

## Article

# Advancing Sustainability: Effective Strategies for Carbon Footprint Reduction in Seaports across the Colombian Caribbean

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**Abstract:** Colombian port terminals in the Caribbean are being called upon to increase the sustainability of their operations to better fit with the environmental dynamics of their locations. Within this context, the Palermo Sociedad Portuaria (PSP) has taken a proactive stance in identifying the factors contributing to its CO<sub>2</sub> emissions. This study evaluated the CO<sub>2</sub> emissions of the PSP in 2019 and 2020 and, through the implementation of sustainable practices (rock dust spreading, composting and reducing the burning of fossil fuels), examined the mitigation of the port's carbon footprint (CF) in the year 2022. Based on collaborative management results and efforts, a set of viable mitigation strategies adapted to port operations was formulated. Viability was assessed through monitoring of the practical implementations encompassing initiatives such as fuel reduction, waste composting and the application of rock dust. The introduction of the CARE system in the operational equipment led to a reduction in fuel consumption over five periods—amounting to an overall emission decrease of 1629 metric tons of CO<sub>2</sub> equivalent (ton CO<sub>2</sub> eq). Meanwhile, the strategic composting of waste generated by port activities (including organic waste, hand towels, coffee grounds and landscaping waste) resulted in the potential reduction of 2 metric tons of CO<sub>2</sub> annually. The application of rock dust (10 kg m<sup>-2</sup>) in the available green spaces within the operational areas contributed to a decrease of 0.00080543 ton CO<sub>2</sub> eq over 45 days. The implementation of these three key measures over the course of a year has the potential to prevent the release of 37 ton CO<sub>2</sub> eq, signifying a 2% decrease in overall CF when compared to the base year of 2020. This investigation was rooted in the current operational reality of the port terminal and its correlated activities. The strategies deployed underscore the feasibility of low-cost solutions that can be emulated across port terminals in pursuit of the holistic aspirations encapsulated in the concepts of a “green port” and a “smart port”.

**Keywords:** carbon footprint; sustainable practices; reduction of carbon emissions; sustainability management



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## 1. Introduction

Littoral regions with adjacent seaports have the capacity to impact the environment by concentrating high quantities of dangerous elements in liquid, solid and gaseous forms. This contamination is capable of contaminating large coastal and maritime regions, in addition to emitting high concentrations of carbon dioxide (CO<sub>2</sub>) into the atmosphere [1,2]. Carbon emissions emanating from bulk shipping comprise the eighth largest source of

global CO<sub>2</sub> pollution [2,3]. The efforts and actions of the International Maritime Organization (IMO), linked to the United Nations (UN), have the aim of helping to reduce CO<sub>2</sub> emissions by approximately 50% by 2050 in relation to 2008 levels of 385 ppm (parts per million) [4,5]. It is estimated that by that time, 15% of global CO<sub>2</sub> emissions will come from vessels used in maritime transport [6,7]. While international maritime shipping contributes to the development of the global economy, it releases up to 850 million metric tons of CO<sub>2</sub> into the atmosphere annually, representing 2.3% of total global emissions [8]. Reducing CO<sub>2</sub> emissions in naval ports is therefore a global need [8], one which can be achieved with contributions from human and commercial activities that lower carbon emissions through the innovative storage, use and maintenance of hydrogen. Escalating concentrations of carbon dioxide in the atmosphere, accompanied by the elevation of other greenhouse gases (GHGs) stemming from natural and human-induced sources, have raised substantial concerns regarding potential climatic repercussions [9]. The dynamics of global climate change are impacting the equilibrium of the Earth's environment, potentially unsettling the delicate balance between Earth's biospheres and oceans [10]. CO<sub>2</sub> plays a pivotal role in global climate equilibrium and is not intrinsically in and of itself harmful. However, the excessive and unsustainable rate of anthropogenic emissions of CO<sub>2</sub> over the past several hundred years has been upsetting our global climate. The urgency to combat global climate change and its wide-ranging impacts is pressing. The global average temperature has already surpassed an average 1.0 °C increase from pre-industrial levels and is forecasted to breach the 1.5 °C threshold stipulated by the Paris Agreement of the United Nations [11] within the upcoming three decades, due to a mean warming rate of 0.18 °C per decade [12]. Worldwide scientific consensus agrees [12] that the concentration of gases such as CO<sub>2</sub> in the atmosphere, originating from anthropogenic sources, disrupt and harm global climate on a widespread scale.

Notwithstanding Colombia's modest contribution of 0.46% of global emissions, García et al. [13] underscore the potential for Colombia's emissions to surge by approximately 50% by 2030 in the absence of robust mitigation measures. Consequently, the country has committed to a 20% carbon emission reduction target by 2030 and a potential 30% reduction with international collaboration. Despite Colombia's relatively low emissions compared to other nations, its cumulative emissions from 1990 to 2012 position it among the 40 countries bearing significant historical responsibility for greenhouse gas generation. This is largely attributed to emissions linked with deforestation [13]. In this context, the Shipping Emissions in Ports report highlights that maritime-related CO<sub>2</sub> emissions constitute between two and three percent of the global tally [14,15]. Correspondingly, maritime-related SO<sub>x</sub> emissions account for between five and ten percent of global emissions, while NO<sub>x</sub> emissions account for 17–31% [14,15].

The inception of the port and business zone on the eastern bank of the Magdalena River dates to 2002, marked by the establishment of the pioneering company Petrocomercial, focusing on biofuel trading [16]. This momentum was followed by the commencement of the Palermo Sociedad Portuaria (PSP) terminal in 2004. The area further expanded to include a total of seven companies engaged in activities ranging from land-free zones to multipurpose port terminals and hydrocarbon storage.

This study is justified by a gap in the scientific literature regarding the implementation of mitigating strategies focused on the release of CO<sub>2</sub> in seaports [2,8]. In this context, the literature [2,8] highlights the importance of scientific investigations capable of allocating measures to reduce emissions of CO<sub>2</sub> in seaports, not only for Colombia but on a global level. One strategy that has resulted in success is the actions implemented by the PSP, which aim to reduce CO<sub>2</sub> through sequestration by using rock dust, composting and reducing the burning of fossil fuels. The main objective of this study is to evaluate the CO<sub>2</sub> emissions of the Palermo Sociedad Portuaria terminal from 2019 to 2020, following the implementation of sustainable practices (use of rock dust, composting of organic waste and reduction of fossil fuel burning) aimed at mitigating CO<sub>2</sub> in relation to the carbon footprint (CF) in the year 2022. The innovation of this study stands out for investigating the reality of the

port terminal, the results of which could result in the implementation of these sustainable practices to reduce the carbon footprint of seaports in other areas of the world. These efforts could result in praise for companies on a global scale, which demonstrate their commitment to implementing sustainability actions and an emphasis on the United Nations' Sustainable Development Goals (SDGs).

