Mean: 1.0 M) and US$ 10,186–100,446 over months, with mean values greater than US$ 70,000 from May to August. The data provided here can help governments and hotels to anticipate cleanup costs for forecasting purposes and industries interested in valorizing *Sargassum*.

1. Introduction

Macroalgae blooms have been rising worldwide, threatening biodiversity and affecting several countries' economies (Smetacek and Zingone, 2013; Xiao et al., 2020). Green tides caused by *Ulva* spp. were first reported in Europe in the 1900s and became widespread in coastal waters of North America, the French Atlantic coast, Asia, and other temperate and tropical beaches in the 1970s–2000s (Charlier et al., 2006, 2007; Xiao et al., 2021). In the 1980s, green tides of *Enteromorpha* spp. and *Cladophora* spp. were reported for Europe (Charlier et al., 2008). Since the 2000s, blooms of the brown seaweed *Sargassum horneri* also occurred in the Yellow Sea and East China, affecting fisheries, aquaculture, and recreation (Hu et al., 2010; Hwang et al., 2016; Qi et al., 2017; Liu et al., 2018; Byeon et al., 2019). In 2011, the massive beaching of two pelagic *Sargassum* species (*S. natans* (Linnaeus) Gaillon and *S. fluitans* (Borgesen) Borgesen) began affecting many nations in the tropical Atlantic, from West Africa to the Caribbean Sea and the Gulf of Mexico, and even extending to Central America, Brazil, and Florida (Gower et al., 2013; Johnson et al., 2013; Smetacek and Zingone, 2013; van Tussenbroek et al., 2017; Johns et al., 2020).

Historically, the distribution of pelagic *Sargassum* species was centered on the Sargasso Sea, with minor quantities arriving in several countries in the tropical Atlantic Ocean (Gower et al., 2013; Frazier et al., 2013). The little periodical landings of these seaweeds were beneficial for the fertilization of dunes and helped to reduce erosion and increase coastal resiliency to storm surges and rising sea levels (Williams and Feagin, 2010). However, massive beaching of pelagic *Sargassum* spp. (from here on *Sargassum*) results in significant ecological, economic, and human health-related impacts. The leachates and organic matter resulting from its decomposition deteriorate the quality of coastal waters by reducing transparency, oxygen, and pH while increasing sulfur and ammonia (van Tussenbroek et al., 2017). These changes have caused the mortality of seagrass meadows (van Tussenbroek et al., 2017) and fauna, including species of economic importance, like lobsters and fish (Rodríguez-Martínez et al., 2019). *Sargassum* removal from the beach with machinery also contributes to beach erosion and compaction (Rodríguez-Martínez et al., 2016; Chávez et al., 2020).

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Pelagic *Sargassum* can also absorb toxic elements like arsenic, cadmium, lead, and mercury (Oyesiku and Egunyomi, 2014; Dzama Addico and De Graft-Johnson, 2016; Milledge et al., 2020; Rodríguez-Martínez et al., 2020; Davis et al., 2021), as well as other pollutants like chlordecone (Devault et al., 2022). Some of these pollutants (e.g., arsenic) can move through the leachates and contaminate coastal waters, disposal sites, and aquifers (Olguin-Maciel et al., 2022) and even enter food webs in coastal environments (Modestin et al., 2022). Other threats to human health include the production of hydrogen sulfide gas during the decomposition of *Sargassum* piles, which can cause respiratory and neurologic diseases (Resiere et al., 2021), and the presence of hydroids attached to its fronds, which can produce skin rashes in humans (Mendoza-Becerril et al., 2020). *Sargassum* also harbors a microbiome, and some of the bacteria associated with it (e.g., Vibrionaceae and Flavobacetiaceae) can produce human and marine species diseases (Michotey et al., 2020; Hervé et al., 2021).

Massive *Sargassum* landings additionally have an economic impact. The accumulation of algae on beaches, foul smells, and changes in the quality of beaches and coastal waters result in the devaluation of beach properties and a reduction in tourist visitation, affecting many countries economies. Economic losses can be significant considering that in the Caribbean, the tourist industry was estimated to be worth US$57.1 B, in 2017, with a projection to increase to US$83.3 B by 2027 (Thompson et al., 2020). To reduce the ecological and socioeconomic impacts caused by *Sargassum*, governments, and hotels spent much labor and resources cleaning up the algae from the beach and coastal waters. To date, the cost of cleanup activities has not been thoroughly evaluated in the affected countries, and only some estimates exist. The annual *Sargassum* cleanup cost across the Caribbean was calculated at US$120 M by Milledge and Harvey (2016) and US$210 M by Davis et al. (2021). However, these values seem underestimated when considering that Salter et al. (2020) reported that in 2018 the hotels located in the northern part of the Mexican Caribbean coast spent around US$128,770–US$284,830 per kilometer of coastline only in personnel wages and transportation of *Sargassum* to disposal sites. Thus, a more exhaustive analysis of the cost of *Sargassum* cleanup from coastal zones is needed to make adequate management budgets and to help industries interested in valorizing these algae conduct cost-benefit studies.

