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Beyond the Bloom: Invasive Seaweed *Sargassum* spp. as a Catalyst for Sustainable Agriculture and Blue Economy—A Multifaceted Approach to Biodegradable Films, Biostimulants, and Carbon Mitigation

Elena Martínez-Martínez [1,2,*], Alexander H. Slocum [3,*], María Laura Ceballos [2], Paula Aponte [4] and Andrés Guillermo Bisonó-León [5]

1 Doctoral School, Catholic University of Valencia San Vicente Mártir, 46001 Valencia, Spain
2 SOS Biotech, Distrito Nacional, Santo Domingo 10127, Dominican Republic
3 Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue Building 3 Room 443, Cambridge, MA 02139, USA
4 CurubaTech, Carrera 10, Bogota 110411, Colombia
5 SOS Carbon S.R.L., Distrito Nacional, Santo Domingo 10127, Dominican Republic
* Correspondence: emartinez@soscarbon.com (E.M.-M.); slocum@mit.edu (A.H.S.)

Abstract: The Anthropocene has ushered in unprecedented environmental challenges, with invasive seaweed blooms emerging as a critical yet understudied facet of climate change. These blooms, driven by nutrient runoff and oceanic alterations, disrupt ecosystems, threaten biodiversity, and impose economic and public health burdens on coastal communities. However, invasive seaweeds also present an opportunity as a sustainable resource. This study explores the valorization of *Sargassum* spp. for agricultural applications, focusing on the development of biodegradable bioplastics and biostimulants. Field trials demonstrated the effectiveness of Marine Symbiotic® Sargassum-derived biostimulant in distinct agricultural contexts. In the Dominican Republic, trials on pepper crops showed significant improvements, including a 33.26% increase in fruit weight, a 21.94% rise in fruit set percentage, a 45% higher yield under high-stress conditions, and a 48.42% reduction in fruit rejection compared to control. In Colombia, trials across four leafy green varieties revealed biomass increases of up to 360%, a 50% reduction in synthetic input dependency, and enhanced crop coloration, improving marketability. Additionally, Sargassum-based biofilms exhibited favorable mechanical properties and biodegradability, offering a sustainable alternative to conventional agricultural plastics. Carbon credit quantification revealed that valorizing Sargassum could prevent up to 89,670 tons of CO_2-equivalent emissions annually using just one Littoral Collection Module® harvesting system, while biostimulant application enhanced carbon sequestration in crops. These findings underscore the potential of invasive seaweed valorization to address multiple climate challenges, from reducing plastic pollution and GHG emissions to enhancing agricultural resilience, thereby contributing to a sustainable Blue Economy and aligning with global sustainability goals.

Keywords: invasive seaweed; *Sargassum* spp.; Blue Economy; sustainable agriculture; bioplastics; biostimulants; carbon credits

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1. Introduction

The Anthropocene is characterized by profound environmental challenges, driven by anthropogenic activities that are disrupting many of Earth's natural systems [1,2]. From rising global temperatures and severe droughts to catastrophic floods and wildfires, the impacts of climate change are pervasive and devastating [3–5]. Humanity now confronts the fragility of the interconnected systems that sustain life on Earth. The proliferation of invasive seaweed blooms exemplifies a critical yet often overlooked facet of the climate emergency. These blooms pose a triple threat—economic, environmental, and public health crises—affecting many coastal communities and ecosystems worldwide [6].

Industrial practices underlying key sectors—some essential for human survival, such as agriculture, and others integral to modern society, such as cosmetics and bioplastics—have significantly contributed to nutrient runoff, CO_2 emissions, and oceanic alterations that exacerbate seaweed invasions [7,8]. However, these same industries also present opportunities for transformative solutions. The valorization of invasive seaweed as a resource rather than a burden reveals pathways for sustainable development, fostering a more resilient and regenerative Blue Economy [9].

1.1. Seaweed Invasions: A Dual-Edged Phenomenon

The proliferation of invasive seaweeds, such as *Sargassum* spp. in the Caribbean, *Rugulopteryx okamurae* in Southern Europe, *Sargassum horneri* in East China and South Korea, or *Undaria pinnatifida* in Argentina, exemplifies the scale and complexity of this emerging global issue [10–13]. These massive blooms disrupt marine ecosystems by smothering coral reefs, depleting oxygen levels, and threatening biodiversity [14]. Economically, such invasions have devastated coastal industries, including tourism and fisheries, while the decomposition of accumulated biomass poses significant public health risks due to the release of toxic gases such as methane (CH_4) and hydrogen sulfide (H_2S), which have been linked to increased incidences of preeclampsia and respiratory conditions, including apnea episodes [10,15–17].

The proliferation of *Sargassum* spp. represents the largest macroalgal bloom ever recorded on Earth, posing significant ecological and socio-economic risks, particularly in the Caribbean region. Composed primarily of *Sargassum fluitans* and *Sargassum natans*, these holopelagic species have formed an extensive floating biomass known as the Great Atlantic Sargassum Belt, stretching from West Africa to the Gulf of Mexico. In 2023 alone, over 24 million metric tons of Sargassum were documented, marking an unprecedented scale of expansion. While Sargassum naturally occurs in the Sargasso Sea—an ecosystem crucial for marine biodiversity—the rapid and unregulated proliferation outside its historical range has transformed it into an ecological disruptor. The invasion of *Sargassum* spp. is primarily driven by anthropogenic and climatic factors. Rising ocean temperatures, elevated atmospheric CO_2 concentrations, and increased nutrient influx from agricultural runoff (particularly nitrogen and phosphorus) have fueled excessive growth. Additionally, shifts in oceanic currents have facilitated the dispersal of Sargassum, leading to persistent and recurrent inundations along coastal areas [17–20]. Despite its widespread impact, *Sargassum fluitans* and *Sargassum natans* have not yet been evaluated on the IUCN Red List, probably due to their recent and rapid expansion. However, the scientific literature widely considers the rapid proliferation of *Sargassum* spp. as an invasive phenomenon due to its disruptive ecological impacts, including the displacement of native species, oxygen depletion in coastal waters, and economic losses in fisheries and tourism [10,17,18].

Despite these challenges, invasive seaweeds harbor significant yet underutilized potential. Rich in bioactive compounds, they can be transformed into high-value products across multiple industries, including agriculture, cosmetics, renewable bioplastics, and pharmaceuticals [21]. The global seaweed market, a key driver of the Blue Economy, was valued at over $19 billion in 2023 and is projected to reach approximately $34 billion by 2028, with a compound annual growth rate (CAGR) of 12.3% [22,23]. More broadly, the

Blue Economy itself generates approximately $2.5 trillion annually, supporting millions of livelihoods worldwide [24]. Systematic harvesting, valorization, and integration of invasive seaweed into sustainable value chains could not only mitigate its environmental and economic damage but also drive innovation and economic development. For vulnerable coastal communities, particularly in the Caribbean, this presents a dual opportunity: addressing a pressing ecological crisis while fostering economic resilience and aligning with global sustainability goals [25].

1.2. Industries Fueling These Invasions: Agriculture's Paradox

Agriculture stands at the crossroads of the climate crisis: it is both a major contributor to environmental degradation and one of the sectors most vulnerable to climate change [26,27]. Agricultural expansion and intensification have accelerated deforestation, biodiversity loss, and greenhouse gas (GHG) emissions, while extreme weather events—intensified by climate change—threaten global food security [26]. As of 2024, agriculture accounts for approximately 21% of global GHG emissions, largely due to methane from livestock, nitrous oxide from fertilizers, and carbon dioxide from land-use changes [28,29]. The sector is also a leading driver of nutrient runoff, which exacerbates eutrophication and coastal dead zones, fueling harmful algal blooms, including invasive seaweed proliferation [30].

The scale of agriculture's vulnerability is equally concerning. It is estimated that more than 500 million hectares of farmland—over 30% of the world's croplands—are already experiencing productivity declines due to soil degradation, droughts, and erratic weather patterns [31,32]. By 2050, food demand is expected to rise by 60%, placing additional strain on already fragile ecosystems [33]. Additionally, intensive agricultural practices contribute to severe water pollution, with agriculture responsible for over 70% of global freshwater withdrawals and generating substantial chemical runoff, including pesticides and nitrogen-based fertilizers, which further accelerate oceanic imbalances [34,35].

Beyond emissions and runoff, one of the least acknowledged yet pervasive agricultural pollutants is plastic waste. Plastics are extensively used throughout the sector, from mulch films that cover the soil to plastic tunnels, greenhouses, and protective sheets designed to shield crops from direct soil contact [36]. It is estimated that over 6.5 million metric tons of plastic are used in agriculture annually, much of which is discarded in the environment, contributing to microplastic pollution and soil degradation [37]. A significant portion of this waste—particularly single-use plastics such as mulch films—decomposes into microplastics, which have been detected in agricultural soils at concentrations even exceeding those found in marine environments [38,39].

Plastic pollution in agricultural systems represents a multifaceted challenge, with cascading effects on soil functionality, crop performance, and food safety. Microplastics alter soil biophysical properties, disrupting water dynamics and microbial symbioses essential for plant nutrition. This degradation often compels reliance on agrochemicals, perpetuating a cycle of soil decline. Critically, microplastics and associated additives (e.g., plasticizers, flame retardants) are assimilated by crops, entering trophic networks with unknown long-term consequences for human health. The persistence of plastic waste in farmlands also facilitates secondary contamination of aquatic systems, amplifying ecological risks [40,41].