## 2. Materials and Methods

### 2.1. Study Area

The Palermo Sociedad Portuaria (PSP) maritime–fluvial terminal is strategically positioned adjacent to Barranquilla, Colombia, located on the eastern bank of the Magdalena River, 1.8 km from its estuary. PSP constitutes an integral component of the logistics cluster within the corporate framework of Coremar [16]. Notably, in 2020, PSP achieved the distinction of being the premier terminal in Colombia for steel operations, underscoring its upward trajectory within the Barranquilla port landscape [16]. Characterized by its multi-purpose functionality, this expansive terminal covers 32 hectares, 20 of which are already developed. Amplifying its strategic placement near the river's mouth, the likelihood of PSP expansion is significant in addition to improving connectivity to the country's interior through both roadways and water routes.

The PSP consists of 700 linear meters of constructed docks, each accommodating an impressive dock capacity of 24 metric tons  $m^{-2}$  [16]. Additionally, the terminal encompasses 10 hectares of open yard, 3.5 hectares of covered area, an assortment of eight versatile warehouses, six vertical silos and a substantial seven-hectare zone exclusively designated for storing coke [16].

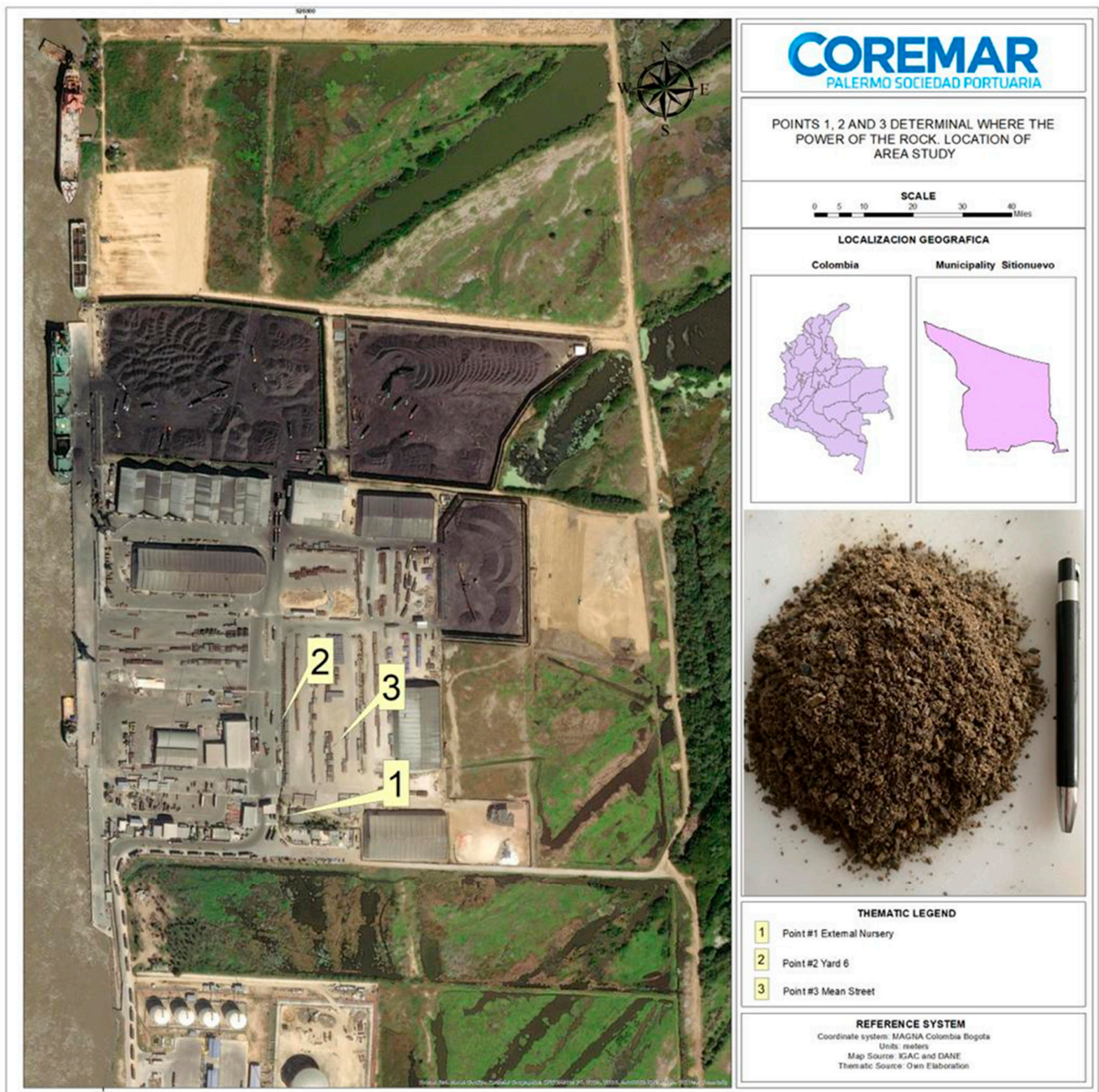
Functioning as a versatile port, PSP seamlessly coordinates the handling of bulk and general cargo operations, encompassing vital processes such as intake, safekeeping and, ultimately, the loading of coke in its final stage. Currently under construction, a dock focusing on bulk liquid transfer will soon be complete, enabling the area to transform into a dynamic hub for liquid-related activities, facilitating inflow and outflow [13,16]. Depicted in Figure 1, the strategic location of the PSP is positioned at km 1.5 along the Barranquilla–Ciénaga route, nestled within the Palermo Corregimiento of the municipality of Sitio Nuevo, Barranquilla.

### 2.2. Methodological Design

As specified in Figure 2, the research was carried out as follows: identification of the sources of CO<sub>2</sub> emissions from the PSP; definition of the CF calculation method; validation of calculations; establishment of alternatives to mitigate CO<sub>2</sub> emissions: reduction of fuel consumption; composting of organic waste generated at PSP; and application of rock dust.

