



Article Bio-Inspired Eco-Composite Materials Seaweed Waste Integration for Sustainable Structural Applications

Daniel Barros^{1,*}, Luís Nobre¹, João Bessa¹, Liliana Leite², Carlos Mota³, Fernando Cunha⁴ and Raúl Fangueiro^{1,5}

- ¹ Fibrenamics, University of Minho, 4800-058 Guimarães, Portugal; luisnobre@fibrenamics.com (L.N.); joaobessa@fibrenamics.com (J.B.); rfangueiro@fibrenamics.com (R.F.)
- ² Tecminho, University of Minho, 4800-058 Guimarães, Portugal; lilianaleite@fibrenamics.com
- ³ Beyond Composite, 4410-309 Canelas, Portugal; carlosmota@beyondcomposite.pt
- ⁴ Givaware, University of Minho, 4800-058 Guimarães, Portugal; fernandoc@givaware.com
- ⁵ Department of Textile Engineering, University of Minho, 4800-058 Guimarães, Portugal
- * Correspondence: danielbarros@fibrenamics.com

Abstract: The increasing levels of atmospheric carbon dioxide (CO₂) and plastic waste in marine environments demand immediate action to mitigate their effects. A promising solution lies in enhancing algal cultivation in marine environments, which not only absorbs CO₂ and produces oxygen (O_2) but also contributes to carbon sequestration. This study aims to develop biodegradable substrates for algae cultivation, facilitating their gradual degradation in marine environments and eventual deposition on the ocean floor, thereby addressing both plastic pollution and CO₂ emissions. We selected various degradable polymers and incorporated differing proportions of algae residue powder (10%, 20%, and 30% by weight) into these substrates. The compositions were processed through extrusion and molded into test samples for hot compression molding. Characterization included assessments of mass loss, morphology, chemical composition, and mechanical strength under both dry conditions and after immersion in seawater for up to two months. The results indicate that the incorporation of algae residue significantly accelerates the degradation of the samples, particularly under extended exposure to seawater. Mass loss measurements indicated that samples with a 30 wt% algae addition experienced mass losses of up to 12% after two months of immersion. Mechanical strength tests demonstrated a reduction of up to 57% in strength due to the incorporation of algae, with seawater immersion further exacerbating this loss. These findings highlight the potential of biopolymer substrates infused with algae residue for effective carbon sequestration through enhanced algae cultivation.

Keywords: algae; carbon capture; biodegradability; sustainability; ocean; eco-composite

1. Introduction

Over the past few decades, human activities have significantly contributed to the rise of CO_2 levels in the Earth's atmosphere, intensifying global warming and climate change. These increasing concentrations of greenhouse gases have triggered widespread ecological imbalances, highlighting the urgent need for innovative and sustainable solutions to mitigate atmospheric CO_2 levels [1–6].

One of the most promising natural mechanisms for reducing CO_2 in the atmosphere is carbon sequestration, a process facilitated by photosynthetic organisms such as plants and algae. Through photosynthesis, these organisms absorb CO_2 , converting it into oxygen and glucose ($C_6H_{12}O_6$), thus playing a critical role in regulating the global carbon cycle [7]. Among photosynthetic organisms, algae stand out due to their exceptional efficiency in capturing CO_2 . It is estimated that algae are responsible for sequestering up to 70% of atmospheric CO_2 , making them pivotal to maintaining climate stability [8,9].



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Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). At the end of their life cycle, algae often sink to the ocean floor, effectively trapping the carbon they have absorbed over time in these deep-sea environments. This natural sequestration process makes algae a crucial component of the biological carbon pump, which sustains oceanic ecosystems and contributes to long-term carbon storage [10,11].

Algae are diverse aquatic organisms ranging from microscopic phytoplankton to large macroalgae. Found in environments as varied as oceans, rivers, and freshwater ponds, they exhibit vast differences in pigmentation, cellular complexity, and ecological adaptation. This diversity is often categorized by their primary colors—green, red, or brown—each with unique characteristics and environmental roles [12–14].