This challenge, however, presents a compelling opportunity for innovation. The urgent need for sustainable alternatives has catalyzed the development of biodegradable bioplastics derived from renewable sources, including invasive seaweeds. By replacing petroleum-based agricultural plastics with biodegradable alternatives, it is possible to reduce plastic pollution while simultaneously addressing the environmental burden posed by previously mentioned seaweed blooms [42,43]. Cross-collaboration between the academic, private, and governmental sectors plays a crucial role in achieving this paradigm shift, ensuring that scientific advancements, industry innovation, and policy frameworks work in synergy to drive sustainable transformation.

1.3. Leveraging Invasive Seaweed for Agricultural Innovation in the Global South

The Caribbean region is acutely familiar with both the challenges of massive seaweed invasions and the vulnerabilities of the agricultural sector. The recurrent influxes of *Sargassum* spp. have imposed severe ecological and economic burdens, while agriculture faces mounting pressures from climate change, soil degradation, and reliance on synthetic inputs [44–46]. At the same time, the global demand for food production continues to rise, increasing the sector's environmental footprint through greenhouse gas emissions, excessive fertilizer use, and plastic waste generation [28,46,47]. These intersecting crises highlight the urgency of integrated, nature-based solutions that address multiple challenges simultaneously—one such approach is the use of biostimulants.

Biostimulants are defined as any product composed of substances, microorganisms, or other materials that independently enhance plant physiological or biochemical processes, leading to improved nutrient absorption, stress tolerance, and overall crop growth [48–50]. Unlike synthetic fertilizers, which primarily supply essential inorganic nutrients, biostimulants exert their effects through diverse mechanisms that influence plant metabolism, root development, and stress response pathways. These effects occur through direct interaction with plant signaling cascades or by stimulating substrate-associated organisms that produce beneficial molecules (e.g., bacteria, yeasts, endophytic fungi). Once applied to crops or soil, biostimulants trigger a variety of physiological responses that contribute to enhanced vigor, resilience, and productivity [49,51,52].

By optimizing plant physiological processes, biostimulants enable crops to withstand environmental challenges and reach their full genetic potential. Additionally, by promoting microbial diversity and activity in the soil, biostimulants foster symbiotic relationships between plants and beneficial microorganisms, thereby improving nutrient cycling, soil structure, and overall substrate health. Moreover, by mitigating the adverse effects of abiotic stress factors, biostimulants contribute to water conservation, reduced chemical input dependency, and biodiversity preservation [49–52].

Among the various categories of biostimulants, seaweed-derived biostimulants have gained significant attention. Extracts from macroalgae, particularly species such as *Ascophyllum nodosum*, *Laminaria* spp., or *Sargassum muticum*, are rich in bioactive compounds such as polysaccharides, polyphenols, and plant hormones, which contribute to their biostimulant properties [48,49]. These compounds elicit plant growth responses through hormonal regulation, stress mitigation, and metabolic enhancement. Although the precise mode of action of most biostimulants remains incompletely understood due to the heterogeneous nature of these products, research has identified specific pathways through which seaweed-derived extracts influence plant growth and stress responses [50,52,53].

Building on this foundation, the present study aims to investigate the integration of seaweed-derived biostimulants with biodegradable bioplastics to develop sustainable agricultural materials. Specifically, this research explores the incorporation of Sargassum-based biostimulants and alginate biofilms into agricultural plastics and coatings to create biodegradable alternatives that not only replace conventional plastics but also enable a controlled release of bioactive compounds. This dual functionality is expected to enhance crop productivity while simultaneously reducing plastic pollution. Unlike conventional synthetic mulching films, which contribute to microplastic contamination and soil degradation, these innovative materials align with circular bioeconomy principles, repurposing biological waste streams to improve soil health, support regenerative agriculture, and mitigate environmental impact [54–59].

Beyond agricultural applications, this study also seeks to evaluate the climate change mitigation potential of controlled Sargassum harvesting and valorization. When left to decay in coastal environments, Sargassum emits methane (CH_4) and carbon dioxide (CO_2), both potent greenhouse gases contributing to global warming [60,61]. By converting invasive Sargassum into biodegradable bioplastics and biostimulants, this research explores its potential role in carbon sequestration and its integration into carbon offset mechanisms. In collaboration with carbon credit certification bodies, emerging methodologies are being piloted to quantify these climate benefits. This interdisciplinary approach aims to bridge coastal ecosystem management, agricultural sustainability, and carbon markets, offering an integrated solution to both environmental and economic challenges [60,62].

2. Materials and Methods

2.1. Sargassum Biomass Collection and Processing

The *Sargassum* spp. biomass used in this study was harvested in the Punta Cana region, Dominican Republic, utilizing the Littoral Collection Module® (LCM®) patented system by SOS Carbon, designed for the efficient and sustainable collection of pelagic Sargassum blooms. This system, capable of collecting 70 metric tons per day, employs local fishing communities and minimizes coastal accumulation, reducing environmental degradation and GHG emissions from natural seaweed decomposition [60].

Once harvested, the biomass underwent mechanical dewatering followed by a drying and stabilization process to prevent secondary fermentation. The processed seaweed was subsequently fractionated for the production of SOS Biotech products:

- Marine Symbiotic® a commercially available Sargassum-derived liquid biostimulant developed by SOS Biotech. This product is formally registered and has received organic certification from the Ministry of Agriculture of the Dominican Republic, confirming its compliance with national agricultural regulations. Marine Symbiotic® has undergone the necessary regulatory evaluations and has also been accredited by the United States Department of Agriculture (USDA), allowing for its legal export through all U.S. border entry points. Furthermore, the product meets the European Union's regulatory thresholds for heavy metal content in agricultural inputs, the most strict ones, addressing a key safety concern associated with seaweed-derived biostimulants. Marine Symbiotic® is currently available for purchase online and through select agricultural retailers in the Dominican Republic [63].
- Alginaqua®: a Sargassum-derived polymer-rich fraction primarily composed of alginate and fucoidan.

2.2. Development and Characterization of Sargassum-Based Agricultural Biofilms

2.2.1. Biofilm Formulation

Agricultural biofilms were developed using Sargassum-derived biopolymer Alginaqua®, incorporating Marine Symbiotic® as an active component. The film-forming solution was prepared by dissolving the Sargassum biopolymer at a 3:100 (w/v) ratio in water until fully solubilized. Agar-agar was then added at a 2:100 (w/v) ratio, and was heated to 90 °C to ensure complete dissolution. The temperature was subsequently reduced to 80 °C for the incorporation of vegetable glycerin at a 3:100 (v/v) ratio, followed by further cooling to 60 °C to add Marine Symbiotic® at a 1:2 (v/v) ratio, for preserving its bioactive properties. Throughout the entire process, the solution was kept under continuous stirring to maintain homogeneity. Thereafter, it was cast onto a silicone-coated aluminum tray and dried under controlled temperature (60 °C) for 6 h to reduce moisture content and ensure proper film formation. It is understood that for commercial scale-up, a continuous process would be developed which would include complete carbon accounting of all inputs and outputs and compare to conventional plastic films produced from hydrocarbons. Initial results are promising, as described below in Section 2.4.

2.2.2. Mechanical and Physical Characterization

The biofilms were evaluated for the following:

- Elongation at break (%) was determined from the stress-strain curves [59].
- Biodegradation of the biofilms was assessed under controlled soil conditions at a temperature of 25–30 °C and a soil moisture content of 60%. Soil temperature was monitored throughout the study using temperature sensors, with the average temperature falling within the range of 25–30 °C. Soil moisture content was maintained at 60% by regular irrigation, and moisture levels were verified using a soil moisture meter. The degradation rate was determined by monitoring the mass loss of the films over 40 days. Samples were retrieved at 5-day intervals during the first 20 days and at 10-day intervals during the last 20 days; cleaned to remove soil particles; dried; and weighed to calculate the percentage of mass loss over time. Visual degradation and structural integrity were also recorded to assess the decomposition process.

2.3. Biostimulant Agronomic Trials

To evaluate the agronomic efficacy of Marine Symbiotic®, a Sargassum-derived biostimulant developed by SOS Biotech, two independent field trials were conducted in the Dominican Republic and Colombia. These locations were strategically chosen to assess the biostimulant's performance across distinct climatic and edaphic conditions, ensuring broader applicability and robustness of the results. The primary difference between the sites was altitude, with the Dominican Republic trial conducted at a lowland tropical environment, whereas the Colombian trial took place at a high-altitude zone. Temperature, precipitation patterns, and soil composition also varied, providing a comprehensive evaluation of the biostimulant's adaptability. Despite these differences, both regions share common climate-related agricultural challenges, including soil degradation, extreme weather variability, and declining crop productivity, making them ideal testbeds for climate-resilient agricultural solutions.

Crop selection was determined based on regional agricultural relevance and economic significance, ensuring that the trials aligned with real-world farming practices. The experiments were conducted in collaboration with local farmers, integrating their standard cultivation protocols to maximize realism and facilitate adoption. This participatory approach not only ensured that the trials were reflective of actual farming conditions but also allowed for an assessment of the practicality and commercial scalability of Marine Symbiotic® in different cropping systems and agroecological zones. Additionally, evaluating the product in two distinct environments enhances the potential for international commercialization, providing critical insights into its performance across diverse agricultural settings.

2.3.1. Dominican Republic: *Capsicum annuum*

The study was conducted in a commercial greenhouse in Constanza, Dominican Republic, to evaluate the effects of Marine Symbiotic® on the growth and yield performance of *Capsicum annuum* (bell pepper). The experimental setup consisted of eight cultivation beds, each measuring 47 m in length, with 235 plants per bed. Four beds were treated with Marine Symbiotic®, while the remaining four served as control plots. All plants were cultivated following local standard agronomic practices for bell pepper production, ensuring the study's relevance to real-world agricultural applications.