This study analyzes the cost of pelagic *Sargassum* cleanup from the beach and coastal waters in the northern Mexican Caribbean. We use data from three of the foremost affected municipalities and five hotels in the state of Quintana Roo to obtain a per-unit cost (cubic meter). We also estimate the annual and monthly variability in the price of cleaning 1 km of the coast in the municipality of Puerto Morelos by using *Sargassum* landing volumes provided by 14 hotels for the years 2018, 2019, 2021, and 2022. The information compiled here can help government agencies and hotels from Mexico and other affected countries to anticipate cleanup costs for forecasting purposes and inform those interested in the valorization of *Sargassum*. The results of this study can help in *Sargassum* management decision-making while selecting cost-effective strategies.

2. Methods

2.1. Study area

The state of Quintana Roo is in the eastern Yucatan Peninsula (Fig. 1). It has 11 municipalities, with nine periodically affected by massive *Sargassum* landings. The state became an important tourist destination with the creation of Cancun in the mid-1970s. Since then, its economy has depended on the tourism industry, representing 75% of the state's GDP and capturing 40% of Mexico's income from tourism in 2020 (SEDETUR, 2022). In 2021, Quintana Roo received almost 15 M tourists representing an income of ~US$10,807 M. The state's principal assets are white-sand beaches, turquoise waters, high biodiversity, and culture. Coastal ecosystems in this region consist of coral reefs, seagrass beds, mangroves, and forests, all linked to species movement and energy and matter flow (Chávez et al., 2020).

Fig. 1. Location of study sites. *Sargassum* removal costs were reported by five hotels (blue dots, sites A-E) and three municipalities (green stars). Base image obtained from Wikimedia Commons.

In the last four decades, the condition of coastal ecosystems in Quintana Roo declined due to urban and tourist developments, climate change, overfishing, coral bleaching and diseases, pollution (Rioja-Nieto and Álvarez-Filip, 2019), and since the end of 2014, the massive influx of *Sargassum* (Rodríguez-Martínez et al., 2016; van Tussenbroek et al., 2017). Since 2018, *Sargassum* landings have become yearly with high-volume stranding (Fig. 2A) lasting from five to seven months during spring and summer, when east and southeast winds predominate (Rodríguez-Martínez et al., 2022). The beach cast volumes are considerable and appear to be increasing in time, with values during the peak landing months in the northern sector of the coastline increasing from a mean of 2360 m^3 km^{-1} in 2015 (Rodríguez-Martínez et al., 2016) to 3816 m^3 km^{-1} in 2018, and 6565 m^3 km^{-1} in 2019 (Rodríguez-Martínez et al., 2022). Beach cast volumes vary along the coast depending on the season, the geomorphology of the shoreline, and the strength and direction of wind and currents (Rodríguez-Martínez et al., 2022).

2.2. Costs data

Sargassum cleanup costs were obtained from five hotels (sites A-E) and three municipalities (Puerto Morelos, Solidaridad, and Tulum) (Fig. 1). The costs were estimated based on the amounts spent on wages, payment of cleanup services, materials, fuel, rental and acquisition of equipment, equipment maintenance, and transportation of the seaweed to disposal sites (Table 1). The material removed from the beach was mainly *Sargassum* (*Sargassum fluitans* III, *S. natans* I, and *S. natans* VIII) but could also contain sand, seagrasses, and other species of macroalgae. The fraction of these components can vary in time and space and is influenced by harvesting methods; however, previous studies on the study region have shown that during the peak landing months, the main element (>85%) was *Sargassum* (Rodríguez-Martínez et al., 2022). This is supported by the images provided in Fig. 2 A-C.

2.2.1. Hotels data

Annual data (2018 and 2019) on the cleanup costs and volumes of *Sargassum* removed from the beach were provided by five hotels in the northern sector of the Mexican Caribbean coast (Fig. 1) that collectively account for 5.4 km of sampling distance over a 40 km section of shoreline (Table 1). Hotels clean their beachfront on a near-daily basis to maintain desired conditions. They use different harvesting methods, with manual ones (Fig. 2B) preferred over mechanical ones (e.g., amphibian bands, harvesting machines, bobcats, bulldozers, and trucks; Fig. 2C and D) when the algae volumes allow it. *Sargassum* volumes were estimated by the number of trucks of known capacity (7 m^3 or 14 m^3) used to transport the algae to disposal sites (Fig. 2E).