Green algae, for instance, are typically found in surface waters where sunlight is most abundant, enabling them to perform photosynthesis efficiently. In contrast, brown and red algae are adapted to deeper environments, with red algae capable of photosynthesizing at depths of up to 200 m due to their ability to utilize low-light wavelengths [15,16]. Despite these differences, algae species collectively contribute to carbon fixation, converting inorganic carbon into organic compounds essential for sustaining life on Earth [17].

Beyond their ecological importance, algae have garnered attention for their practical applications. Algae cultivation is increasingly used for food production, medicinal purposes, agriculture, and biofuel generation. Additionally, their ability to regulate atmospheric CO₂ through photosynthesis makes them a critical asset in combating climate change [18–20].

However, marine environments face growing challenges that demand urgent attention. Plastic pollution, originating from domestic waste, fishing activities, and other human sources, has become a pervasive problem in oceans worldwide. Plastics harm marine life and disrupt ecosystems, with long-term consequences that extend far beyond the ocean [21–23]. Efforts to combat this issue have focused on improving recycling practices, enhancing waste management systems, and developing biodegradable materials to replace conventional plastics [24–26].

Another pressing issue is the proliferation of algae along coastal regions, often driven by nutrient pollution. This excessive growth can degrade water quality, harm biodiversity, and disrupt aquatic ecosystems, affecting both marine species and coastal communities. Despite its challenges, this surplus of algae presents an opportunity to repurpose these residues as raw materials for innovative solutions [27].

To address these interconnected challenges, this study proposes the development of biodegradable substrates incorporating algae biomass. These substrates serve as a platform for algae cultivation, enhancing their potential for carbon sequestration while simultaneously offering a sustainable alternative to conventional plastics [28,29].

The concept involves integrating up to 30 wt% of algae biomass into the substrate composition, utilizing algae that have already absorbed CO_2 during their lifecycle. This approach not only promotes carbon fixation but also minimizes the environmental footprint of the materials used, aligning with global efforts to reduce dependency on non-biodegradable plastics [30–32].

By leveraging biodegradable materials, these substrates are designed to degrade naturally in marine environments, further contributing to the reduction of plastic waste. Over time, as the substrates break down, they will settle on the ocean floor, carrying the algae with them. Both the algae and their biodegradable substrates will function as carbon sinks, effectively sequestering carbon without leaving harmful residues in the ecosystem [33,34].

The inclusion of residual algae from coastal accumulations into this solution represents an additional environmental benefit. Instead of allowing these residues to decompose and release methane—a potent greenhouse gas—they can be transformed into valuable raw materials. This process not only mitigates the impact of excess algae on aquatic ecosystems but also supports a circular economy by reusing what would otherwise be waste [35–37].

By combining algae biomass with biodegradable substrates, this approach offers a multifaceted strategy to tackle key environmental issues. It addresses the rising levels of

atmospheric CO_2 , reduces the environmental burden of plastic pollution, and promotes the sustainable use of algae, transforming a natural resource into a vital tool for combating climate change [38–40].

The proposed approach focuses on the development of biodegradable substrates designed to address the growing issue of plastic pollution in the ocean. These substrates are intended to break down naturally over time and ultimately settle on the ocean floor, reducing long-term environmental impact. To enhance their effectiveness in carbon sequestration and minimize the use of biopolymers, the substrates will incorporate up to 30 wt% algae biomass. Since algae naturally capture carbon during their life cycle, this incorporation not only contributes to the reduction of CO_2 levels but also reduces the overall environmental footprint of the substrate material. This dual approach of addressing plastic pollution and promoting carbon fixation through algae biomass provides a sustainable solution to two significant environmental challenges.