The biostimulant was applied via foliar spray and drench irrigation at a concentration of 1 L of Marine Symbiotic® per 200 L of water. Applications were performed at 15-day intervals, beginning at the early vegetative stage and continuing until harvest.

At the first harvest stage, 10 plants were randomly selected for detailed biometric and yield assessments. The following parameters were recorded:

- Fruit weight (g per fruit)—Individual fruit mass was measured using a precision digital scale.
- Fruit size distribution (%)—Fruits were categorized into three commercial size classes: G (small), GG (medium), GGG (large).
- Fruit set (%)—The proportion of successfully developed fruits per plant was estimated based on the number of fruiting nodes per internode.
- Yield per plant (g)—The total marketable fruit weight per plant was recorded.
- Total yield per bed—Total weight per cultivation bed. Rejection rate (%)—The proportion of non-marketable fruits was determined based on the total weight of discarded fruits per 20-pound (9.07 kg) harvested box.

One of the cultivation beds selected for this study had previously exhibited low productivity due to high solar radiation and temperature stress, resulting from greater exposure compared to other beds. To assess the potential stress-mitigating effects of Marine Symbiotic®, the yield obtained from this bed was compared to historical yield data from previous growing seasons under similar environmental conditions.

2.3.2. Colombia: Leafy Greens

The field trial was conducted in collaboration with CurubaTech, a Colombia-based AgriTech company specializing in digital solutions for agricultural traceability and peer-to-peer advisory systems. The study was carried out in partnership with four farming families whose primary livelihood depends entirely on agriculture. Consequently, these households are highly susceptible to climate variability, fluctuations in fertilizer prices, and the regulatory and environmental challenges associated with fertilizer use. The experiment aimed to evaluate the effects of Marine Symbiotic® on the growth and development of four leafy green crops: *Spinacia oleracea* (spinach), *Lactuca sativa var. batavia* (Batavia lettuce), *Lactuca sativa var. crispa* (curly green lettuce), and *Brassica rapa var. japonica* (mizuna).

The trial was conducted in Ciudad Bolívar, Bogotá, Colombia, The study area exhibits a cold, humid climate characteristic of the Andean highlands, with mean annual temperatures ranging from 12 °C to 18 °C. The region follows a bimodal rainfall pattern, with total annual precipitation between 800 mm and 1200 mm. Relative humidity remains consistently high, ranging from 70% to 90%, creating favorable conditions for crop development while also increasing the susceptibility to fungal diseases. The soils are slightly acidic, with pH values between 5.0 and 6.5, which may influence nutrient availability and plant growth. Additionally, the altitude ranges from 2600 to 3200 m above sea level, imposing specific constraints on agricultural practices due to lower temperatures and intensified solar radiation.

The total experimental area measured 66 m^2, with each crop consisting of 38 plants per treatment, totaling 150 plants per crop (including the control plot, which also had 38 plants per treatment, along with the three treatment groups). Standard agronomic practices were followed in the control plot. Treatments were applied every 15 days, starting from early vegetative growth until harvest maturity. The experimental groups for each crop were as follows:

- Control (untreated)—Standard irrigation and fertilization protocol without biostimulant application.

- Foliar application—Marine Symbiotic applied via foliar spray at a concentration of 5 mL/L, applied at 15-day intervals.
- Root application—Marine Symbiotic applied via drench irrigation at a concentration of 5 mL/L, applied at 15-day intervals.
- Reduced synthetic input treatment—Marine Symbiotic applied in combination with a 50% reduction in synthetic fertilizer inputs.

At the end of the trial, morphological and biomass parameters were recorded for each treatment group:

- Shoot fresh weight (g)—Measured using an analytical balance.
- Plant height (cm)—Measured from the base to the highest leaf.
- Root length (cm)—Measured from the base of the shoot to the root tip.
- Measurements were taken from 5 randomly selected plants per treatment.

2.3.3. Statistical Analysis

Statistical analyses were performed using `stats` package from `scipy` in a Python 3.12.4 based notebook

In the greenhouse trial evaluating the effects of Marine Symbiotic® on *Capsicum annuum*, a one-way analysis of variance (ANOVA) was used to assess significant differences in yield-related parameters, including fruit weight, yield per plant, and total yield per bed, between the biostimulant-treated plants and historical control data. When ANOVA indicated significant differences ($p < 0.05$), post hoc pairwise comparisons were performed using Tukey's Honestly Significant Difference (HSD) test to identify specific treatment effects. Fruit size distribution (%) was analyzed with a Mann–Whitney U test to determine if the biostimulant application influenced the proportion of fruits in commercial size categories (G, GG, GGG). Assumptions of normality and homogeneity of variance were verified using the Shapiro–Wilk and Levene's tests, respectively.

In the Colombian trial, where the effects of Marine Symbiotic® were assessed on four leafy green crops (*Spinacia oleracea*, *Lactuca sativa var. batavia*, *Lactuca sativa var. crispa*, and *Brassica rapa var. japonica*), a two-way ANOVA was employed to evaluate the effects of treatment (control, foliar application, root application, reduced synthetic input) and crop variety on weight, plant height, and root length. The interaction effects between treatment and crop variety were also examined. Where significant differences were observed ($p < 0.05$), Tukey's HSD test was applied for pairwise comparisons. Normality and homoscedasticity of the data were confirmed prior to analysis using the Shapiro–Wilk and Levene's tests.

All statistical tests were conducted at a significance level of $\alpha = 0.05$. Results are presented as mean ± standard deviation (SD).

2.4. Carbon Credit Quantification Protocol

A carbon credit assessment protocol was used to evaluate the GHG mitigation potential of Sargassum valorization and biostimulant crop CO_2 caption enhancement.

2.4.1. Baseline Scenario I: Natural Decomposition of Sargassum in Coastal Environments, Leading to Methane and CO_2 Release

To quantify GHG mitigation potential of Sargassum repurposing, a baseline scenario was established following the methodology outlined by the Gold Standard for Waste Management projects [64]. This scenario assumes that, in the absence of the project intervention, *Sargassum* spp. would undergo uncontrolled decomposition in coastal environments or be disposed of in solid waste disposal sites (SWDS), leading to anaerobic degradation and methane (CH_4) emissions.

The baseline emissions were determined using Gold Standard approach:

- Definition of waste macroalgae flow—The natural accumulation of *Sargassum* spp. on Caribbean coastlines was assessed based on historical biomass stranding data. It was assumed that, under baseline conditions, a significant portion of this biomass would be left to decompose anaerobically on beaches, in nearshore waters, or in SWDS.
- Anaerobic decomposition and methane emission potential— Methane emissions were estimated using the First Order Decay (FOD) model, as defined in the CDM TOOL 4 methodology for emissions from SWDS. The methane correction factor (MCF) was applied to account for different decomposition conditions (e.g., deep piles vs. surface-level exposure).
- Emission factors and calculation of avoided methane emissions— The biochemical methane potential (BMP_j) of Sargassum was used to estimate the fraction of degradable organic carbon (DOC) that would decompose into CH_4 and CO_2

Methane emissions were calculated using the following equation:

$$BE_{CH_4,y} = \sum_{x=1}^{y} \left(W_{j,x} \times DOC_j \times DOC_f \times MCF_y \times F \times GWP_{CH_4} \right) \quad (1)$$

where

- $W_{j,x}$ = Amount of Sargassum disposed at SWDS in year x (t).
- DOC_j = Fraction of degradable organic carbon in Sargassum (weight fraction).
- DOC_f = Fraction of DOC decomposed under SWDS conditions (default: 0.5).
- MCF_y = Methane correction factor (default: 1.0 for anaerobic SWDS).
- F = Fraction of CH_4 in landfill gas (default: 0.5).
- GWP_{CH_4} = Global warming potential of methane (28 for a 100-year horizon).

The total baseline emissions for year y were computed as

$$BE_y = BE_{CH4,y} + BE_{CO2,y} \quad (2)$$

where

- $BE_{CH4,y}$ accounts for avoided methane emissions from Sargassum decomposition;
- $BE_{CO2,y}$ includes indirect CO_2 emissions due to biomass degradation.

2.4.2. Baseline Scenario II: Potential CO_2 Sequestration via Biostimulant Agricultural Application

The application of seaweed derived biostimulants, such as Marine Symbiotic®, has been observed to enhance crop productivity, leading to increased biomass accumulation and sugar synthesis. This study establishes a protocol to quantify the additional carbon sequestration resulting from its application by evaluating two key parameters:

- Increase in total crop biomass → A proxy for enhanced organic carbon storage in plant tissues.
- Increase in sugar content (Brix degrees) → A proxy for enhanced photosynthetic CO_2 fixation.

Under baseline conditions, crop growth is limited by conventional agricultural inputs, and carbon sequestration is determined by standard plant growth rates without the application of the biostimulant. The additional CO_2 capture resulting from the biostimulant application is assessed as the difference between the treated and untreated crops.

For the quantification of carbon sequestration in crops, the following is assumed:

1. Biomass accumulation as a proxy for organic carbon storage—Plants absorb atmospheric CO_2 and convert it into structural and storage biomass. The additional CO_2

sequestered due to Marine Symbiotic application is estimated based on dry biomass accumulation and its carbon content.

2. Measurement of above-ground biomass (AGB)—At crop maturity, total plant biomass is harvested and separated into above-ground (stems, leaves, fruits) and below-ground (roots) fractions. Fresh weight (FW) is recorded immediately using an analytical balance. Samples are dried at 60 °C until constant weight to determine dry biomass (DB).
3. Estimation of organic carbon storage—The dry biomass is converted into sequestered organic carbon using a known carbon-to-biomass ratio (C fraction, CF). Literature values indicate that the carbon content of herbaceous crops ranges between 42% and 48% of dry biomass [65,66].