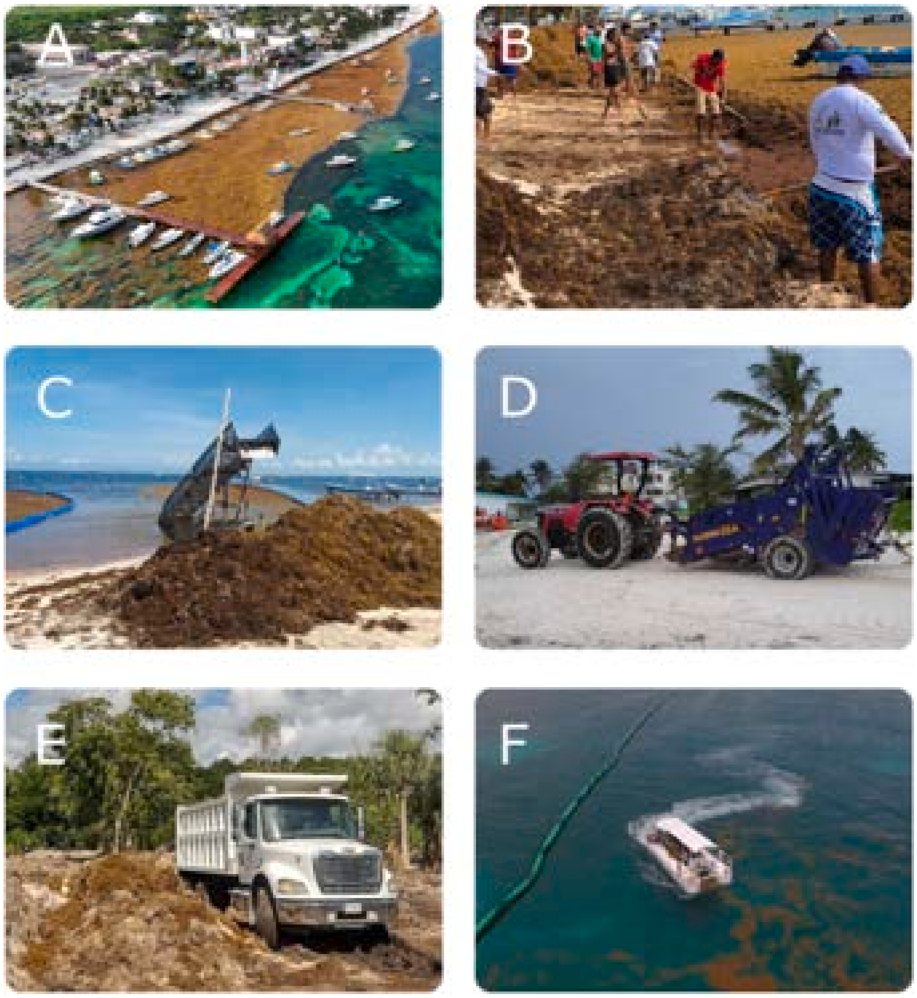

Fig. 2. *Sargassum* cleanup from the beach and coastal waters in the Mexican Caribbean. A) Aerial photograph of *Sargassum* on the beach and coastal waters of Puerto Morelos, Mexico (photo: Lorenzo Álvarez-Filip, B) Manual removal, C) Amphibian bands (photo: Fabiola Sánchez), D) Harvesting machine pulled by a tractor, E) Truck used for disposal, F) Barrier placed close (<100 m) to shore and *Sargassum* vessel (photo: Alejandro de Luna).

2.2.2. Municipal data

Municipalities are responsible for the cleanup of public beaches. Depending on beach characteristics and resources, they employ different strategies. The data analyzed in this study correspond to the year 2020 for the municipality of Solidaridad and 2021 for Puerto Morelos and Tulum municipalities. All three municipalities are severely affected by *Sargassum* landings in the Mexican Caribbean (Chávez et al., 2020). Municipal data were obtained through the National Transparency Platform (NTP), with request numbers 645121 (Solidaridad municipality) and 645,221 (Tulum municipality). Data for the Puerto Morelos municipality were provided by the Maritime Terrestrial Federal Zone (ZOFEMAT) office.