2. Experimental

2.1. Materials

To produce the different biodegradable compositions, four different biopolymers were used: polyhydroxyalkanoates (PHAs), PHARADOX—PHAX10007, purchased from Helian Polymers (Belfeld, The Netherlands); polyhydroxybutyrate (PHB), BIOMER P226 purchased from Biomer (Schwalbach am Taunus, Germany); polylactic acid (PLA), Ingeo Biopolymer 6100D purchased from Resinex (Braga, Portugal); and BioCop, BIOMIND CCB07H5 purchased from CABOPOL (Porto de Mós, Portugal). These biopolymers were mechanically mixed with 10, 20, and 30 wt% of powdered fucus algae acquired from Porto-Muiños (A Coruña, Spain) that was initially processed through the twin-screw hot melt extrusion (HME) method to ensure excellent mixing homogeneity.

Then plates of each combination were subsequently produced by hot pressing, using temperatures corresponding to the melting point of each polymer (170 to 205 °C). Finally, samples were cut for conducting biodegradability tests on a laboratory scale. In Figure 1, a schematic representation of the production cycle for different sample combinations is presented.



Figure 1. Schematic representation of the production of each sample combination.

2.2. Sample Development

Various combinations of samples were produced via the compression molding process, using different types of biodegradable polymers with and without the addition of algae residue. The HME was performed using a co-rotating twin-screw equipped with screws with a 20 mm diameter, an L/D ratio of 44:1, four conveying elements zone, and a round-shaped die with a 3 mm diameter. Regarding the temperatures of the six heating zones, a range between 150 to 180 °C, and the feed screw and extruder speeds were 20 and 40 RPM, respectively. After the extruder die, each combination produced wire was ground to obtain pellets of PHA, PHB, PLA, and BioCop mixed with algae in 100:0, 90:10, 80:20, and 70:30

weight percentages, as listed in Table 1. Then, the processed plates of each combination were hot-compression molded at 180 to 200 °C for 20 min at 5 bar and finally cooled in the equipment using water. From this, produced plates were cut into flexural test specimens according to the ISO 178 (Plastics—Determination of flexural properties) standard for flexure test [41].

Polymer	Melting (°C)	Polymer:Algae Ratio (%)	Reference	Polymer	Melting (°C)	Polymer:Algae Ratio (%)	Reference
РНА	175	0	PHA_0	PLA	185	0	PLA_0
		10	PHA_10			10	PLA_10
		20	PHA_20			20	PLA_20
		30	PHA_30			30	PLA_30
РНВ	180	0	PHB_0	BioCop	200	0	BioCop_0
		10	PHB_10			10	BioCop_10
		20	PHB_20			20	BioCop_20
		30	PHB_30			30	BioCop_30

Table 1. Produced samples.

The specimens were prepared and divided into four groups according to the degradation exposure time. Each of the four groups was characterized immediately after: Group A, after processing; Group B, after 1 month of immersion in water; Group C, after 2 months of immersion in water; Group D, after 2 months of air storage.

2.3. Aging Test Conditions

The tests were carried out over 2 months in our laboratory under controlled conditions (temperatures between 15.6–18.1°C), and we used 15 L of seawater collected from Apúlia beach, located in the Braga district, Portugal (41°28′56.2″ N, 8°46′44.1″ W). This work was carried out according to an adaptation of the experimental procedure conducted in the study by Morgan Deroiné [42].

The samples from Groups B and C were immersed in water on 19 January 2024, with Group B samples being removed on 19 February and Group C samples being removed on 19 March 2024. Samples from Group A were not subjected to any aging process, while those from Group D were air-stored, exposed to visible light, and maintained at the laboratory's ambient temperature. The pH measured at the beginning of the tests and after 1 and 2 months remained practically unchanged, recording a value of 6.9–7.1.

All specimens were marked and weighed, and the ones from Groups B and C were placed inside the seawater at a depth of 10 cm. From these groups, four samples per condition were removed after the 1 and 2-month stages, washed with distilled water, and dried at 50° C for 12 h in an oven. Afterward, the samples were weighed again to assess any potential mass losses and then mechanically characterized.