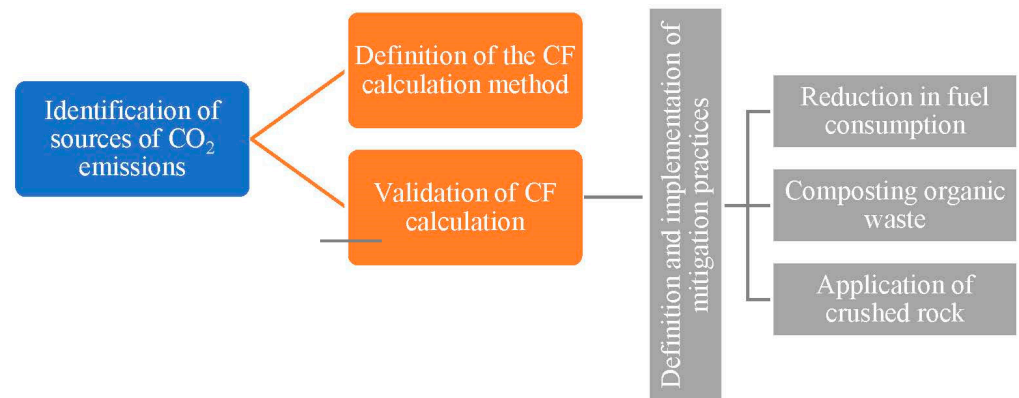
The study encompassed two distinct phases, the first of which involved an analysis of the port's CO<sub>2</sub> emission sources. The second consisted of the determination of whether these emissions fall under the organization's control [2]. The primary sources of CO<sub>2</sub> emissions were categorized into two main groups: (a) direct and (b) indirect sources [17,18]. (a) Direct emissions encompassed: emissions linked to diesel consumption for port infrastructure and lighting, emissions associated with R410a refrigerant usage, emissions originating from acetylene consumption, emissions connected to gasoline usage in concession vehicles, emissions arising from diesel consumption in freight vehicles and electricity consumption [17,18]. (b) Indirect emissions involved: diesel consumption from land transportation of PSP personnel, distance covered during national and international air travel for corporate purposes by collaborators, treatment of waste and wastewater, generation of recyclable and ordinary waste and contribution of biochemical oxygen demand (BOD) for both domestic and industrial wastewater [2,17,18].



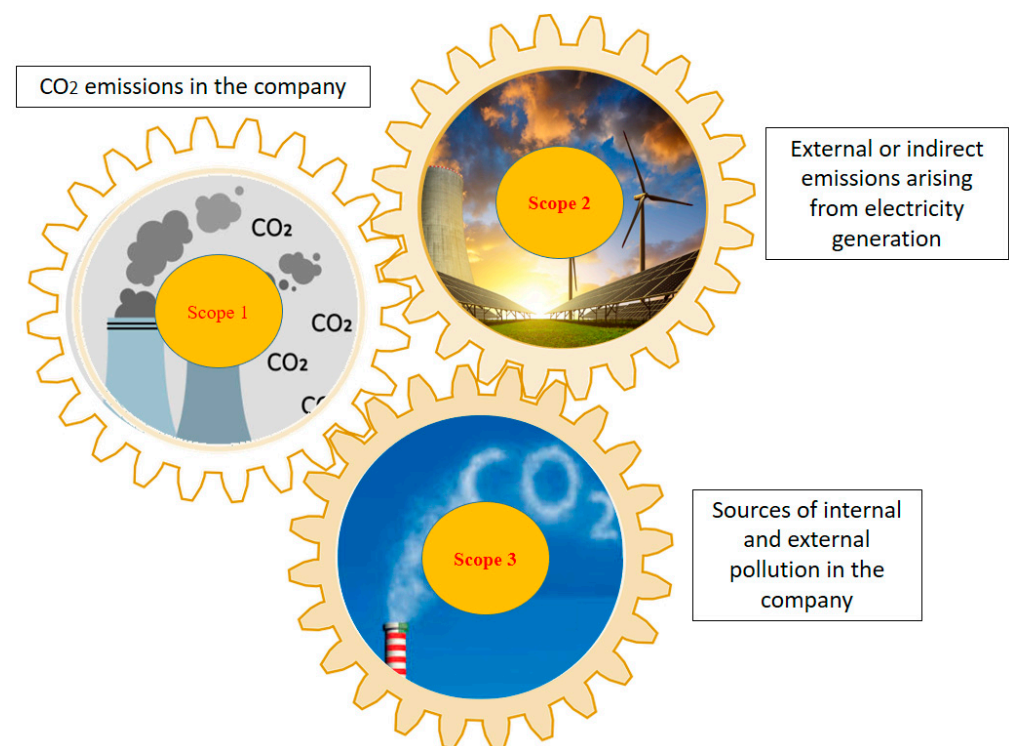


**Figure 1.** Location of the study areas within the Palermo Sociedad Portuaria (PSP), Colombia.

To quantify the port's carbon footprint (CF), the methodology proposed by WPCI [19] specifically designed for assessing CF in port terminals was adopted. The fieldwork included data collection utilizing the tool specified by WPCI [19]. This approach would yield a CF measured in overall CF. The ongoing implementation of these strategies was also tracked, based on reasoning and deductive logic. The WPCI [19] methodology was chosen for this study in an effort to allow for a way to standardize calculations of greenhouse gas emissions for ports around the world (exclusive for seaports). Regarding the carbon footprint calculation, Semarnat [20] defined three levels (Figure 3): Scope 1 encompasses direct emissions from sources owned or controlled by the company; Scope 2 covers external or indirect emissions arising from electricity generation purchased by the company; and Scope 3 encompasses external or indirect emissions originating from the supply chain or the utilization of products or services sold by the company (including waste disposal).



**Figure 2.** Methodological scheme of the study (CF = carbon footprint).



**Figure 3.** The three levels (scopes) involved in the calculation of the carbon footprint.

### 2.2.1. Quantification of GHG Emissions

The calculation of greenhouse gas (GHG) emissions for the Palermo Sociedad Portuaria was carried out based on the collection of activity data for each of the categories included in the different scopes and the corresponding GHG emission factors available in the scientific literature [20]. The quantification methodology and the emission factors used in the quantification of the emissions in each category of the scope contemplated in the inventory of greenhouse gases of the terminal are referenced [20].

Carbon footprint reduction strategies examined were mainly related to their feasibility of execution. They include CO<sub>2</sub> sequestration through basaltic rock, where enhanced terrestrial rock weathering (ERG) is a biogeochemical carbon dioxide removal (CDR) strategy which accelerates the natural geological processes of carbon sequestration through the application of crushed silicate rocks such as basalt to agricultural lands and forested landscapes. ERG has been shown to sequester CO<sub>2</sub> at rates of two to four t CO<sub>2</sub> ha<sup>-1</sup>, one to five years after a single application [21]. Improved soil weathering of silicate rocks implemented on agricultural land has the potential to be used for CO<sub>2</sub> mitigation [22]. Such



simple methodologies are necessary to mitigate climate change, improve food security, preserve soil and limit ocean acidification.