In Solidaridad municipality, the public beach attended (3.5 km) is in the town of Playa del Carmen. In 2020, the *Sargassum* cleanup service was provided by a private company. The operation involved installing a 2.5 km barrier 100 m from the beach. Two *Sargassum* boats harvested the algae accumulated on the barrier (Fig. 2F), which was later manually packed in 1 m^3 bags and transported to the beach by two scows. Municipal workers transported the bags to the municipal waste treatment plant. These workers were also in charge of removing from the beach the *Sargassum* that crossed the barrier and cleaning the beach sector not protected by it. They used manual labor and mechanical methods (harvesting machines, bulldozers, amphibian bands, and trucks). In Puerto Morelos municipality, the 1.8 km long beach in front of the town's main square was cleaned using manual and mechanical methods. The algae were transported inland to a dumping site in an old quarry. In Tulum municipality, the cleanup was performed only by manual labor, as machinery access to beaches was impossible. Five public beaches were attended, covering a linear distance of 909 m: Santa Fe (260 m), Pescadores (100 m), Maya (200 m), Mezzanine (149 m), and Punta Piedra (200 m). The algae were moved to disposal points along the beach, extended, and left to sundry.

The *Sargassum* volume removed from the beach was estimated by the number of trucks of known capacity (14 m^3) used to transport the algae to disposal sites in Solidaridad and Puerto Morelos and by the number of 6 ft^3 wheelbarrows employed in Tulum. *Sargassum* biomass estimations may vary depending on the timing and method of collection, the amount of sand and water retention, and differences in the degree of compaction; however, in all sites, the algae were removed less than 24 h after landing.

2.3. Data analysis

To compare the costs of *Sargassum* cleanup among hotels, municipalities, and those described in the literature for other species of macroalgae, we calculated the cost of harvesting one cubic meter and cleaning 1 km of beach in one year. Since the data are for different periods, we used the compound interest formula to adjust the prices for inflation to December 2022. Mexicos' inflation rates were obtained from the Instituto Nacional de Estadística, Geografía e Informática (INEGIM;

Table 1
The annual cost of *Sargassum* cleanup for three Municipalities (Puerto Morelos, Solidaridad, and Tulum) and five hotels along the northern Mexican Caribbean coast. The peso/dollar exchange rates were 19.22 in 2018, 19.25 in 2019, 21.48 in 2020, 20.29 in 2021, and 20.11 in 2022 (Taken from: https://www.macrotrends.net/2559/us-dollar-mexican-peso-exchange-rate-historical-chart). The adjustment for inflation (to December 2022) considered the rates: 4.83% in 2018, 2.83% in 2019, 3.15% in 2020, 7.36% in 2021, and 7.82% in 2022 (Taken from (https://www.inegi.org.mx/temas/inpc/). Hotel names are not provided for confidentiality reasons. PM: Puerto Morelos, Sol: Solidaridad, Tul: Tulum.

Variable	Municipalities			Hotels				
	PM	Sol	Tul	A	B	C	D	E
Period	Jan–Dec 2021	Jan–Dec 2020	Jan–Dec 2021	Jan–Dec 2018	Jul 2018–Jun 2019	Jun 2018–May 2019	Jan–Dec 2018	Jan–Dec 2018
Beachfront distance (km)	1.8	3.5	0.909	2.2	0.2	0.438	0.86	1.7
Sargassum removed (m^3)								
Total	19,842	35,366	9808	90,051	4714	11,205	12,275	29,538
Per kilometer	11,023	10,105	10,790	40,932	23,570	25,582	14,273	17,375
Cost ($US)								
Wages	166,963	596,198	332,566	261,121	44,999	60,920	48,993	143,569
Equipment	246,427	601,062	197,141	1,374,870	–	–	93,653	93,652
Rentals	27,986	793,855	–	–	14,231	21,009	19,089	191,742
Maintenance	35,042	43,897	10,843	208,117[a]	–	–	–	22,674
Disposal	167,643	398,547	0	237,102	54,805	101,021	97,935	102,376
Materials	100,324	185,714	70,971	–	–	–	–	77,523
Total cost ($US)	744,385	2,619,273	611,521	2,081,210	114,035	182,950	259,670	631,536
Cost per kilometer	413,547	748,364	672,741	946,005	570,175	417,694	301,941	371,492
Cost per m^3 of *Sargassum*	38	74	62	23	24	16	21	21
Adjusted for inflation (December 2022)								
Cost per kilometer	451,943	858,925	733,720	1,105,164	659,960	486,058	285,460	434,375
Cost per m^3 of *Sargassum*	41	85	68	27	28	19	20	25

[a] Includes the cost of materials.

https://www.inegi.org.mx/temas/inpc/). The adjusted costs were converted to US dollars. The compound interest formula was given by

$$P_t = (1 + i)^{kt} P_0$$

Where P_0 is the original principal, t is time in years, i = r/k with r the annual interest rate and k the number of times interest is compounded per year, and Pt is the principal at time t (Palacios, 2022).