2.4. Characterization Techniques

2.4.1. Weight Loss

Following weight is a useful method to characterize irreversible degradation. To Groups B, C, and D, the percentage loss, W_{lost} , was determined on drying specimens by Equation (1):

$$W_{lost}(\%) = \frac{W_i - W_f}{W_i} \times 100 \tag{1}$$

where W_i indicates the initial sample's weight and W_f the sample's weight after aging specimens (after immersion).

2.4.2. Morphology Evaluation—Scanning Electron Microscopy (SEM)

The specimen's morphology evaluation was made using the Scanning Electron Microscopy (SEM), a widely employed technique in scientific research for visualizing material morphology at micro and nanoscale levels. SEM utilizes an electron beam to generate high-resolution images of the sample surface. In this study, SEM analysis was conducted on specific areas of different specimens using an FEI Nova 200 SEM instrument (Hillsboro, OR, USA). This analysis aimed to evaluate the interactions between the polymer and algae, as well as to assess structural degradation after aging.

2.4.3. Fourier Transform Infrared Spectroscopy (FTIR)

The materials' chemical composition was assessed utilizing Fourier Transform Infrared Spectroscopy (FTIR) coupled with the Attenuated Total Reflection (ATR) technique, employing SHIMADZU—IRAffinity-1S instrumentation (Kyoto, Japan). Spectra acquisition was conducted in transmittance mode, encompassing 45 scans across a wavenumber range from 4000 to 400 cm^{-1.} This methodology facilitates the comparison of the chemical compositions of each prepared sample, allowing for an evaluation of the influence of different percentages of algae and the effects of aging on the final properties.

2.4.4. Mechanical Characterization—Flexural Test

Flexural tests were conducted under controlled environmental conditions in a laboratory setting (at 21°C and 50% relative humidity), according to the ISO 178 standard, utilizing a universal test machine, Hounsfield H100KS (Redhill, UK). For these tests, a 2.5 kN load cell and a crosshead speed of 5 mm/min were used. Four specimens were tested under each condition, and measurements for each section were taken just before the tests.

3. Results and Discussion

3.1. Weight Loss

Figure 2 displays the mass loss results for all samples produced utilizing different biopolymers with varying percentages of incorporated algae. The measurements were conducted both prior to immersion in natural seawater and after being submerged for one and two months.

After immersing various material combinations for two months, an overall mass loss was observed. However, the mass loss primarily occurred in combinations where algae were added to the composition between 20 and 30 wt%. For samples with less than 10 wt% of added algae, the recorded mass losses were negligible.

The highest mass losses were observed in combinations utilizing PLA biopolymer (up to 10%) and BioCop (up to 13%), with the addition of 30 wt% algae in their structure. In these combinations, during the two-month immersion in seawater, a greater disintegration of the PLA and BioCop additives with 30 wt% of algae showed higher mass loss.

Samples with higher algae content exhibited greater degradation due to increased exposure to seawater on both the surface and within the samples. The organic nature of the algae contributed to this effect, as demonstrated by the porosity observed in these combinations through SEM analysis. This led to an enlarged surface area in contact with seawater. Consequently, the combination of a larger surface area and the disintegration of the algae as filler resulted in increased deterioration of the produced bio-composite substrates.



Figure 2. The percentage of weight loss of biopolymers with different algae additions in natural seawater over two months of samples with (**a**) PHA, (**b**) PHB, (**c**) PLA, and (**d**) BioCop.

3.2. Morphology Evaluation

Initially, various combinations of produced samples were visually inspected, and the BioCop samples were selected for a more detailed morphological analysis because they exhibited the highest degradation rate according to mass loss studies. To achieve this, as depicted in Figure 3, a comparison of the surface of samples with different algae concentrations was initially conducted.