The fuel reduction technology known as CARE consists of a technology-based system for reducing GHG and particulate matter emissions through increased energy efficiency. Efficiency is defined as the reduction and/or better use of liquid fuels used as an energy resource for the operation of mobile or stationary machines [10]. CARE consists of a set of protocols and procedures that are governed by the methodology of the United Nations Intergovernmental Panel on Climate Change for inventory of greenhouse gases [10].

Composting activities are a part of the circular economy involving reducing, reusing and recycling agricultural waste to promote sustainable agriculture and minimize environmental pollution. The urgency of the need to establish strategies to achieve sustainability is well documented [23].

### 2.2.2. Carbon Footprint Calculation

The CF calculation for the base year 2019 adheres to the guidelines established in the Greenhouse Gas Protocol [20]. The 2019 GHG inventory encompasses both the terminal's internal consumption, as well as operational and service-related activities. The results are expressed in metric tons of carbon dioxide equivalent (ton CO<sub>2</sub> eq). The Palermo Sociedad Portuaria's greenhouse gas inventory encompasses emissions of CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, PFCs and HFCs, all measured in ton CO<sub>2</sub> eq, and falls within the following categories:

Scope 1: Emissions stemming from fuel consumption (gasoline and diesel) for terminal vehicles; usage of internal refrigerants for air conditioning in administrative areas; fuel consumption for cogeneration of energy; and acetylene consumption. The specific activities considered as sources of direct GHG emissions are: diesel consumption for lighting plants and towers (measured in gallons/year); R410a refrigerant consumption (measured in kg/year); acetylene consumption (measured in kg/year); gasoline consumption for concession vehicles (measured in gallons/year); and diesel consumption for cargo vehicles (measured in gallons/year).

Scope 2: Indirect emissions are attributed to electricity consumption typical of the Palermo Sociedad Portuaria's operations. Due to data limitations, the breakdown of emissions derived from energy consumption (e.g., air conditioning, lighting of port roads and common areas) is not available. The activities considered as sources of indirect GHG emissions include the general electricity consumption of the port's facilities (measured in MWh/year).

Scope 3: This encompasses emissions linked to land and air transportation of employees, along with those related to waste and wastewater treatment. The activities considered as sources of other indirect GHG emissions are: distance traveled on domestic (national) trips (measured in miles/year); distance traveled on international trips (measured in miles/year); diesel consumption for administrative routes (measured in gallons/year); amount of ordinary waste generated (measured in metric tons/year); amount of recyclable waste generated (measured in metric tons/year); and biochemical oxygen demand (BOD) contribution from ARnD (measured in kgBOD/year).

Exclusions in the inventory and emission quantification encompass activities derived from terminal expansion. Additionally, emissions from cargo transportation within the terminal and those related to moored motor vessels during port operations at the dock are excluded. The CF calculation for the base year 2020 follows the guidelines set by the Greenhouse Gas Protocol [20]. Similarly, exclusions in the inventory and emission quantification pertain to terminal expansion and cargo transportation within the terminal, as well as emissions associated with moored motor vessels during port operations at the dock.

### 2.2.3. Fuel Consumption Reduction

The fuel reduction technology known as CARE encompasses a system designed to curtail greenhouse gas (GHG) emissions and particulate matter through enhanced energy

efficiency. Efficiency, in this context, pertains to optimizing the utilization of liquid fuels as an energy resource for both mobile and stationary machinery within the implementing company's operations [10].

As per decree 2532 of 2001, article 2, CARE is defined as a structured assembly of domestic or imported equipment, components or machinery, tailored to the accomplishment of measurable and verifiable outcomes. These outcomes encompass reducing the demand for renewable natural resources, preventing and/or decreasing the volume and/or enhancing the quality of liquid waste, atmospheric emissions or solid waste. This approach adheres to a set of protocols and procedures in line with technical standard ISO 14064-1 and the United Nations Intergovernmental Panel on Climate Change's Greenhouse Gases Inventory methodology [10].

The technology's development spans three distinct periods [10]: 1. Baseline: This phase establishes initial numerical data derived from measured variables of interest in a mobile or stationary source. These data facilitate the quantification of liquid fuel consumption essential for the source's operation within a productive period. 2. Cleaning period: This interval is dedicated to cleaning the engine fuel system. During this phase, the CARE system refrains from collecting data concerning fuel consumption or emissions generated by the source. 3. Post-installation period: This/these period(s) reflect(s) the reduction in emissions resulting from the energy efficiency achieved through the CARE system. Reductions are accounted for in an annual inventory of mitigated emissions. The CARE system, developed by NTC ISO 14064-1, was successfully integrated into an elevator-type mobile lifting system with a 16-metric-ton capacity. This equipment is employed in the port's logistics activities, specifically for cargo movement during operations. The Palermo Sociedad Portuaria owns 11 identical such pieces of equipment, which are pivotal in ship-related operations.

#### 2.2.4. Solid Waste Composting

One of the strategies proposed to mitigate the Palermo Sociedad Portuaria's CF involves reducing the amount of ordinary waste generated. As of 2020, this factor contributed approximately 2.51 ton CO<sub>2</sub> eq to the CF of Scope 3. In line with this objective, a comprehensive experiment was initiated on 13 December 2021, aimed at composting specific waste materials [24]. These waste materials include pruning remnants, coffee residues, disposable hand towels, sewage system sediments and organic food waste—all byproducts stemming from port-related activities.

The composting experiment commenced with the mechanical amalgamation of these diverse waste materials. A hand shovel was employed to ensure thorough mixing until complete homogenization was achieved. To facilitate the experiment's execution and monitoring, a six-week timeline was established, including meticulous observation and evaluation of the entire process. Methodology and crucial variables governing the composting process were regulated, including content consistency, temperature, aeration and pH levels. These parameters notably influence the decomposition dynamics inherent to composting [24]. Maintaining the proper pH throughout the composting process is essential in order to achieve success [24]. pH level should fall within the range of 5.5 to 8.5, indicative of optimal conditions for effective composting.

Table 1 provides a comprehensive overview of the quantities of waste materials involved in this composting endeavor. By systematically addressing these variables and meticulously adhering to the experimental timeline, the project sought to demonstrate the feasibility and effectiveness of waste composting as a potent strategy for carbon footprint reduction at the Palermo Sociedad Portuaria.