To estimate the monthly and annual variability in *Sargassum* cleanup costs in the municipality of Puerto Morelos, we use data on the volume (cubic meters) of *Sargassum* removed by 14 hotels in the municipality of Puerto Morelos during the years 2018, 2019, 2021, and 2022. The mean monthly costs were obtained using the mean landing volumes per month during the four study years and the mean per-unit (cubic meter) price estimated for the four hotels that provided financial information within this municipality (sites A-D in Fig. 1). The beach fronts of these hotels range from 0.2 to 1.7 km, and they collectively account for 6.7 km of sampling distance.

All analyses were done in R (R Core Team, 2021) using packages: ggpubr (Kassambara, 2020), plyr (Wickham, 2021), and tidyr (Wickham, 2021). A reproducible record of all statistical analyses and underlying data is available on GitHub (https://github.com/rerodriguezmtz/Sargassum-Cleanup-Costs).

3. Results

3.1. Hotels cleanup costs

The annual volumes of pelagic *Sargassum* removed from hotel beaches along the northern Mexican Caribbean coast varied among sites, ranging from 14,273 m^3 km^{-1} to 40,932 m^3 km^{-1} (Table 1). The per-unit (cubic meter) *Sargassum* cleanup prices went from US$ 19–28 after adjusting for inflation to December 2022 (Table 1). Hotels spent between US$ 0.3–1.1 M per kilometer of beach (Table 1) annually to keep them in suitable conditions.

The per-unit (cubic meter) cost variability among hotels was influenced by management strategies rather than the volume of algae removed. For example, the per-unit costs of hotels A and B were similar (US$ 27 vs. US$ 28), even though the first received 58% more *Sargassum* per kilometer of beach than the second (Table 1). Hotel A is in an area periodically affected by high *Sargassum* landings and has a beachfront of 2.2 km. In 2018, 66% of its annual budget was invested in equipment. On the other hand, hotel B has a small beachfront (0.2 km) and hired an external beach cleaning service. Hotel C had the lowest per-unit cost (US $ 19). Most of the beach cleaning was done by its staff and only hired a cleaning company during the *Sargassum* peak landing months. However, it should be noted that this hotel did not report expenses in equipment during the study period because, historically, their beach has received large amounts of seagrasses, and they already owned machinery. The per-unit costs of hotels D (0.86 km beachfront) and E (1.7 km) were US$ 20 and US$ 25, respectively. Both hotels acquired and rented machinery and used their staff to remove the algae.

The disposal costs of *Sargassum* represented between 11% and 55% of the hotels' beach cleanup budgets. Transportation prices varied depending on the distance between the hotels and the disposal sites. In Puerto Morelos, for example, the price of a truck (14 m^3 truck) trip ranged between US$ 125 and US$ 200 depending on if the distance was lower or greater than 5 km. The fees charged by disposal sites also varied between municipalities. In Puerto Morelos, the hotels sent the *Sargassum* to an old quarry at the cost of ~US$ 20 per truck (14 m^3), whereas in Solidaridad, they sent it to the municipal garbage dump at the cost of ~US$ 100 per truck. In just one case, a hotel (Hotel A) had an area to sundry the algae and recovered the sand before sending it to the disposal site. This considerably reduced the volume and weight of the biomass transported to the final disposal site and the cost. In the other four hotels, transportation costs (Table 1) represented a higher proportion of the budget, as there were no temporal disposal spaces within their properties, so the *Sargassum* had to be sent to disposal sites almost daily. According to hotels and cleaning companies, the weight of one cubic meter of fresh *Sargassum* can vary from 200 kg to 420 kg (mean = 276.4: 95% CI = 45.7), depending on the amount of sand and humidity. This variability can affect disposal expenses, mainly when the prices are based on the weight of trucks rather than on the volume, as occurs in the garbage dump of Solidaridad municipality.

3.2. Municipalities' cleanup costs

The biomass of *Sargassum* removed annually from the public beaches of the three studied municipalities was similar, with volumes ranging from 10,105 m^3 km^{-1} to 11,023 m^3 km^{-1} (Table 1). However, the annual costs went from US$: 0.4–0.8 M per kilometer (Table 1). The per-unit (cubic meter) prices were higher in Solidaridad (US$ 85) and Tulum (US$ 68) than in Puerto Morelos (US$ 41) (Table 1). These differences were related to the cleanup strategies employed.

In Solidaridad, 30% of the annual budget was used to hire a cleanup service (barrier + boats; Fig. 2F). Still, the municipality also invested a substantial amount of the funding in equipment (23%) and wages of staff (22%) to work in the beach sector not protected by the barrier. The transportation of the algae to disposal sites represented 15% of the budget, and only 1.7% was spent on maintenance. Tulum municipality spent 54% of the budget on wages, as *Sargassum* removal from the beach is done mainly by manual labor. 32% of the budget was used to buy minor machinery and 1.8% on maintenance. This municipality has no transportation expenses because trucks cannot access the beach, so the *Sargassum* is extended on the dry beach and left to sundry. In Puerto Morelos municipality, the *Sargassums* management strategy has been to invest in equipment over the years. In 2021, 33% of the beach cleanup budget was used to buy equipment, 4.7% on its maintenance, and 22% on disposal. During the peak *Sargassum* landing months, 22% of the budget was spent on the wages of external workers.