From Figure 3a, it is evident that after two months of immersion in seawater, the specimens, particularly when comparing Group A (without submersion) and Group C (after two months of submersion), have slightly lost color and become rougher, indicating surface degradation caused by the saltwater. These changes were more pronounced in the specimens with a higher percentage of algae addition (BioCop_30%).

Through Figure 3b, the analysis of the lateral surface of the specimens with 30 wt% algae added reveals the appearance of cracks in the structure after two months of immersion. These cracks are more evident in the specimens with 30 wt% resulting from the degradation of the polymer matrix when in contact with saltwater. This degradation is caused by the hydrolysis process, which breaks the chemical bonds of the polymer, and possibly by microbial action, where microorganisms in the water metabolize the polymer, accelerating its degradation. However, it would be necessary to assess the microbial activity in the water after 2 months to validate this theory [43,44].

For a more detailed analysis, SEM images were captured of the specimen's surfaces and in the fracture zone (after flexural tests) to investigate the internal state of the produced samples (presence of voids, bonding between matrix and algae, for example), as presented in Figure 4.



Figure 3. Morphological analysis of BioCop samples with varying percentages of algae, with and without immersion in seawater (Groups A and C): (a) Frontal surface of the samples; (b) Lateral surface of the BioCop_30% sample.



Figure 4. SEM micrographs of the samples surfaces: (**a**) BioCop_0% and (**b**) BioCop_30% without submersion in seawater (Group A), and (**c**) BioCop_0% and (**d**) BioCop_30% with two months of seawater submersion (Group C).

Figure 4 effectively helps evaluate how the surface of samples changes with varying algae percentages and immersion times in seawater. Figure 4a,b allow for a comparison of the surfaces of BioCop_0% and BioCop_30% samples, appearing regular without impurities, only revealing small voids resulting from air bubble entrapment during the compression molding process. No discernible differences in surface characteristics between the two samples are observed, regardless of algae presence.

Figure 4c,d illustrate the same samples after two months in seawater, revealing increased surface roughness and the presence of particles adhering to them. This indicates that seawater significantly alters the surface, initiating the degradation of the samples. Notably, the sample with 30 wt% algae exhibits cracks and appears more worn, suggesting that the presence of algae accelerates the degradation process. This accelerated degradation may result from the higher algae content in the BioCop matrix, leading to greater water absorption and enhanced contact between the surface and seawater.

Next in Figure 5, SEM images will be presented of the fracture zone of the samples (observed after flexural tests).



Figure 5. SEM micrographs of the samples fracture zone: (**a**) BioCop_0% and (**b**) BioCop_30% without submersion in seawater (Group A), and (**c**) BioCop_0% and (**d**) BioCop_30% with two months of seawater submersion (Group C).

Figure 5a,b facilitate a comparison of the fracture zone between BioCop_0% and BioCop_30% samples, revealing significant structural differences. The BioCop_0% sample exhibits a more homogeneous fracture with some voids and structural flaws attributed to air entrapment within the matrix, rendering the sample fragile in these regions due to a lower polymer matrix content. With the addition of 30 wt% algae, an irregular fracture pattern is

observed, characterized by the presence of voids and protruding areas possibly attributable to algae agglomerates. Notably, the increased irregularity in the internal structure of the 30 wt% sample translates to greater fragility, displaying a brittle fracture. As the algae in the structure reduces the number of connections between the BioCop matrix, it contributes to its fragility.

Moving to Figure 5c,d, where the samples were submerged in seawater for two months, the sample without algae addition exhibits an unchanged internal structure. Conversely, the sample with 30 wt% algae addition displays a more heterogeneous fracture zone, featuring larger void spaces resulting from water ingress and subsequent structure degradation upon exposure to seawater.

These observations indicate that the exposure of samples to seawater accelerates the degradation of the tested specimens, particularly those with higher algae percentages.