#### 2.2.5. Rock Dust Application

A supply of 10 metric tons of rock dust, characterized as 10% of particle sizes below 4 mm and 90% below 0.6 mm, was sourced from Aggregates Río Negro, Palomino, La Guajira (Figure 1). The elemental composition analysis of the rock dust involved the

determination of simple oxides using X-ray fluorescence (XRF) technology (Siemens, model SRS-3000) at the Materials Identification and Analysis Laboratory, University of Passo Fundo, Brazil.

**Table 1.** Materials used for the start of composting.

Components	Quantity (kg)
Sewage biosolids	40
Coffee pulp residues	35
Disposable towels	8.5
Organic waste	25
Organic pruning	17
Total	125.5

Following a comprehensive assessment of the port terminal premises, the decision was made to distribute 10 kg of rock dust per square meter, adhering to the guidance provided by Kelland et al. [21]. This application strategy was enacted across a total area of 564 m<sup>2</sup>, specifically targeting three distinct points within the terminal—namely, yard number six, the main internal pathway and the external greenhouse. Notably, all of these designated areas shared similar characteristics as garden/green spaces.

To effectively monitor CO<sub>2</sub> capture, data collection occurred at specific intervals: 09:00, 12:00, 16:00 and 20:00 h. These timeframes were strategically selected to align with the operational patterns of the port terminal (Figure 1). A portable and cost-effective CO<sub>2</sub> meter engineered for air quality assessment was utilized for data collection. The CO<sub>2</sub> meter was equipped with a dual screen capable of displaying three simultaneous parameters—CO<sub>2</sub> level, temperature and humidity—with built-in backlighting for situations with low light conditions. Employing cutting-edge non-dispersive infrared (NDIR) wave technology, the meter was designed with sensor capabilities. Manual calibration was recommended and performed. The meter utilized easily supported outdoor calibration around 380–420 ppm. The meter incorporates a “hold” function that retains current measurement readings on the screen for either 8 h (time-weighted average function) or 15 min (short-term exposure limit). Additional features encompass max, min and average readings, along with various audible alarms to signal CO<sub>2</sub> levels, featuring an audible alarm of approximately 80 dB.

### 2.3. Statistical Analyses

For data analysis, a designated environmental professional involved in the project collected measurements at each specified point within the defined areas [2]. These measurements were meticulously recorded using the designated measurement format. The subsequent analysis of these data was conducted using Minitab software (version 21.1.0), which encompassed a normality test. This test involved employing the Kolmogorov–Smirnov goodness-of-fit test due to the characteristics of the data. This test was conducted both before and after the application of the rock powder.

To ascertain whether there exists any noteworthy disparity in CO<sub>2</sub> levels across various measurement times (09:00, 12:00, 16:00 and 20:00 h), the Kruskal–Wallis parametric test was undertaken. This statistical evaluation assessed the null hypothesis, which posited that the medians of CO<sub>2</sub> measurements captured during the four-hour sample intervals remained consistent.

For a comprehensive assessment of the data, a broader comparison was executed by encompassing all measurements captured within the four-hour intervals. This analysis was performed to determine whether any statistically significant differences existed [2]. This process was repeated separately for each hourly range before and after the rock powder application.



Following the data collection processes in the field, surveys, interviews and a literature review were conducted and compiled to calculate the overall carbon footprint of the PSP [25]. Subsequently, this study presented the quantified emissions outcomes along with the strategies undertaken to curtail the CF [25].

The quantification methodology obtained for calculating emissions was derived from the fuel consumption of port vehicles for the mobilization of goods and related activities [25,26]. The calculations were based on obtaining activity data and resulting fuel consumption, both diesel and gasoline, along with the use of emission factors corresponding to each of the GHGs considered (see table of emission factors), in which each equation ( $\text{metric tons CO}_2 \text{ eq} = \sum \text{CACPM} \times \text{generic FE} \times \text{F conversion}$ ) applied in other studies was used to calculate greenhouse gas emissions [25,26] and applied to Scopes 1, 2 and 3.

### 3. Results and Discussion

#### 3.1. GHG Inventory and CF Calculation

Table 2 provides a comprehensive overview of the calculated emissions for 2019 and 2020. In 2019, 59.39% of GHG emissions, expressed in ton CO<sub>2</sub> eq, corresponded to Scope 1 emissions. This means that approximately 1295.7 metric tons of CO<sub>2</sub> equivalent were generated by the PSP's direct activities. Furthermore, 14.34% corresponded to Scope 2 emissions, that is, just under 313 metric tons of CO<sub>2</sub> equivalent were generated by electricity consumption. The remaining 26.27%, equivalent to 572.9 metric tons of CO<sub>2</sub> equivalent, corresponded to Scope 3 (Table 2). Direct GHG emissions related to Scope 1 include emissions derived from fuel consumption by all loading equipment, cranes, front-end forklifts, large cranes and trucks, in addition to emissions related to the use of gases (acetylene) for welding and refrigerants. In the reference year of this inventory, the Palermo Sociedad Portuaria directly emitted 2181.18 metric tons of CO<sub>2</sub> equivalent, of which 73% resulted from the consumption of diesel in loading, internal transport and unloading activities as well as for the cogeneration of electrical energy.

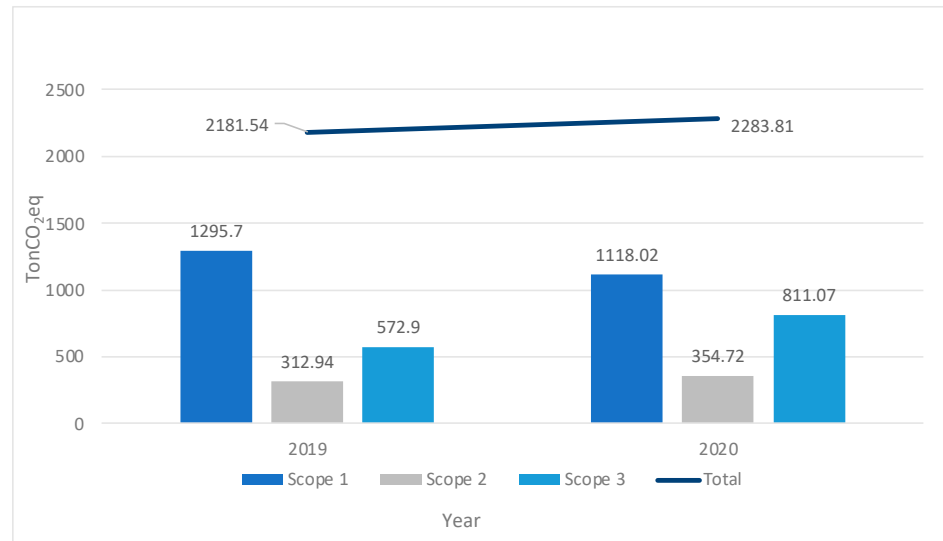
**Table 2.** Consolidated GHG equivalent emissions per scope in the Palermo Sociedad Portuaria for the years 2019 and 2020.