3.3. Annual and monthly variability in Sargassum cleanup costs in Puerto Morelos municipality

Using data from the years 2018, 2019, 2021, and 2022, we estimate that the mean monthly volumes of *Sargassum* removed by 14 hotels from the beach of Puerto Morelos municipality ranged from 589 to 3763 cubic meters per kilometer within a year (Fig. 3). The volumes were high (mean > 2000 m^3 km^{-1}) from April to August, intermediate (1000–2000 m^3 km^{-1}) in February, March, September, and October, and relatively low (<1000 m^3 km^{-1}) in January, November, and December (Fig. 3). Considering the mean monthly volumes and the mean per-unit (cubic meter) cleanup cost estimated for the hotels that provided financial information within the municipality of Puerto Morelos (US$27; Hotels A-D from Table 1), we obtain annual costs ranging from US$ 0.8–1.5 M per km during the four study years (Mean: 1.0 M) with mean monthly fees from US$ 10,186 to US$ 100,446 per km (Fig. 3). Extrapolating these costs to the total beach length of Puerto Morelos municipality (17 km), the estimated yearly cleanup costs would range from US$ 13.6–25.5 M, depending on *Sargassum* landing volumes.

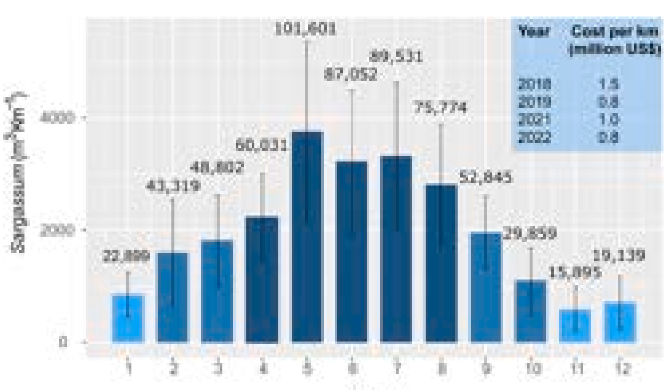

Fig. 3. Monthly mean (±95% CI) volume (m^3) of beach cast *Sargassum* removed per kilometer of coastline by fourteen hotels in Puerto Morelos municipality using data from 2018, 2019, 2021, and 2022. The numbers above each plot indicate the mean cleanup cost per kilometer, considering a per-unit (m^3) price of US$ 27. The data in the top right corner correspond to the estimated annual fees per kilometer.

4. Discussion

The harvesting of massive amounts of beachcast macroalgae is necessary to prevent the effects of decomposition on coastal ecosystems, preserve their desired aesthetic and recreational values, and reduce the risk of respiratory and neurologic diseases in humans. However, there is surprisingly little scientific information regarding the beaching quantities of macroalgae species during bloom periods and the associated cleanup costs, despite their tendency to become more frequent and abundant due to climate change and ocean eutrophication (Smetacek and Zingone, 2013). Pelagic *Sargassum* has become the biggest seaweed bloom in the world, and Mexico is among the most affected nations (Torres-Conde, 2022). Our results show that the north sector of the Mexican Caribbean coast has received yearly volumes ranging from 10, 790 to 40,932 m^3 per kilometer. This quantity is considerably higher than that of *Ulva* sp. harvested in the French city of Brittany (~35 m^3 km^{-1} yr^{-1}; Charlier et al., 2006) and *Sargassum horneri* removed from the coastline in Shinangun, Korea (~1.5 tons per ha; Hwang et al., 2016).

Our estimates of the annual *Sargassum* cleanup costs in Mexico (range: ~US$ 0.3–1.0 M per kilometer) are considerably higher than the yearly budget (~US$ 0.07 M km^{-1}) spent in Galveston Island, EEUU, on maintaining ~52 km of the public beach, as they only move the *Sargassum* from the main strand to less tourist-sensitive back areas to compost (Milledge and Harvey, 2016). The yearly budget spent to clean 1 km of the beach in Galveston is equal to or even lower than the monthly cost in Puerto Morelos municipality during the peak landing months (range: ~US$ 0.07–0.1 M). On the other hand, the annual cleanup costs in Mexico are lower than the yearly budget estimated by the government of Miami City to remove the *Sargassum* from 24 km of the coast (US$ 45 M or US$ 1.9 M km^{-1}; Hanks, 2019 in Braun, 2020).