3.3. Chemical Evaluation—FTIR

In this section, FTIR test results are presented, specifically focusing on the BioCop combinations, due to having the highest degradation rate as indicated by mass loss studies. This aims to evaluate how algae addition percentage (Figure 6) and seawater immersion time (Figure 7) affect the chemical structure.

From the FTIR spectrum, peaks in the region of 2924 and 2850 cm⁻¹ are observed, arising from the C-H bonds of CH₂ and CH₃ groups. Peaks between 2400–2300 cm⁻¹ are characteristic of the presence of CO₂, which will be present in the added algae. This range of peaks is not visible in the sample with 0 wt% addition but becomes evident with increasing algae addition [45,46]. The peak assigned to 1712 cm⁻¹ represents the C–O and C=O bonds of the ester group [47]. The peak at 1357 cm⁻¹ corresponds to C-O-H bonds and CH₂ twisting. It is further noted that the absence of bands above 3000 cm⁻¹ indicates that the combinations under study lack OH or NH groups. Finally, increasing the presence, thereby reducing the intensity of the detected peaks, which is evident in the obtained results.



Figure 6. FTIR spectra of BioCop combinations with different percentages of algae addition, without exposure to seawater (Group A).



Figure 7. FTIR spectra of BioCop_10% with different times of exposure to seawater.

Now, to better understand the changes in chemical bonds, the FTIR spectra before and after immersion in seawater were compared for the BioCop_10% sample. This sample was chosen because it allowed for the clearest comparison.

When examining the FTIR spectrum of BioCop_10% before and after two months of immersion in seawater, minimal disparity was noted. Furthermore, the displacement of peaks towards higher frequencies, coupled with reduced intensity, suggests a degradation process resulting from chemical bond breakage. Additionally, the migration of certain peaks implies potential degradation of the produced biocomposites, as in the example of 2850 to 2845 cm⁻¹ [46]. It was observed that a slight increase in the intensity of the peaks at 2300 cm⁻¹ may be attributed to water absorption and interaction with the functional groups of the algae and the biopolymer during aging. This peak, associated with carbonate groups and changes in hydrogen bonding, indicates that the interaction of seawater with the materials may have promoted reactions that resulted in new products or alterations in chemical structure, leading to an increase in absorption in this region [48,49].

3.4. Flexural Test

Figures 8 and 9 present the flexural test results for various samples, showing both flexural strength and modulus. The data is organized into groups (A, B, C, and D) according to biopolymer type and whether samples were immersed in seawater, with durations specified.

Based on the results obtained, it is evident that regardless of the type of biopolymer used, there was a decrease in flexural strength with increasing algae addition as a filler material, up to 30 wt%.

Considering compositions without algae addition, those composed of PLA (80–100 MPa), BioCop (30–45 MPa), PHB (30–35 MPa), and finally PHA (15–20 MPa) exhibit the best flexural strength. However, with increasing algae addition up to 30 wt%, a decrease in flexural strength was observed. Among these combinations, PLA compositions experienced the greatest loss, with PHA_0% starting at 80–100 MPa and decreasing to 20–50 MPa for PHA_30%.

Furthermore, there is a general trend indicating a decrease in flexural strength when samples are immersed in seawater, accelerating their degradation process compared to samples exposed to air. This is observed as both Group B and C (1 and 2 months of immersion) showed a loss of strength compared to samples immediately after processing (Group A). Examining Group D, representing samples kept out of seawater for 2 months, the loss of strength is negligible compared to samples immediately after processing.



Figure 8. Flexural strength of biopolymers with different algae additions in natural seawater over two months of samples with (**a**) PHA, (**b**) PHB, (**c**) PLA, and (**d**) BioCop.



Figure 9. Flexural modulus of biopolymers with different algae additions in natural seawater over two months of samples with (**a**) PHA, (**b**) PHB, (**c**) PLA, and (**d**) BioCop.