Emissions	2019 (ton CO <sub>2</sub> eq)	2020 (ton CO <sub>2</sub> eq)
Scope 1	1295.7	1118.0
Scope 2	312.9	354.7
Scope 3	572.9	811.1
Total	2181.5	2283.8

If we compare the total emissions of 2181.5 metric tons of CO<sub>2</sub> and relate it to the amount of cargo moved in the same year, we can infer that, in 2019, the PSP emitted 0.000092 metric tons of CO<sub>2</sub> equivalent for each metric ton of cargo moved (Table 2). In 2019, the PSP handled 2,368,972 metric tons of cargo, comprised of steel, general cargo (large parts), containers, coke, fertilizers, liquid bulk cargo, industrial products and piping. As for the consumption of 410A refrigerant and acetylene, the contribution represents less than 3% of the total direct emissions generated.

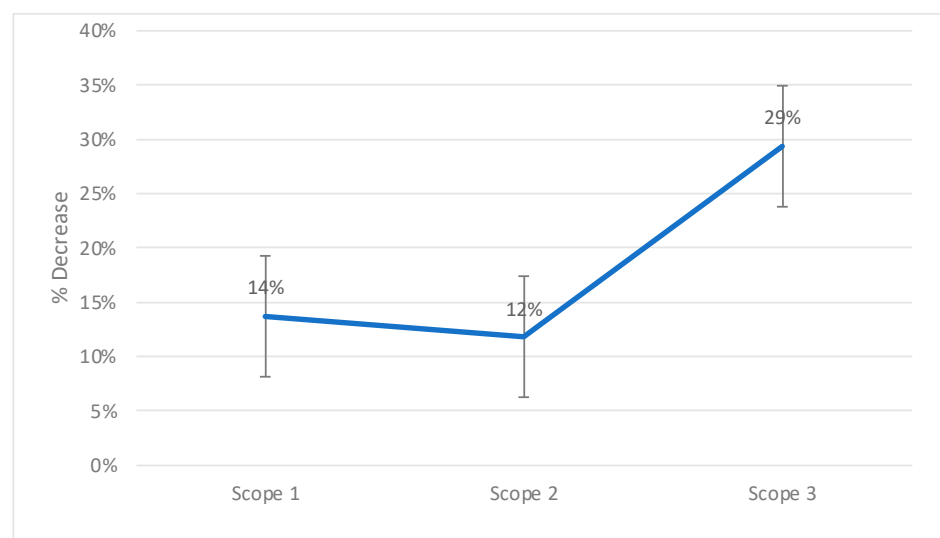
Figure 4 presents a consolidated overview of emissions for the years 2019 and 2020. Scope 1 emissions account for 59.39% of the total ton CO<sub>2</sub> eq, encompassing around 1.2 metric tons stemming from the PSP's activities. Scope 2 emissions comprise 14.34%, equating to a little less than 0.5 metric tons of CO<sub>2</sub> equivalent from electrical energy consumption. Scope 3 emissions account for 26.2% of the total equating 572.9 ton CO<sub>2</sub> eq. Compared to the comparison year of 2020 (Figure 4), there was a 14% decrease in emissions reported in Scope 1, mainly due to the reduction in diesel consumption in power plants, the stabilization of the energy service and the decrease in night work. However, Scope 2 showed an increase of 12% due to the stabilization of the energy service (Figure 4). In this

context, Scope 3 recorded an increase of 29%, mainly due to the supply of fuel by the PSP to companies affiliated with the operation and third-party equipment, an activity that was not in force in the base year.



**Figure 4.** CF comparison between 2019 and 2020.

The validity of the CF for both 2019 and 2020 has been confirmed through validation by the Colombian Institute of Certifications (Icontec). This validation process, accompanied by a corresponding certificate, bolsters the reliability and credibility of the data and calculations (Figure 5). With regard to Scope 1, in 2019 and 2020 (Figure 5), there was an increase in fuel consumption (diesel) in plants, motor pumps and lighting towers by 35%. A 20% reduction in fuel (diesel) consumption by the operation's equipment is also noticeable. However, the carbon footprint in the two years does not show significant changes as a result of these variations. Regarding Scope 3, the most significant changes occur in 2020 due to the increase in fuel consumption of third-party equipment (equipment rented from a supplier, to which the company supplies fuel). This increase was considerable, at 90%. However, this variation occurred in 2019, as the Palermo Sociedad Portuaria did not provide fuel for third-party equipment that year and did not keep records.



**Figure 5.** Reduction in 2020 CF (validated) as compared to 2019 CF.

With regard to waste, there is a reduction in the carbon footprint generated by waste, including wood and common waste. In this scope (Figure 5), there is a total increase in emissions of 29%. This increase is mainly due to the fuel consumption of third-party equipment, which resulted in an emission of 245 metric tons of CO<sub>2</sub>. If we isolate third-party fuel consumption data, the carbon footprint for the two years in Scope 3 would be similar (566 tons of CO<sub>2</sub>). A net increase of 102 metric tons of CO<sub>2</sub> can be noted, represented by the 245 metric tons of CO<sub>2</sub> from the fuel supplied to third parties by the company, which were not included in the 2019 calculation. The reduction of 142 metric tons of CO<sub>2</sub> in 2020 as compared to 2019 was due to a reduction in the amount of waste generated by port activity as well as a reduction in fuel consumption of its own equipment by 20%.

In 2019, the Palermo Sociedad Portuaria directly emitted 2181.18 metric tons of CO<sub>2</sub> equivalent. Of this total, 73% (1608 metric tons) results from diesel consumption in loading, internal transport, unloading and cogeneration of electrical energy activities. Relating the total emissions to the cargo mobilized in 2019, it can be inferred that the PSP emitted 0.000092 ton CO<sub>2</sub> eq per metric ton of mobilized cargo. This year saw the PSP handle 2,368,972 metric tons of cargo, including steel, general cargo, containers, coke, fertilizers, clean bulk, liquid bulk, industrial products and pipes. The contribution from refrigerant R410a and acetylene is relatively minor, accounting for less than 3% of total direct emissions.