The per-unit (cubic meter) *Sargassum* cleanup costs estimated in the present study varied from US$ 19–28 for hotels and US$ 41–85 for municipalities. Hotels' costs are similar to some reported for the cleaning of other macroalgae that land massively on beaches, such as *Sargassum muticum* in the UK in the early 1980s (~US$ 21 m^3; Critchley et al., 1986) and green algae, mostly *Ulva* and *Enteromorpha*, in Brittany, France, in the early 1990s (~US$ 40 m^3; Morand and Briand, 1996). The costs obtained for Mexico were also close to the prices reported for harvesting macroalgae from lagoons and estuaries, such as *Cladophora* and *Ulva* from Peel-Harvey Estuary, Australia, in the 1990s (~US$ 13 m^3; Atkins et al., 1993) and *Enteromorpha*, from the Olympics sailing venue in Quingdao, China in 2008 (~US$ 32 m^3; Wang et al., 2009).

The results obtained in the present study suggest that the variability recorded in the per-unit (m^3) *Sargassum* cleanup costs in the northern Mexican Caribbean was related to the management strategies employed and their optimization in time rather than to the length of the attended beach or the volumes removed. Overall, the per-unit costs for hotels were about two to four times less than those of municipalities. Hotels always try to minimize their costs by improving their efficiency. After seven years of periodical *Sargassum* landings to this region, many hotels have identified and optimized the cleanup strategies that suit them better. Hotels with beachfront of considerable length (e.g., >1 km) preferred to invest in machinery, and those with small beach fronts (e.g., <200 m) found it more cost-effective to rent the cleanup service. Mixed strategies could be effective for beaches of intermediate length. On the other hand, the administrative period of municipalities lasts three years and ends coincidentally by the time *Sargassum* landings decrease (September 30th). The municipal authorities must familiarize themselves with the *Sargassum* phenomena and its cleaning strategies. Commonly, the leaving administration does not pass on the acquired expertise, and the newcomers need a period to develop their management strategies based on trial and error. It is also frequent for the leaving authorities to abandon the machinery and materials without proper maintenance, so the arriving administration has to invest part of the beach cleanup budget in repairing or replacing. This lack of continuity between administrations increases the cleanup costs. It delays the beginning of activities, making harvesting more difficult, as fresh *Sargassum* is easier to remove from the beach than after it has decomposed and accumulated for weeks or months. The delay in cleanup actions also increases the ecological impacts and the human-health related problems, as the decomposing algae produce leachates (van Tussenbroek et al., 2017; Olguin-Maciel et al., 2022) and toxic gases (Resiere et al., 2021).

Cleanup strategies also influenced cost variability among municipalities. For instance, Puerto Morelos municipality has invested in equipment over the years. Its annual *Sargassum* cleanup cost was almost half that of Tulum, which relies on labor-intensive and time-consuming manual techniques, as machinery access to the beach is impossible. In contrast, Solidaridad rented a cleanup service to collect most of the algae on the coastal waters in front of a public beach with high tourist visitation. The decision was made partially to mitigate beach erosion, which in the last decades has increased in the area (Ruiz-Martínez et al., 2013). *Sargassum* harvesting with machinery usually results in a substantial loss of sediment. According to several studies, between 37 and 90% of the material removed from beaches can be sand (Rodríguez-Martínez et al., 2016; Oxenford et al., 2021; Roig-Munar et al., 2022). In Mexico, *Sargassum* cleanup activities have reduced the length of some beaches by almost half since the events began (Chávez et al., 2020). Thus, even though in the short term it might be more expensive to employ *Sargassum* cleanup strategies that prevent these algae from reaching the beach, in the long term, this could reduce the overall cost of coastal zone management. For example, the nourishment of 12 km of Cancun beach after Hurricane Wilma (2005) had a cost of US$19 M (Martell et al., 2020).

Sargassum disposal procedures also significantly influenced the cleanup costs, as the charges could consume over half of the annual budget for beach cleanup. Disposal expenses of other macroalgal blooms have also been reported to vary greatly depending on the method. For example, the cost of disposal of *Ulva* blooms in Ireland varied greatly (range: ~US$: 5–81 per cubic meter), depending if it was done on arable land or landfills (Wan et al., 2017). In the present study, Tulum municipality did not invest in disposal as they left the algae on the beach to sundry. However, this might be difficult to achieve on beaches with high-volume strandings or insufficient space. Also, by doing this, the nutrients and chemical compounds transported by *Sargassum* might remain on the beach, changing its composition, color, and quality. Coastal ecosystems could even become polluted with toxic elements (e.g., arsenic; Rodríguez-Martínez et al., 2020) and pesticides (e.g., chlordecone; Devault et al., 2022) absorbed by *Sargassum*, which can later enter coastal food webs, resulting in ecological impacts and threatening human health (Modestin et al., 2022).