The total additional carbon storage due to Marine Symbiotic® is calculated as follows:

$$Csequestered = (DB_{treated} - DB_{control}) \times CF \tag{3}$$

where

- $DB_{treated}$ = dry biomass per plant in treated crops (g).
- DB_{cotrol} = dry biomass per plant in untreated crops (g).
- CF = Carbon fraction of biomass.

The total CO_2 sequestered per hectare is then calculated as follows:

$$CO_2 = C_{sequestered} \times \frac{MW_{CO_2}}{MW_C} \times A \tag{4}$$

where

- MW = molecular weight;
- A = crop density (plants per hectare).

Sugars synthesized during photosynthesis are a direct product of atmospheric CO_2 assimilation. The increase in Brix degrees (°Bx) in Marine Symbiotic-treated crops reflects enhanced carbon fixation.

For the measurement of sugar accumulation, fruit sap is extracted at harvest and analyzed using a digital refractometer. Three independent measurements are taken per sample to determine Brix degrees (°Bx). Although sugars are already accounted for in dry biomass, their measurement provides evidence of the increase in photosynthesis due to the biostimulant.

2.4.3. Baseline Scenario III: Potential CO_2 Reduction for Farming Plastics Replacement

The life cycle of conventional agricultural plastics follows three primary stages: production, usage, and disposal. In the production stage, agricultural plastics such as polyethylene, polypropylene, and polyvinyl chloride (PVC) are derived from petrochemical feedstocks through energy-intensive processes, contributing significantly to CO_2 emissions. During the usage phase, these plastics are employed for short-term applications, including soil mulching and crop wrapping, and are subsequently discarded, accumulating in agricultural environments. In the disposal stage, plastics are typically landfilled, incinerated, or degraded into microplastics, each of which generates additional CO_2 emissions either through direct incineration or the release of carbon during degradation [67–69].

In contrast, the Sargassum-based bioplastic offers a reduced carbon footprint across its life cycle. The primary feedstock, *Sargassum* spp., is harvested directly from marine environments, resulting in minimal CO_2 emissions compared to petroleum-based plastics. The bioplastic production process utilizes low-energy, aqueous-based methods, avoiding the fossil fuel-intensive processes used in conventional plastic production. Additionally, the biodegradability of the bioplastic eliminates CO_2 emissions typically generated during disposal, such as incineration or landfill degradation.

The potential CO_2 reduction is calculated by comparing the carbon emissions of conventional agricultural plastics with those of the Sargassum-based bioplastic across their respective life cycles.

3. Results

3.1. Sargassum-Based Agricultural Biofilm

The mechanical performance of the Sargassum-based biofilms was evaluated in terms of elongation at break (%), providing insights into flexibility and structural integrity. The formulated biofilms exhibited an elongation at break of 25.8 ± 3.4%, which falls within the expected range for alginate–agar-based bioplastics. The incorporation of vegetable glycerin contributed to improved flexibility, preventing excessive brittleness while maintaining film integrity (Figure 1).

Figure 1. Morphology of the Sargassum-based biofilm formulated with Marine Symbiotic® and Alginaqua®.

The biodegradability of the biofilms was assessed under controlled soil conditions (25–30 °C, 60% soil moisture) over a period of 40 days. Progressive mass loss was recorded throughout the experiment (Figure 2). By the end of the trial, 91.9 ± 5.1% of the initial biofilm mass had degraded, indicating efficient biodegradation within the expected time-frame for seaweed-based biodegradable films. The visual assessment revealed progressive fragmentation after 10 days, with significant disintegration by day 40, suggesting suitability for short-term agricultural applications.

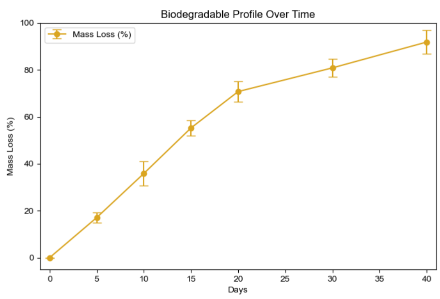
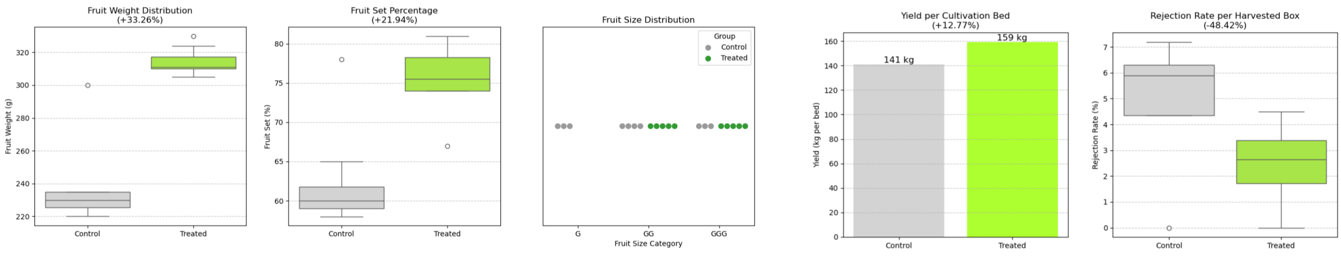


Figure 2. Biodegradation profile of the Sargassum-based biofilm under soil conditions.

3.2. *Capsicum annuum*

3.2.1. Fruit Weight, Size Distribution, and Set Percentage

The application of Marine Symbiotic® resulted in a significant increase in average fruit weight compared to the control group ($p < 0.05$). The mean fruit weight in treated plants was 314.1 ± 7.9 g, representing a 33.26% increase compared to the control group (235.7 ± 25.3) (Figure 3a). Regarding fruit size distribution, treated plants produced a higher proportion of large fruits (GGG category) compared to the control group. In the treated group, 100% of the fruits were classified as GG or GGG, whereas in the control group, only 60% reached these commercial size standards (Figure 3a). The fruit set rate per plant was also significantly higher in the treated group ($p < 0.05$), indicating enhanced reproductive success and productivity. The average fruit set in treated plants was 75.6 ± 3.95%, compared to 62.1 ± 7.07% in the control group (Figure 3a). This represents a 21.94% increase in fruit set percentage following Marine Symbiotic® application.



(**a**) (**b**)

Figure 3. Impact of Marine Symbiotic® on *Capsicum annuum*. (**a**) Comparison of fruit weight, set percentage, and size distribution in treated (green) and control (grey) plants. (**b**) Comparison of yield per cultivation bed and rejection rate per harvested box in treated (green) and control (grey) plants.

3.2.2. Yield per Cultivation Bed and Rejection Rate

Total yield per cultivation bed was higher in the treated group, with values of 159 kg, compared to 141 kg in the control beds. This represents an increase in total yield of 12.77% following Marine Symbiotic® application (Figure 3b). The proportion of non-marketable fruits was slightly lower in the treated beds. The rejection rate per 20-pound (9.07 kg) harvested box was lower in the treated group compared to the control group (Figure 3b), and the treated group exhibited a 48.42% reduction in fruit rejection compared to the control.

3.2.3. Yield Under High-Stress Conditions

The cultivation bed selected for evaluation under high solar radiation and temperature stress exhibited a notable improvement in yield following Marine Symbiotic® application, 45% higher than previous records. Compared to historical yield data from previous growing cycles, the treated bed showed a higher total production, suggesting potential stress-mitigating effects associated with the biostimulant application.

3.3. *Leafy Greens*

3.3.1. Spinach

The application of Marine Symbiotic® treatments resulted in significant increases in plant weight across all treated groups compared to the control. The RA treatment exhibited a 23.2% increase in mean plant weight (54.2 ± 17.9 g) relative to the control group (44.0 ± 11.6 g; $p = 0.0223$), showing a statistically significant difference. The FA treatment showed the highest increase, with a 57.0% rise in plant weight (69.2 ± 8.6 g; $p = 0.0004$), which was statistically significant. The FA50 treatment demonstrated a significant 38.6%

increase (61.0 ± 16.1 g; p = 0.0149). The maximum plant weight recorded in the RA-treated group was 92 g, whereas the control group reached a maximum of 56 g (Figure 4).

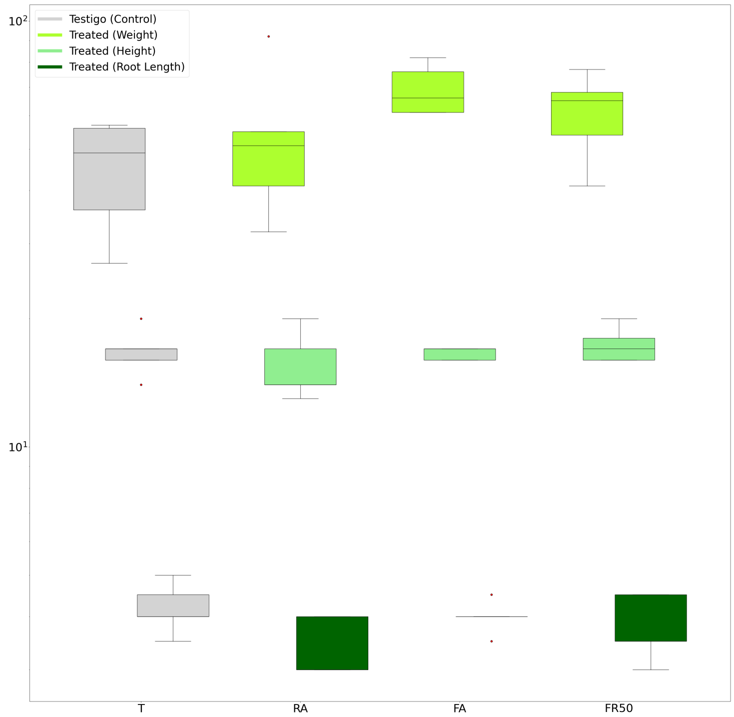


Figure 4. Impact of Marine Symbiotic® treatments on plant weight, height, and root length in spinach (*Spinacia oleracea*): comparative analysis across treatment groups using logarithmic scale.