In some instances, such as with the PLA_0% and 30 wt% samples, as well as all BioCop samples, a loss of properties was observed even without water exposure. This indicates that both PLA and BioCop biopolymers degrade when exposed to visible light. However,

the degradation of these materials is significantly worsened when submerged in seawater, particularly in samples with a 30 wt% algae addition.

Considering only the percentage addition of 0 and 30 wt% of algae for different biopolymers (within Group A), a loss of resistance of 17.1% for PHA, 30.2% for PHB, 57.9% for PLA, and 50.5% for BioCop was observed. These results demonstrate that samples produced using PLA and BioCop exhibit the greatest loss of mechanical properties with algae addition up to 30 wt%.

Examining the property losses for samples with 30 wt% algae addition before and after 2 months of immersion in seawater (Group A and Group C), a loss of 52.9% for PHA_30%, 40.8% for PHB_30%, 63.6% for PLA_30%, and 97% for BioCop_30% was observed. These results again highlight a greater loss of mechanical properties for PLA and BioCop compositions with 30 wt% algae addition.

In summary, increasing the algae content up to 30 wt% and immersing the samples in seawater for two months led to a decline in mechanical properties, highlighting internal structural degradation due to prolonged seawater exposure and higher algae concentrations. These findings indicate the promising potential of using substrates made from PLA or BioCop with 20% to 30% algae addition for algae cultivation. This approach facilitates gradual disintegration over time, allowing for the natural detachment and decomposition of algae after their life cycle, thereby minimizing environmental harm.

In the overall results obtained for Young's Modulus, there were no significant variations observed with increasing algae addition up to 30 wt% for the different types of polymers used. However, there was a decrease in the modulus when the samples were immersed in seawater for 1 and 2 months.

Among the combinations tested, those containing PLA exhibited the highest flexural modulus, ranging from 2.5 to 4 GPa. In contrast, the combinations associated with PHA showed a lower flexural modulus, with values between 0.5 and 1 GPa.

Considering immersion time up to 2 months, a decrease in mechanical strength was also observed due to deterioration caused by seawater for all produced combinations. Similarly to the tensile strength results, comparing samples tested after production (Group A) with those exposed only to visible light for two months, slight decreases in properties were noted. In some combinations, such as PLA_30%, BioCop_20%, and BioCop_30%, significant decreases in flexural modulus (approximately 39%, 29%, and 49%, respectively) were observed. This difference arises from structural weakening due to the presence of defects, such as voids, found within the samples, resulting from the production process. However, there is a need to produce new compositions to avoid the presence of such defects.

4. Conclusions

This study emerged from the need to create biodegradable substrates for algae cultivation, aimed at enhancing carbon capture. Various composite combinations, produced with different polymers and algae percentages, were evaluated for degradation capacity. Through laboratory tests using seawater, we observed:

- Algae-infused materials, particularly those with higher algae content, showed greater mass loss. Notably, PLA- and BioCop-based composites experienced the most sub-stantial weight loss after two months of seawater exposure.
- Scanning Electron Microscopy (SEM) analysis indicated that an increase in algae content within BioCop compositions led to both surface and internal breakdown when immersed in seawater, especially for BioCop_30.
- Chemical analysis through FTIR of the BioCop compositions revealed that while algae addition did not alter chemical bonds, it weakened the peak intensity, indicating bond weakening. Comparison of FTIR spectra before and after seawater exposure showed bond weakening or disappearance due to material degradation.
- Flexural tests further demonstrated that PLA compositions exhibited higher mechanical resistance than other combinations, while increased algae content reduced flexural

strength across all samples. Two months of seawater immersion contributed to a further reduction in flexural strength due to structural degradation.

The study concludes that developing substrates for algae cultivation using biodegradable polymers combined with algae waste holds substantial potential. This approach not only supports algae growth and facilitates their settling on the ocean floor without causing environmental harm, but it also increases sustainability by reducing plastic consumption. Furthermore, it accelerates degradation, aligning with broader ecological goals.

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Conflicts of Interest: Carlos Mota is employed by Beyond Composite. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

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