An efficient method to reduce *Sargassum* disposal volumes and costs was implemented by hotel A, which left it to sundry within the property and recovered the sand to nourish their beach before its clearance. Nevertheless, this strategy can only be implemented in hotels with available land and large budgets, which are uncommon along the Mexican Caribbean. Some disposal strategies employed in other countries are not allowed in Mexico. For example, Gray et al. (2021) developed a low-cost (<US$ 1 per cubic meter) collection device. It consists of modules attached to artisanal fishing boats that collect the algae in nets tied to barges that tow them to the deep ocean, where the *Sargassum* is pumped to ~150–200 m deep. Nevertheless, as the authors mention, there are risks to the process that demand further studies, including by-catch of marine species, some of which could be endangered (e.g., sea turtles) and the migration of sunken *Sargassum* outside the intended sink zone. Strategies for the treatment and valorization of *Sargassum* also need to be explored. For example, life cycle assessment and life cycle costing methodologies (Mainardis et al., 2021; Vance et al., 2022) have been employed to analyze different strategies for seagrass treatment and valorization and could be helpful to quantify and assess the economic and environmental impacts of *Sargassum* on Caribbean nations.

As Jonvier et al. (2021) stated, only a few studies have focused on the economic impacts of macroalgal blooms, and many underestimate the actual costs as these often extend beyond the time and machinery used to clear and dispose of the macroalgae. Additional data to the ones reported in the present study is required to estimate the economic impact of *Sargassum* blooms on the Mexican Caribbean coast. Other variables that need to be quantified include 1) the amounts lost from cancellations and compensations (e.g., moving tourists to other hotels, giving them attractions entrances, and providing services not included in their original traveling packages), 2) the repair of electronic equipment (e.g., elevators, air conditioning, televisions) corroded by gases produced during *Sargassum* decomposition, 3) the restoration of coastal ecosystems, and 4) income reduction from recreational activities on the beach and coastal waters. Also, tourists' ratings of hotels on digital platforms have a reputational effect that can reduce repeated purchases, recommendations, and even brand equity.

Based on the results obtained in the present study, *Sargassum* cleanup costs from beaches and coastal waters could be reduced by improving management strategies. For example, the greater the extension of the beach, the more necessary it is to invest in *Sargassum* removal machinery. Municipalities should develop adequate *Sargassum* management protocols that are passed to successive administrations. They could benefit from the experiences of hotels with lower per-unit cleanup costs. In addition, annual municipal budgets must include equipment maintenance and storage expenses to reduce future costs and ecological impacts. Overall, *Sargassum* disposal strategies need to be improved to reduce costs. Research should focus on developing technology to reduce the weight and volume of these algae before their transportation to disposal sites. Additionally, cleanup strategies must consider the future use of harvested biomass by industries and the protection of coastal ecosystems and human health.

Considering the scarcity of reliable information to assess the economic impacts of macroalgal blooms, we recommend the development of standardized monitoring protocols to determine the variability of beach cast volumes in space and time and the costs associated with different harvesting methods and management strategies. In the case of *Sargassum*, the mean annual cleanup costs obtained for the municipality of Puerto Morelos during four major landing events was one million dollars per kilometer. This price suggests that the costs estimated by Milledge and Harvey (2016) and Davis et al. (2021) for the annual cleanup of these algae across the Caribbean (US$ 120 and US$ 210 M, respectively) are underestimated. Expanded datasets than the one used in the present study are needed to model costs associated with *Sargassum* cleanup across the Caribbean and other affected Atlantic nations and determine more efficient removal strategies.

5. Concluding remarks

Pelagic *Sargassum* cleanup from beaches and coastal waters is expensive. Still, management actions can be optimized to reduce costs, as shown by some hotels that receive large volume strandings. For municipalities, reducing the cleanup costs would allow for extending the operation to more coastal sectors, reducing negative ecological, economic, and human-health impacts. *Sargassum* management programs should consider the fragility of the coastal ecosystems rather than just maintaining the most important touristic destinations. The cost of inaction will be much greater than mitigation concerning *Sargassum's* massive landing effects. The recovery of the services that coastal ecosystems provide will require restoration actions that are expensive and have unpredictable outcomes. If *Sargassum* landings are adequately managed, the tourist industry will be protected, and so will the economy of Caribbean countries. On the contrary, if the massive arrivals of *Sargassum* remain unattended, tourist visitation is likely to decline, leading to unemployment and bringing various social problems, including increased poverty and crime.

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

The data are available in a Github repository. The link has been included in the document

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