In terms of plant height, all treated groups showed significant increases compared to the control. The RA treatment resulted in a 14.9% increase in height (17.0 ± 2.0 cm) compared to the control group (14.8 ± 1.3 cm; p = 0.0231). Both the FA and FA50 treatments exhibited a 17.5% increase in height, with average heights of 17.4 ± 0.9 cm (p = 0.0091) and 17.4 ± 1.4 cm (p = 0.0124), respectively. The maximum height recorded in treated plants was 20 cm for RA, FA, and FA50, while the control group reached a maximum of 17 cm (Figure 4).

Regarding root length, the results showed slight variations across all treated groups compared to the control. The RA treatment exhibited a decrease of 16.7% in root length (3.5 ± 0.5 cm) compared to the control group (4.2 ± 0.5 cm; p = 0.1752), though this difference was not statistically significant. The FA treatment showed a slight decrease of 2.4% in root length (4.1 ± 0.5 cm; p = 0.2490), while the FA50 treatment exhibited a 7.1% decrease (3.9 ± 0.5 cm; p = 0.1344), though these differences were not statistically significant. The maximum root length recorded in treated plants was 4.5 cm for RA, FA, and FA50, while the control group had a maximum of 5 cm (Figure 4).

3.3.2. Batavia Lettuce

The application of Marine Symbiotic® treatments resulted in significant increases in plant weight across all treated groups compared to the control. The RA treatment exhibited the most pronounced effect, with a 185.7% increase in mean plant weight (142.6 ± 10.1 g) relative to the control group (52.0 ± 10.6 g; $p = 1.11 \times 10^{-6}$), demonstrating a statistically significant difference. The FA treatment also showed a substantial increase in plant weight, with a 76.4% rise (82.0 ± 17.7 g; p = 0.0197), which was statistically significant. In contrast, the FA50 treatment resulted in a slight reduction in plant weight by 14.8% (35.6 ± 6.1 g; p = 0.2666), though this difference was not statistically significant. The maximum plant weight recorded in the RA-treated group was 155 g, while the control group reached a maximum of 59 g (Figure 5).

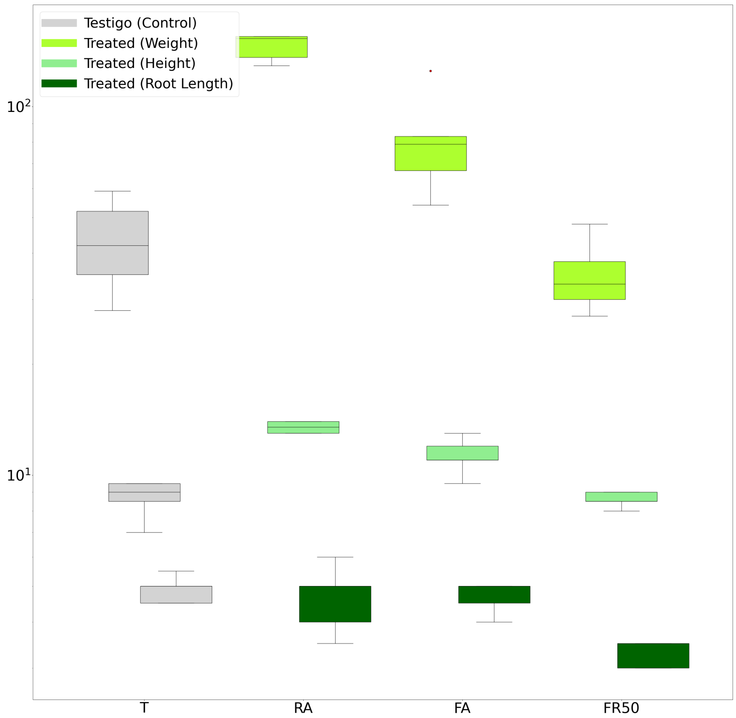


Figure 5. Impact of Marine Symbiotic® treatments on plant weight, height, and root length in Batavia (*Lactuca sativa var. batavia*): comparative analysis across treatment groups using logarithmic scale.

In terms of plant height, the RA treatment led to a 22.3% increase, with a mean height of 13.6 ± 0.5 cm compared to the control group (9.0 ± 0.5 cm; $p = 1.43 \times 10^{-5}$), indicating a statistically significant difference. Similarly, the FA treatment resulted in a 32.6% increase in mean height (11.5 ± 1.0 cm; $p = 0.0082$), which was also statistically significant. The FA50 treatment showed a modest increase of 5.9% in plant height (8.8 ± 0.6 cm; $p = 0.8465$), though this difference was not statistically significant. The maximum plant height observed in the RA-treated group was 14 cm, whereas the control group reached a maximum of 9.5 cm (Figure 5).

Regarding root length, the RA treatment resulted in a 29.4% decrease, with a mean root length of 4.2 ± 0.8 cm compared to the control group (4.8 ± 0.5 cm; $p = 0.6844$), though this difference was not statistically significant. The FA treatment showed a marginal 1.5% increase in root length (4.8 ± 0.4 cm; $p = 0.4860$), which was also not statistically significant. In contrast, the FA50 treatment exhibited an 11.1% reduction in root length (3.9 ± 0.5 cm; $p = 9.66 \times 10^{-5}$), which was statistically significant. The maximum root length recorded in the RA-treated group was 6 cm, while the control group reached a maximum of 5.5 cm (Figure 5).

3.3.3. Curly Green Lettuce

The application of Marine Symbiotic® treatments resulted in noticeable changes in plant weight compared to the control group. The RA treatment showed a significant 360% increase, with a mean weight of 77.6 ± 16.5 g, compared to the control group, which had a mean of 22.0 ± 5.3 g ($p = 0.000$), indicating a statistically significant difference. The FA treatment exhibited a 15.4% increase, with an average weight of 53.3 ± 8.2 g ($p = 0.0442$), which was statistically significant, while the FA50 treatment demonstrated a 60.4% increase, with an average weight of 30.6 ± 7.3 g ($p = 0.0043$), also statistically significant. The maximum weight recorded in treated plants was 97 g for RA, while the control group reached a maximum of 22 g (Figure 6).

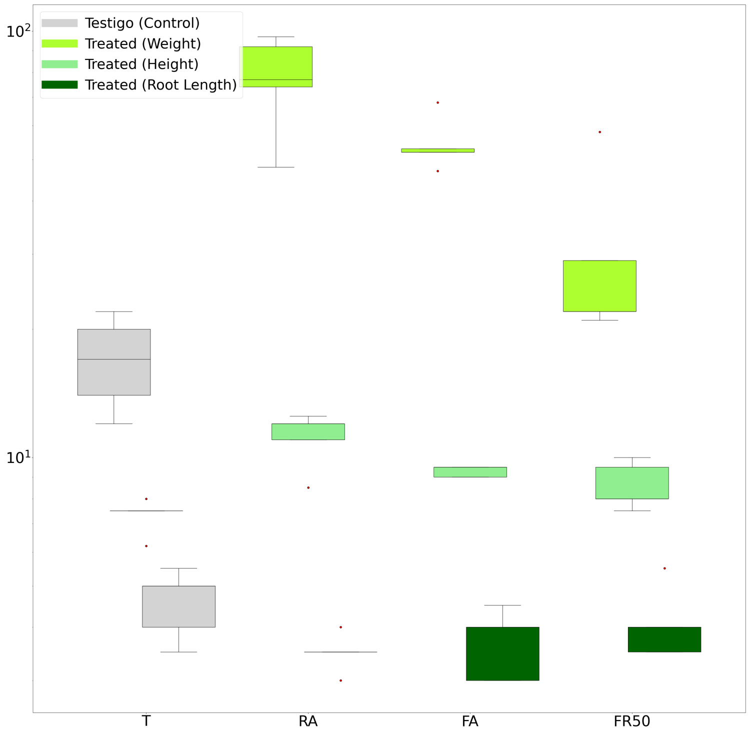


Figure 6. Impact of Marine Symbiotic® treatments on plant weight, height, and root length in curly green lettuce (*Lactuca sativa var. crispa*): comparative analysis across treatment groups using logarithmic scale.

For plant height, the RA treatment resulted in a significant 50.7% increase, with a mean height of 12.5 ± 1.0 cm, compared to the control group, which had a mean of 8.0 ± 0.7 cm (p = 0.0322), indicating a statistically significant difference. The FA treatment showed a 15.4% increase, with an average height of 9.3 ± 0.3 cm (p = 0.03159), which was statistically significant, while the FA50 treatment resulted in a 20.0% increase, with an average height of 9.1 ± 0.4 cm (p = 0.0056), which was also statistically significant. The maximum height recorded in treated plants was 12.5 cm for RA, whereas the control group had a maximum height of 8.0 cm (Figure 6).