Scope 1 emissions for 2019 and 2020 (Figure 5) display a 35% increase in fuel consumption (diesel) for plant operations, motor pumps and lighting towers. Conversely, there is a 20% reduction in diesel consumption for operational equipment. This balance results in minimal changes to the CF for both years. In comparison to the 2020 data, Scope 1 emissions exhibit a 14% decrease, primarily attributed to stabilized energy services, reduced nighttime work and less reliance on power generation plants for administrative areas. Scope 2 experienced a 12% increase due to stabilized energy service, while Scope 3 recorded a 29% rise mainly due to fuel supply to third-party equipment, which was not conducted in the base year.

Scope 3 experienced the most significant change, with a 90% increase in fuel consumption by third-party equipment in 2020. However, this rise is the result of a fuel supply that was not documented in 2019. Waste-related emissions decrease, and the overall increase in emissions is driven by third-party equipment fuel consumption. Excluding these data, the carbon footprint for both years in Scope 3 remains highly similar (566 ton CO<sub>2</sub> eq).

In summary, a net increase of 102 metric tons of CO<sub>2</sub> is attributed to fuel supplied to third parties in 2020, which was not previously considered in the 2019 calculation. A decrease of 142 metric tons of CO<sub>2</sub> in 2020, as compared to 2019, is due to reduced waste generation and a 20% drop in fuel consumption by the port's own equipment. The carbon footprint results for the years 2019 and 2020 can be compared with the results of other port terminals in the region and around the world [2], as shown in Table 3.

**Table 3.** Comparison of CF results between port terminals.

Terminal	CF (ton CO <sub>2</sub> eq)	Year	Comments
Palermo Sociedad Portuaria—Barranquilla	2181	2019	
	2283	2020	-
Port of Santa Marta	6773	2011	-
Port of Oslo, Norway	1346	2008	This does not include the carbon footprint of waste generated from activities.
Port of Olympia	1239	2017	This does not include the carbon footprint of waste generated from activities.
Port of Rotterdam, The Netherlands	33,1	2019	-
Port of Spain	33,408	2008	-

Although no recent results were found from other port terminals in the Barranquilla region, the Port of Santa Marta, located in Santa Marta Bay, is the closest competitor terminal, handling 5,632,512 metric tons of cargo in 2020. Its CF was 6773 metric tons of CO<sub>2</sub> (Table 3). That same year, the Palermo Sociedad Portuaria handled less than half that amount (2,141,210 metric tons), with a CF approximately 70% lower (Table 3). Other ports listed in Table 3 have ongoing mitigation strategies in place, such as the port of Rotterdam [27].

Ultimately, this entire process culminates in both financial and environmental advantages [28]. It is imperative to cultivate novel modes of thinking, engendering fresh moral and value criteria and fostering new behaviors. Consequently, expedited strategies must be devised to lead nations away from their current, often detrimental growth and development trajectories, steering them toward the course of sustainable development.

However, the business development within this study is not aligned with the establishment of sustainable practices [2]. Despite engagement in sustainability-related activities, these efforts primarily manifest as isolated campaigns and training, lacking clear objectives and verification mechanisms. The absence of GHG emissions measurements and the dearth of formal sustainability practices aligned with the UN Sustainable Development Goals (SDG) are evident. In light of these considerations, ports and/or their management companies must synchronize their operations with the environmental dynamics of their respective areas. They must craft strategies to harmonize their activities with the surrounding environment. This approach concurs with [29], which scrutinizes diverse methodologies developed in the port and maritime industry from 2005 to 2020, aimed at calculating and mitigating CO<sub>2</sub> emissions and limiting climate change impacts.

### 3.2. Fuel Consumption Reduction

An initial test phase was conducted in order to determine a baseline fuel consumption at the port. The monitoring encompassed a total of five periods, leading to an accumulated reduction of 1.6295677 ton CO<sub>2</sub> eq. A comprehensive depiction of the outcomes is presented in Table 4. The adoption of fuel consumption reduction technology in port operational equipment represents a proprietary approach, with the terminal serving as a pilot for the methodology's development. The results have aligned with the company's objectives: (i) a reduction in fuel consumption and (ii) a decrease in GHG emissions. If the company chooses to apply this technology to its fleet of 11 pieces of equipment, its CF can be reduced by 22 metric tons of CO<sub>2</sub>, equivalent to 3% of overall fuel consumption. This technology comes at a cost of approximately EUR 9000.

**Table 4.** Mitigated emissions projections/year.

Period	Hours/Period	Baseline Fuel Consumption	Metric tons of CO <sub>2</sub> Generated	Post-Installation Fuel Consumption	Gallons of Fuel Saved	Metric Tons of CO <sub>2</sub> Post-Installation
Period 0	185.22	158.44	1.47	0	0	0
Period 1	192.79	164.91	1.53	143.79	21.12	0.210
Period 2	198.08	169.43	1.57	144.73	24.71	0.246
Period 3	354.5	303.23	2.81	264.28	38.96	0.388
Period 4	278.21	237.98	2.20	209.41	28.57	0.284
Period 5	429.84	367.68	3.40	317.24	50.44	0.502
Total	1638.64	1401.67	12.98	1079.44	163.8	1.630

In line with these observations, employing clean energy emerges as a notable mitigation strategy for curtailing GHG emissions [30]. A dynamic method based on activity levels of cargo handling equipment was utilized to estimate air pollutant emissions [31]. The outcome indicated significant air pollution reduction was achieved in 2017 if equipment engines met the Chinese Tier III standard post-upgrade. This underscores the urgency of



phasing out older equipment causing atmospheric pollution in ports and transitioning to newer, more technologically advanced, environmentally friendly alternatives.

It is worth highlighting that international terminals have proactively pursued diverse strategies to mitigate GHG emissions, as exemplified by a study conducted by Sdoukopoulos et al. [32]. European ports have embraced novel operating practices and invested in advanced technologies to augment energy efficiency and yield additional energy savings. Initiatives such as ISO 50001 certification, Ecoports certification, adoption of electric vehicles and the deployment of a swift charging network across port locations (coupled with solar and wind energy production and intelligent public lighting) collectively aim for an 85% reduction in CO<sub>2</sub> emissions. The integration of a new mobile hydrogen supply station also warrants attention, as hydrogen fuel usage is projected to curtail fuel consumption by 24% while simultaneously enhancing air quality (with a 40% reduction in particulate matter and a 10% reduction in CO<sub>2</sub> emissions).

### 3.2.1. Solid Waste Composting

The organic wastes listed in Table 1 were carefully blended and subjected to a 42-day composting process. The material exhibited comprehensive degradation, resulting in a pleasing tonality and appearance, with a pH reading of 7.04.