In terms of root length, the RA treatment showed a decrease of 20%, with a mean of 3.7 ± 0.4 cm, compared to the control group, which had an average root length of 4.6 ± 0.7 cm (p = 0.2871), which was not statistically significant. The FA treatment exhibited a 12.5% decrease in root length, with an average of 3.8 ± 0.3 cm (p = 0.5354), which was also not statistically significant, while the FA50 treatment showed a 7.0% increase, with an average of 4.0 ± 0.7 cm (p = 0.5714), which was not statistically significant. The maximum root length recorded in treated plants was 4.5 cm for FA, whereas the control group reached a maximum of 5.5 cm (Figure 6).

3.3.4. Mizina

For weight, the foliage (FA) treatment showed a significant increase compared to the control, with a mean difference of 136.6 g (p = 0.0003), corresponding to an approximate 135% higher weight in the foliage treatment. Similarly, the radicular (RA) treatment showed a significant increase in weight, with a mean difference of 116.4 g (p = 0.0013), which represents approximately 116% higher weight than the control. The FR50 treatment showed an approximate 48% higher weight in the FR50 treatment (p = 0.0022) (Figure 7).

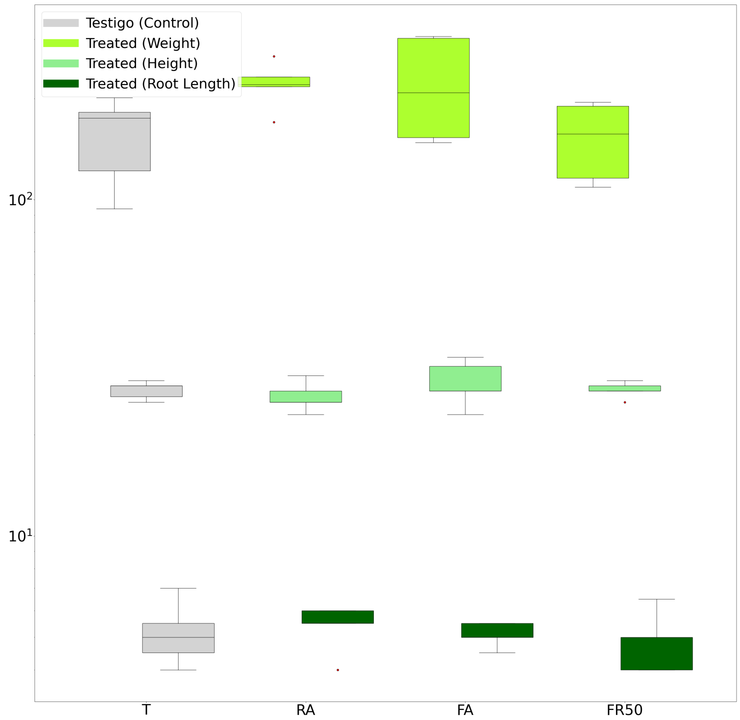


Figure 7. Impact of Marine Symbiotic® treatments on plant weight, height, and root length in Mizina (*Brassica rapa var. japonica*): comparative analysis across treatment groups using logarithmic scale.

Regarding height, no significant differences were found between the treatments and the control. FA treatment showed a mean difference of 1.4 cm (p = 0.855), indicating no significant impact on height. Similarly, RA treatment had a mean difference of −1.0 cm (p = 0.9399), which also suggests no significant effect on height. FR50 treatment exhibited a mean difference of 0.0 cm (p = 1.0), further confirming that the treatments did not influence plant height. In terms of root length, there were no significant differences between the treatments and the control. FA treatment showed a mean difference of −0.1 cm (p = 0.998), indicating no notable effect on root growth. Similarly, RA treatment exhibited a mean difference of 0.2 cm (p = 0.9845), and FR50 treatment had a mean difference of −0.3 cm (p = 0.951), both of which suggest that the treatments did not affect root length significantly (Figure 7).

3.4. Carbon Credit Quantification

3.4.1. Baseline Scenario I

1. CO_2 Avoidance 2023–2025 Projects

   Between 2023 and 2024, SOS group projects valorized 65 tons of Sargassum, preventing its uncontrolled decomposition in coastal environments or solid waste disposal sites (SWDS). The avoided methane emissions were calculated using the First Order Decay (FOD) model, as outlined in the CDM TOOL 4 methodology for emissions from SWDS (Equation (1)). The following parameters were applied:

   - Fraction of degradable organic carbon (DOCj): 0.5 (default value for Sargassum).
   - Fraction of DOC decomposed under SWDS conditions (DOCf): 0.5.
   - Methane correction factor (MCFy): 1.0 (for anaerobic conditions in SWDS).
   - Fraction of CH_4 in landfill gas (F): 0.5.
   - Global warming potential of methane ($GWPCH_4$): 28 (100-year horizon).
   - Amount of Sargassum (W_j, x): 65 tons.

Thus, the valorization of 65 tons of Sargassum resulted in 227.5 tons of CO_2-equivalent (CO_2e) avoided methane emissions.

2. Annual Avoidance Capacity of One Littoral Collection Module® (LCM®)
Each LCM® has a harvesting capacity of 70 tons of Sargassum per day. Assuming operation during a 12-month period, the total amount of Sargassum harvested annually by one LCM® system is 25,620 tons.
Using the same emission factors and formula (Equation (1)), it is estimated that a single LCM® system operating at full capacity during the 6-month high season can harvest enough Sargassum to be valorized to prevent 89,670 tons of CO_2e annually by avoiding methane emissions from Sargassum decomposition.

3.4.2. Baseline Scenario II

1. Carbon Sequestration in the Current Study (150 m^2)
The current study evaluated the impact of Marine Symbiotic® on crop biomass accumulation and carbon sequestration in experimental plots covering 150 m^2 across Colombia and the Dominican Republic. The biomass increase observed in crops treated with Marine Symbiotic ranged from a minimum of 15.4% to a maximum of 360% compared to untreated controls. These minimum and maximum values were used to estimate the range of CO_2 sequestration, as calculated using Equations (3) and (4).

- CO_2 Sequestration Calculations

$$\begin{aligned} CO_{2,\text{min}}(\text{total}) &= 242.81\ \text{g CO}_2/\text{m}^2 \times 150\ \text{m}^2 \\ &= 36{,}421.5\ \text{g CO}_2 = 0.036\ \text{tons CO}_2 \\ CO_{2,\text{max}}(\text{total}) &= 5676\ \text{g CO}_2/\text{m}^2 \times 150\ \text{m}^2 \\ &= 851{,}400\ \text{g CO}_2 = 0.851\ \text{tons CO}_2 \end{aligned}$$

- Biomass Increase Due to Marine Symbiotic

$$\begin{aligned} DB_{\text{treated,min}} &= DB_{\text{control}} \times 1.154 \\ &= 1000\ \text{g/m}^2 \times 1.154 = 1154\ \text{g/m}^2 \\ DB_{\text{treated,max}} &= DB_{\text{control}} \times 4.6 \\ &= 1000\ \text{g/m}^2 \times 4.6 = 4600\ \text{g/m}^2 \end{aligned}$$

- Additional Carbon Sequestration
The additional carbon sequestered due to Marine Symbiotic was calculated as follows:

$$\begin{aligned} C_{\text{sequestered,min}} &= (DB_{\text{treated,min}} - DB_{\text{control}}) \times CF \\ C_{\text{sequestered,min}} &= (1154\ \text{g/m}^2 - 1000\ \text{g/m}^2) \times 0.43 \\ &= 66.22\ \text{g C/m}^2 \\ C_{\text{sequestered,max}} &= (DB_{\text{treated,max}} - DB_{\text{control}}) \times CF \\ C_{\text{sequestered,max}} &= (4600\ \text{g/m}^2 - 1000\ \text{g/m}^2) \times 0.43 \\ &= 1548\ \text{g C/m}^2 \end{aligned}$$

- Final CO_2 Sequestration Estimates

$$CO_{2,\min} = 66.22 \text{ g C/m}^2 \times \frac{44}{12} = 242.81 \text{ g CO}_2/\text{m}^2$$

$$CO_{2,\max} = C_{\text{sequestered,max}} \times \frac{44}{12}$$
$$CO_{2,\max} = 1548 \text{ g C/m}^2 \times \frac{44}{12} = 5676 \text{ g CO}_2/\text{m}^2$$

2. Carbon Sequestration in the Total Scope of Marine Symbiotic Application® Marine Symbiotic® is currently being applied in crops across Spain, the United States, the Dominican Republic, Colombia, and Puerto Rico, covering a total area of 32 hectares (320,000 m^2). The same biomass increase range (15.4% to 360%) and carbon fraction (CF = 0.43) were applied.

$$CO_{2,\min}(\text{total}) = 242.81 \text{ g CO}_2/\text{m}^2 \times 320{,}000 \text{ m}^2 = 77{,}699{,}200 \text{ g CO}_2 = 77.70 \text{ tons CO}_2$$
$$CO_{2,\max}(\text{total}) = 5676 \text{ g CO}_2/\text{m}^2 \times 320{,}000 \text{ m}^2 = 1{,}816{,}320{,}000 \text{ g CO}_2 = 1816.32 \text{ tons CO}_2$$

3. Brix Degrees increased Brix degrees are a measure of the total soluble solids (TSS) in plant sap, which include sugars, organic acids, and other dissolved compounds. Sugars, such as glucose and sucrose, are the primary components of TSS and are produced during photosynthesis. Since sugars are carbon-based compounds, an increase in Brix degrees directly reflects an increase in carbon fixation and storage.

$$6\,\text{CO}_2 + 6\,\text{H}_2\text{O} + \text{light energy} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 \text{ (glucose)} + 6\,\text{O}_2$$

In addition to the crops analyzed in this study, Marine Symbiotic® has been tested on more than 15 additional crops, including tomato (*Solanum lycopersicum*), banana (*Musa* spp.), lemon (*Citrus limon*), and beet (*Beta vulgaris*). Brix degree measurements, obtained using a refractometer, revealed a significant increase in soluble sugar content, ranging from 24% to 73% compared to untreated controls.

3.4.3. Baseline Scenario III

The carbon footprint of the Sargassum-based bioplastic is significantly lower due to its renewable origin and biodegradability. Based on LCA studies for similar bioplastics (e.g., PLA) [67–69], the following emissions are estimated:

1. Production Phase:
   - Emissions: Approximately 1.2 kg CO_2 per kg of bioplastic.
   - Source: Cultivation of Sargassum, extraction of polymers, and manufacturing processes.
2. Disposal Phase:
   - Composting: Releases 0.75 kg CO_2 per kg of bioplastic.
   - Source: Biodegradation of organic materials under controlled conditions.
3. Total Carbon Footprint:

For every 1 kg of Sargassum-based bioplastic, the total emissions are approximately 1.95 kg CO_2 (sum of production and composting).

The avoided emissions were calculated as the difference between the emissions of conventional plastic and bioplastic:

$$\text{Avoided Emissions} = \text{Emissions (Conventional Plastic)} - \text{Emissions (Bioplastic)}$$

$$\text{Avoided Emissions} = 5.25\,\text{kg CO}_2/\text{kg} - 1.95\,\text{kg CO}_2/\text{kg} = 3.3\,\text{kg CO}_2/\text{kg}$$

4. Discussion

4.1. Sargassum-Derived Agricultural Biostimulants and Bioplastics

The results of this study demonstrate the potential of Sargassum-derived bioproducts, including biostimulants and bioplastics, in enhancing crop productivity and reducing the environmental impact of conventional products. The formulation and characterization of Sargassum-based agricultural biofilms indicate their suitability as biodegradable alternatives to conventional agricultural plastics, while the application of Marine Symbiotic® biostimulant significantly improved plant growth and yield across multiple crops, even under stress conditions.

4.1.1. Sargassum-Derived Films

The mechanical analysis of the Sargassum-based biofilms revealed an elongation at break of 25.8 ± 3.4%, aligning with the expected range for alginate–agar-based bioplastics. Furthermore, the biodegradation assay demonstrated 91.9 ± 5.1% mass loss within 40 days, confirming the biofilm's potential as a short-term biodegradable mulch. These results align with previous studies on seaweed-derived bioplastics, which have shown comparable biodegradability under similar soil conditions [70,71]. The degradation rate ensures minimal environmental accumulation, addressing the issue of persistent agricultural plastic waste, while serving at the same time as a progressive biostimulant release mechanism.

Moreover, the use of low quantities of vegetable glycerol poses no major environmental concerns while also having the ability to provide some benefits. Studies have shown that the application of solutions with glycerol to soil can be used to temporarily immobilize and then release nitrogen, and also as a co-substrate during the biodegradation of polycyclic aromatic hydrocarbons (PAHs) in soil. Some research has also evaluated the effects of applying aqueous glycerol solutions as foliar sprays and irrigation on short-term plant growth, with positive results. Furthermore, the use of glycerol in agriculture has been found to have benefits, such as increased crop yields and improved soil quality [72–74].

If a longer degradation period is required, various organic modifications can be applied to tailor the bioplastic's longevity for specific agricultural needs, such as incorporating chitin or chitosan to enhance mechanical strength, adding nanocellulose or natural fibers like hemp and flax, and coating with natural waxes or lignin to minimize water permeability. Furthermore, adjusting the composition by increasing alginate content or incorporating modified starches can extend stability, while curing with calcium ions (Ca^{2+}) or blending with PHAs and PHBs can enhance durability [71,75]. Importantly, many of these compounds can be sourced from waste materials, such as the extraction of chitosan from crustacean shells, demonstrating an opportunity for circular economy integration. By carefully selecting these modifications, bioplastics can be engineered to degrade within a tailored timeframe, optimizing sustainability and functionality for specific crop cycles.

4.1.2. Sargassum-Derived Biostimulant

The remarkable improvement in Capsicum annuum fruit weight (33.26% increase) and fruit set percentage (21.94% increase) suggests that the biostimulant influences fundamental growth regulation pathways. These observations align with the known presence of plant growth regulators in seaweed extracts, including cytokinins, auxins, and gibberellins [48,49,76]. The auxin-like compounds likely promoted cell elongation and fruit development, while cytokinins may have delayed leaf senescence, thereby extending the photosynthetic activity period. This hormonal interplay would explain both the increased yield and the improved fruit quality metrics observed in our study.

Yield assessments further corroborated the biostimulant's efficacy, with a 12.77% increase in total yield per cultivation bed and a 45% increase in yield under high-stress conditions. The biostimulant's particularly strong effect under high-stress conditions points to its role in activating stress response mechanisms. Previous research has shown that seaweed-derived compounds can modulate the expression of genes involved in antioxidant production and osmotic regulation, including ABA-responsive genes, such as At5g66400 and At5g52310 [69]. In our system, the phenolic compounds and polysaccharides present in the Sargassum extract may have stimulated the production of protective metabolites such as proline and glycine betaine, while simultaneously upregulating antioxidant enzymes like glutathione reductase and ascorbate peroxidase. This dual action would mitigate oxidative damage caused by environmental stressors, already reported in previous studies demonstrating the mitigating effects of seaweed-derived biostimulants on drought and heat stress [76–78], also explaining the reduced fruit rejection rates (48.42% decrease) and improved crop performance under adverse conditions.

The differential responses observed among crop species, with spinach and Batavia lettuce showing particularly strong growth responses, may reflect variations in species-specific metabolic pathways. The modulation of nutrient transporter genes (e.g., BnNRT2.1 for nitrogen uptake) by seaweed extracts has been well documented [79–81], and such mechanisms could account for the enhanced nutrient use efficiency suggested by the reduced root growth in some treated plants. Furthermore, feedback from collaborating farmers highlighted additional practical benefits of Marine Symbiotic®. Farmers reported the successful cultivation of crops that are typically challenging to grow in the region, attributing this achievement to the use of the biostimulant. They also noted a noticeable improvement in leaf coloration, with treated plants exhibiting more intense pigmentation, which enhanced marketability and consumer appeal. This increased pigmentation can be linked to the role of citoquinins and auxins in chloroplast development and the regulation of photosynthetic gene expression. Citoquinins promote chlorophyll biosynthesis and chloroplast differentiation, while auxins influence leaf expansion and the organization of photosynthetic tissues. Moreover, the presence of alginate-derived oligosaccharides in the biostimulant may enhance carbon fixation pathways by upregulating genes associated with photosystem activity and chloroplast function. Studies have shown that plants treated with seaweed extracts exhibit upregulation of genes involved in carbon fixation, leading to increased starch synthesis and improved photosynthetic performance. Additionally, flavonoids and other polyphenolic compounds present in the extract possess antioxidant properties, helping to stabilize chlorophyll molecules and prevent oxidative degradation under stress conditions [76,79–82].

The findings of this study underscore the dual potential of Sargassum-derived products in agriculture. The biostimulant significantly enhanced crop productivity, particularly under stress conditions, while the bioplastic formulation offers a sustainable alternative to conventional agricultural plastics. Future research will focus on optimizing biopolymer formulations to improve mechanical strength and tailor biodegradability for different crop cycles. Additionally, further investigation will aim to elucidate the molecular pathways underlying these beneficial effects and refine biostimulant formulations to meet specific crop requirements and environmental conditions. Long-term field trials will also be conducted to assess the broader ecological impacts and economic viability of large-scale applications.

Research and development efforts remain ongoing, with new research exploring Alginaqua® applications in the textile sector and the development of additional Sargassum-derived formulations by SOS Biotech. These include Marine Blossom®, a flower preservative; Marine Soil®, a hydroponic substrate; Atabey's Nectar®, a cosmetic extract with antioxidant, SPF, and anti-aging properties; and Chlorovita®, a bioactive pigment for the nutraceutical and textile industries. These innovations further expand the potential of Sargassum and other invasive seaweed valorization, reinforcing its role in sustainable biotechnology and the Blue Economy.

4.2. Carbon Credit Potential and Greenhouse Gas Mitigation

The potential of Sargassum valorization and Marine Symbiotic application in reducing greenhouse gas (GHG) emissions and enhancing carbon sequestration is also significant. Through the quantification of CO_2-equivalent (CO_2e) avoidance and carbon capture, these results underscore the role of seaweed-based interventions in mitigating climate change.

The valorization, both directly and indirectly, of 65 tons of Sargassum between 2023 and 2024 by SOS Carbon and SOS Biotech prevented 227.5 tons of CO_2e from being released into the atmosphere by avoiding methane emissions from uncontrolled decomposition. The methane avoidance calculations, based on the First Order Decay (FOD) model, align with methodologies established by CDM TOOL 4 for landfill emissions [64]. The potential scalability of this approach is further demonstrated by the annual harvesting capacity of a single LCM® which, if fully operational for six months, could prevent 89,670 tons of CO_2 annually, reinforcing the climate mitigation benefits of Sargassum valorization at scale. Furthermore, the LCMs® are operated by local fishermen who have seen their livelihoods threatened by invasive Sargassum.

The application of Marine Symbiotic® further amplifies carbon sequestration through enhanced biomass accumulation in treated crops. The experimental results demonstrated biomass increases ranging from 15.4% to 360%, with direct implications for carbon fixation and soil organic carbon storage. This effect is significant when extrapolated beyond the current 32-hectare deployment of Marine Symbiotic® across Spain, the United States, the Dominican Republic, Colombia, and Puerto Rico.