The presence of microorganisms serves as a positive indicator, suggesting effective degradation leading to the attainment of a neutral compost. This underscores how composting practices align with the principles of the circular economy: fostering the reduction, reuse and recycling of agricultural waste to bolster sustainable agriculture while also mitigating environmental pollution. This further accentuates the imperative of devising strategies to realize sustainable goals [24].

The management of a smart port encompasses pertinent elements such as environmental management systems and waste and water management [33,34]. The conclusion of the composting procedure yielded 247 kg of compost [24]. To achieve pH neutrality in the compost, coffee pulp residue was utilized due to its proficient pH-neutralizing attributes, attributed to its nitrogen-rich composition.

The visual presence of microorganisms stems from the substantial addition of organic matter, accelerating and optimizing the process of biodegradation [24]. The appealing coloration can be attributed to the nutrient-rich contributions of pruning waste, predominantly comprised of vegetative remains. The implementation of regular moistening and the use of a plastic covering created a conducive environment for the proliferation of microorganisms, facilitating effective component degradation. Incorporating composting into the company's framework can yield a reduction of 2 tonCO<sub>2</sub>eq to average emissions stemming from conventional waste management over one year.

Wide adoption of solid waste composting processes could avert emissions totaling 25,007 ton CO<sub>2</sub> eq over a decade [35]. Composting stands as a cost-effective technology with minimal investment and maintenance expenses. Furthermore, it generates organic compost, a high-quality product applicable in agriculture with commercial value. This compost serves as an ideal substrate for cultivating vegetables, fruit and forest seedlings, effectively recycling nutrients and carbon within the soil [35,36].

### 3.2.2. Rock Dust Powder Application

The outcomes of the XRF analysis, as outlined in Table 4, closely resemble the findings of [37], who conducted petrographical, mineralogical and chemical characterization of the same rock type employed in this study. The kinetics of constituent element release rates within rock minerals exhibit distinct variations [38]. Depending on the mineralogical composition of the rock and external conditions, certain minerals might persist in dissolving and capturing CO<sub>2</sub> even after the first year of application [37]. Remarkably, the dacite powder under study demonstrated an impressive capacity to sequester CO<sub>2</sub> within just 45 days, manifesting in a range from a minimum of 0.00004698 ton CO<sub>2</sub> eq to a maximum of 0.0000892 ton CO<sub>2</sub> eq post-application (Table 5). We anticipate that beyond the initial year,

the rates of CO<sub>2</sub> sequestration could surpass the values projected [21]. This study indicated CO<sub>2</sub> sequestration rates of 2–4 metric tons of CO<sub>2</sub> ha<sup>-1</sup>, 1–5 years after a single application.

**Table 5.** XRF results of the analyzed rock dust sample.

Oxides	Content	Oxides	Content
	64.38		
	18.79%		
	4.11%		
SiO <sub>2</sub>	0.53%	TiO <sub>2</sub>	0.54
	3.88%		
	3.70%		
	2.10%		
	1.86% 64.38%		
Al <sub>2</sub> O <sub>3</sub>	18.79	P <sub>2</sub> O <sub>5</sub>	0.13
Fe <sub>2</sub> O <sub>3</sub>	4.11	BaO	0.10
	53%		
K <sub>2</sub> O	3.88	MnO	0.09
Na <sub>2</sub> O	3.70	Cl	0.06
MgO	2.10	ZrO <sub>2</sub>	0.06
CaO	1.86	-	-

The rock dust's role as a direct CO<sub>2</sub> absorber [21] induced shifts in CO<sub>2</sub> measurement at different time intervals (09:00, 12:00, 16:00 and 20:00 h). At point 1, the median difference amounted to 0.00000512 ton CO<sub>2</sub> eq. For point 2, the difference was 0.00004698 ton CO<sub>2</sub> eq. Moreover, at point 3, the median shift measured 0.0000892 ton CO<sub>2</sub> eq, indicating lower CO<sub>2</sub> levels during that hourly range post-rock-dust application. Although the research is ongoing, early indications suggest that CO<sub>2</sub> reduction is noteworthy in the treated areas.

Over a 45-day monitoring period to assess the impact of rock dust application, a maximum reduction value of 89.2 ppm was recorded, translating to 0.000089 metric tons of CO<sub>2</sub>. CO<sub>2</sub> sequestration rates stemming from dacite rock weathering in the study area align with findings by Kelland et al. [21], where soils were amended with ground basalt. Variations in application rates, rock types, irrigation strategies and experiment duration all contribute to divergence in CO<sub>2</sub> outcomes. Kelland et al. [21] estimated that accelerated weathering of coarse-grained rock could result in an estimated total CO<sub>2</sub> capture of ~3 metric ton CO<sub>2</sub> ha<sup>-1</sup> in 2 years, potentially increasing to ~4 metric ton CO<sub>2</sub> ha<sup>-1</sup> after 5 years. The accelerated weathering of silicate rocks on agricultural land holds the potential for atmospheric CO<sub>2</sub> sequestration, offering prospects for climate change mitigation, bolstered food security and enhanced soil health [22,37].

The carbon footprint results for the years 2019 and 2020 can be compared with the results of other port terminals both in the region and around the world, as shown in Table 3. Although no recent results were found from other port terminals in the region of Barranquilla, the results obtained show that, compared to the closest competition terminal, the Port of Santa Marta, located in Santa Marta Bay, handled 5,632,512 metric tons of cargo in 2020, including solid bulk, liquids, coal, general cargo and round [2].

#### 4. Conclusions

The CO<sub>2</sub> emissions of the Palermo Sociedad Portuaria (PSP) during 2019 and 2020 were used to determine the feasibility of allowing for the implementation of sustainable practices (rock dust application, composting and reduction of fossil fuel burning) to help mitigate CO<sub>2</sub> emissions and reduce the port's CF in the year 2022. Concerning the fuel reduction technology, this novel approach yields a monthly reduction of approximately 0.2 ton CO<sub>2</sub> eq per piece of equipment. This research culminated in the acquisition of equipment by the port terminal to refine the baseline and establish the exact contribution to greenhouse gas reduction by December 2022. The application of rock dust represents a fresh paradigm,

functioning as a direct CO<sub>2</sub> absorber. The process entails CO<sub>2</sub> measurements taken from June onward, across two designated areas within the terminal at predefined time slots (09:00, 12:00, 16:00–20:00). The CO<sub>2</sub> sequestration rates via dacite rock weathering in this study mirror distinct factors, including application rate, rock type, irrigation strategies utilized and experimental duration. Each factor contributes to variations in CO<sub>2</sub> sequestration outcomes. Therefore, it is suggested for future studies to continue these sustainable, viable, innovative and economical alternatives, which have the potential to reduce carbon footprints in Colombian and global seaports.

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