In addition to biomass accumulation, the study observed a substantial increase in Brix degrees in treated crops, with enhancements ranging from 24% to 73%. As Brix degrees serve as an indicator of carbohydrate accumulation from photosynthesis, these results suggest that Marine Symbiotic® not only improves plant productivity but also facilitates greater carbon fixation and internal carbon storage, reinforcing its role in supporting agricultural carbon sequestration.

The carbon footprint reduction potential of Sargassum-based bioplastics demonstrates a significantly lower environmental impact compared to conventional hydrocarbon-based plastics. Based on life cycle assessment (LCA) studies of similar bioplastics [67,68,70], we estimated that for every kilogram of Sargassum-derived bioplastic replacing one kilogram of conventional plastic, an avoidance of 3.3 kg of CO_2 is achieved. This represents a substantial reduction in carbon emissions, particularly when replacing conventional agricultural plastics. As highlighted in the Section 3.4.3, conventional plastics are associated with significantly higher emissions due to fossil fuel extraction, polymerization processes, and their long-term environmental persistence.

These findings underscore the multifaceted benefits of Sargassum valorization, spanning methane avoidance, enhanced agricultural carbon capture, and bioplastic-based emissions reductions. This approach is particularly crucial for the Caribbean region, which has recorded over 24 million tons of Sargassum arrivals in past years and is currently experiencing one of the largest influxes on record [83]. Implementing large-scale Sargassum valorization initiatives is essential not only for mitigating environmental damage but also for creating economic opportunities in affected coastal communities. Additionally, these strategies can be adapted to other regions facing similar invasive seaweed crises, offering a nature-based solution to environmental degradation while fostering economic diversification. This is particularly relevant for the Global South, where developing sustainable, locally-driven markets is key to ensuring economic resilience and environmental sustainability.

Future research is needed on refining the carbon quantification methodologies by incorporating direct field measurements of soil carbon sequestration, expanding LCA analyses for Sargassum-based materials, and assessing the long-term carbon retention effects of Marine Symbiotic-treated soils. Moreover, integrating these approaches into carbon credit frameworks could facilitate the monetization of Sargassum valorization efforts as part of global nature-based climate solutions.

4.3. The Need for Multi-Sectoral Collaboration and Policy Development

The effective and sustainable valorization of Sargassum requires multi-sectoral collaboration among academia, industry, and policymakers to ensure the scalability and long-term viability of proposed solutions. However, the absence of clear legislation governing the collection, processing, and commercialization of Sargassum-based products severely limits investment, innovation, and sustainable economic growth in regions most affected by these seaweed invasions. To overcome these barriers, it is imperative that governments establish clear and standardized regulations for Sargassum management. Such regulations would create a solid legal framework, encouraging investment and innovation, and ensuring the responsible use of this valuable resource.

Given the increasing global focus on ocean sustainability and the Blue Economy, international and national regulatory bodies must take steps to integrate Sargassum into broader marine conservation and sustainability initiatives. In 2025, the 'Year of the Oceans', global events such as the United Nations Ocean Conference in Nice [84,85] present a pivotal opportunity to advocate for the creation of policies that standardize Sargassum management, facilitate carbon credit integration, and introduce certification mechanisms for Sargassum-derived products. These efforts would not only enhance market access but also promote investor confidence, accelerating the growth of the industry. Given the increasing global focus on ocean sustainability and the Blue Economy, international and national regulatory bodies must take steps to integrate Sargassum into broader marine conservation and sustainability initiatives.

To maximize the impact of Sargassum valorization, it is crucial that policymakers recognize the interconnectedness of global seaweed invasions. The challenges posed by Sargassum are not isolated but part of a broader issue affecting various regions across the globe. By merging policies that address Sargassum with strategies for managing other invasive seaweeds, a more cohesive and effective response can be developed. Coordinating efforts across different species of invasive seaweeds will foster synergies in research, technology development, and environmental management, ensuring that Sargassum solutions can be adapted to other regions facing similar challenges.

In order to bridge the gap between scientific research and real-world application, it is essential that innovations in Sargassum valorization are designed with industrial scalability and economic viability in mind. Solutions must be both environmentally sustainable and financially attractive to encourage private-sector investment and community participation. Furthermore, these technologies should be tailored to the specific socio-economic conditions of the regions in which they will be deployed. For example, in regions like the Caribbean, where invasive algae have profound ecological and economic impacts, solutions should be co-developed with local communities to ensure that they address both environmental challenges and economic opportunities. This collaborative approach would foster job creation, skill development, and long-term economic resilience.

Policymakers must also create funding mechanisms and incentives to encourage public–private partnerships, which will play a critical role in scaling up Sargassum-based solutions. This could include offering tax incentives, grants, and subsidies to businesses and research institutions focused on the commercialization and sustainable use of Sargassum. Additionally, the establishment of certification standards for Sargassum-derived products would help ensure market credibility, enhance consumer confidence, and support sustainable practices within the industry.

An equally important step is the integration of carbon credit schemes into the Sargassum valorization process. Policymakers should work to create frameworks that allow for the generation of carbon credits through the responsible collection and processing of Sargassum, incentivizing companies to invest in sustainable practices while also contributing to climate change mitigation efforts.

Furthermore, governments should prioritize research and development in the area of invasive seaweeds, including Sargassum, by funding and supporting interdisciplinary collaborations. This would enable the identification of scalable solutions that benefit both the environment and local economies. Additionally, by fostering regional cooperation on seaweed management, countries facing similar challenges can share knowledge, resources, and technologies, improving their collective ability to tackle the issue. The formation of regional alliances could also promote the exchange of best practices and facilitate the development of joint solutions.

Sustainable and responsible harvesting practices must be a cornerstone of any regulatory framework. Governments should establish guidelines to ensure that Sargassum collection does not negatively impact marine ecosystems, balancing environmental protection with economic use. It is also critical to create mechanisms for technology transfer, particularly between developed and developing nations. These platforms would help ensure that innovative solutions are accessible to all regions, regardless of their economic standing.

Finally, policymakers must ensure that local communities are actively involved in the development and implementation of Sargassum valorization strategies. Engaging communities in decision-making processes and incorporating their knowledge into policy development will ensure that solutions are both effective and locally appropriate. This approach would not only foster ownership of the solutions but also promote job creation and skill development, empowering coastal communities to participate in the emerging Blue Economy.

Looking ahead, it is critical that scientific research, industry expertise, and policy frameworks align to unlock the full potential of Sargassum valorization as a scalable, sustainable, and economically beneficial solution. By fostering a cohesive regulatory landscape that integrates Sargassum management with broader seaweed invasion policies, promoting localized, community-driven innovation, and leveraging the growing global momentum for ocean sustainability, Sargassum-based initiatives can play a pivotal role in addressing both environmental and socio-economic challenges in the Global South and beyond.

5. Conclusions

Invasive seaweed blooms, driven by climate change and nutrient runoff, pose significant ecological and economic challenges. However, this study demonstrates that *Sargassum* spp. can be effectively transformed into commercial biostimulants and biodegradable biomaterials, addressing key sustainability concerns while supporting agricultural productivity and climate mitigation.

Field trials conducted in two distinct agricultural contexts—pepper crops in the Dominican Republic and leafy greens in Colombia—provided critical evidence of the agronomic benefits of Marine Symbiotic®. In the Dominican Republic, the biostimulant significantly improved fruit weight (+33.26%), fruit set percentage (+21.94%), and yield stability under high-stress conditions (+45%), while reducing fruit rejection rates by 48.42%. In Colombia, applications on leafy greens resulted in biomass increases of up to 360%, a 50% reduction in synthetic input dependency, and intensified crop pigmentation, enhancing marketability. The consistency of these results across varied climatic and soil conditions highlights the versatility and scalability of Sargassum-derived agricultural inputs.

Beyond agronomic applications, Sargassum-based biofilms formulated with Alginaqua® demonstrated favorable mechanical properties and biodegradability, offering a viable alternative to conventional plastic mulch films. This dual-function innovation not only reduces plastic waste but also enhances plant resilience through bioactive compounds. Furthermore, carbon credit assessments revealed that a single Littoral Collection Module® (LCM®) system could prevent up to 89,670 tons of CO_2-equivalent emissions annually, reinforcing the role of Sargassum valorization in global decarbonization efforts.

The trials conducted in two distinct regions not only validated the commercial viability of Sargassum-derived products but also underscored their adaptability to diverse agricultural settings. By integrating invasive seaweed valorization into global sustainability frameworks, this approach has the potential to transform an environmental crisis into an economic opportunity, particularly for coastal regions in the Global South, where the socioeconomic benefits of sustainable blue industries are most needed. Ongoing research by SOS Biotech continues to expand applications, with innovations such as Marine Blossom®, Marine Soil®, Atabey's Nectar®, Escumacua®, and Chlorovita® further enhancing economic viability within sustainable industries.

These findings emphasize the need for policy frameworks that integrate Sargassum valorization into existing Blue Economy strategies. The absence of clear legislation governing the collection, processing, and commercialization of Sargassum-based products remains a significant barrier to investment, innovation, and sustainable economic growth. Given the increasing global recognition of ocean sustainability, international and national regulatory bodies must establish comprehensive policies that facilitate the responsible and effective use of Sargassum and other invasive seaweeds.

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Conflicts of Interest: Elena Martínez-Martínez, María Laura Ceballos and Andrés Guillermo Bisonó-León are part of SOS Group (SOS Biotech and SOS Carbon) the organization that developed the products and technologies studied in this research. Paula Aponte and Alexander H. Slocum are independent researchers with no financial or commercial affiliations to SOS Biotech or SOS Carbon . The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. Furthermore, the external funders organizations of this specific research had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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