Evaluating Seaweed as a Sustainable Solution: A Path Toward Eco-Friendly Bioplastics and Biofuels

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Abstract

Sustainable materials gain importance as material production increases carbon emissions, driving climate change. Seaweed is a promising material that holds many sustainable end uses–such as biofuel creation and alternatives to single-use plastics. A main challenge for implementing sustainable materials, like seaweed, is their cost and performance compared to traditional materials. This study focuses on which seaweed products are most sustainable to produce, use, and dispose of compared to traditional materials. The study also analyzes the cost of production, the price for customers, and the consumers' use of the products. Through a literature review, eleven seaweed products are identified as more sustainable compared to their traditional counterparts. These products were ranked using a custom framework that considered the sustainable materials' CO_2 emissions, disposal methods, production costs, and marketability compared to current traditional products. Bioplastics were identified as the most promising material for further commercialization, as compared to seaweed-based biofuels and bio-papers. Although current uses for seaweed are not as economically feasible as other current market products, a larger scale of production can significantly lower the costs of these more eco-friendly alternatives.

Introduction

In 2018, the total municipal solid waste (MSW) generated in the United States amounted to 292.4 million tons, averaging 4.9 pounds per person daily.[1] Out of this, around 69 million tons were recycled, while 25 million tons were composted. This still leaves about 198 million tons of untreated waste.[1] The growing amount of waste in the world poses a danger to the future of the Earth.

Sustainable materials can be used to lower or minimize environmental impact, reduce the use of non-renewable resources, such as coal and petroleum, and promote long-term environmental balance. These materials are typically biodegradable, recyclable, or derived from renewable resources, making them crucial for addressing environmental issues such as climate change, resource depletion, and waste overgeneration.[2] As many industries look toward more sustainable practices, seaweed has emerged as a highly promising base for sustainable materials due to its production scalability and minimal environmental footprint during farming and material processing.[3]

While many types of seaweed can produce sustainable materials, brown seaweed (Phaeophyceae) and its end-product materials offer several advantages over traditional petroleum-based materials. Unlike conventional crops like corn, which can be used for sustainable materials, seaweed does not require fresh water, fertilizers, or large areas of arable land for cultivation.[3] It grows in marine saltwater environments, often in abundance, and its rapid growth rate makes it an attractive candidate for large-scale production.

Furthermore, seaweed cultivation actively contributes to carbon sequestration and can aid in mitigating ocean acidification by absorbing carbon dioxide.[4] These environmental benefits and versatility have made seaweed a key focus of sustainable material research.

The global production of brown seaweed is substantial, with an estimated 30 million tons harvested annually, primarily in Asia. [5] [6] Despite the promise of seaweed, production costs remain a significant challenge. The cost of cultivating seaweed can vary widely depending on the species, location, and farming method, but scaling up production to meet growing demand will require technological advancements and cost reductions.[7]

The potential for seaweed-based products extends across a wide range of markets. In the food industry, seaweed has long been used as a nutrient-rich ingredient, but its application is now expanding to packaging, biofuels, and even textiles.

For instance, products like seaweed-based polymers, biofuels, and packaging are gaining attention for their eco-friendly attributes, offering lower carbon footprints, biodegradability, and reduced reliance on fossil fuels. The cosmetic industry also uses seaweed to incorporate its antioxidant and moisturizing properties in skincare products, while textiles made from seaweed fibers offer a sustainable alternative to synthetic fabrics.[8] [9]

These varied applications highlight the versatility of seaweed and its potential to disrupt industries that heavily rely on unsustainable materials. The environmental impact, economic cost, and consumer satisfaction can be assessed for these applications to identify the most promising materials and applications to bring to market.

Seaweed's potential for scalability makes it an ideal candidate for further research and commercialization in various markets.[10] This paper explores existing and emerging uses of seaweed as a sustainable material in order to identify the most promising applications for widespread commercial use. By investigating seaweed's environmental and economic viability, this paper aims to contribute to the growing area of sustainable materials and highlight where seaweed could make the most significant impact.

Methods

This study developed a framework to evaluate the sustainability, production costs, and marketability of seaweed-based products, such as seaweed polymers and biofuels, in comparison to traditional materials. The goal was to identify seaweed products that are both more eco-friendly and cost-effective while still being easily adopted by consumers. The methods involved conducting a detailed literature review, creating a rating system to compare different products, and applying this system to various seaweed-based products to determine which ones show the most potential for commercialization. This evaluation framework considered key factors such as environmental impact, production costs, and how easily consumers would adapt to these products.

Literature Review

A comprehensive review of scientific articles, environmental reports, government publications, and company websites was conducted to collect data on how different material characteristics–such as sustainability, cost, and consumer adoption–are evaluated in existing research. Important sustainability metrics identified from the literature included carbon footprint, energy consumption, waste generation, costs, and biodegradability. This review helped create clear guidelines for comparing the environmental performance of seaweed-based products with conventional materials, such as petroleum-based plastics or fossil fuels.

Framework Development

Using insights from the literature review, of articles and life cycle analyses a scoring system was designed to evaluate seaweed-based products across three main categories: sustainability, production cost, and marketability. The system's ratings are from 1 to 5, from lowest to highest.

1. Sustainability: This category examines how environmentally friendly the product is during production, use, and disposal. Factors such as lower carbon emissions, reduced energy use, and biodegradability were included. Products that had less environmental impact compared to current materials were rated higher. Rankings for sustainability were split between CO_2 emissions and ease of recycling and were weighed evenly to make the sustainability score.

Table 1.

Descriptions of CO_2 emission criteria scores.

Score	**CO_2 Emission Criteria**
1	The same CO_2 emissions, or more, for the algae-based product
2	1-39% Less CO_2 emissions for the algae-based product
3	40-69% Less CO_2 emissions for the algae-based product
4	70-99% Less CO_2 emissions for the algae-based product
5	Carbon Neutral or negative emissions

Table 2.

Descriptions of waste management criteria

Score	**Waste Management Criteria** [11]
1	Non-recyclable (Sent to landfill or to be incinerated without energy collection
2	Recovery (combustion, gasification, anaerobic digestion, or landfill gas recovery)
3	Recyclable (sent to be recycled or composted industrially)
4	Reuse (repairable, washable, intended for several uses, or compostable at home)

5	Prevention (Cutting out single-use products)

2. Cost: This section focused on the cost of producing seaweed products, including raw materials, manufacturing, and market price. Seaweed products were rated higher if their production costs were close to those of conventional materials.

Table 3.

Description of Cost Criteria score.

Score	**Cost Criteria**
1	The market price is greater than 300% of the traditional product's cost
2	The market price is 201-300% greater than the traditional product's cost
3	The market price is 100-200% greater than the traditional product's cost
4	The market price is 51-100% greater than the traditional product's cost
5	The market price less than or is within 50% of the traditional product's cost

3. Marketability: This category assessed how likely consumers are to adopt seaweed-based products. Factors such as ease of use, how well the product fits into consumers' lives, and whether it meets the growing demand for sustainable options were considered. Products were rated higher based on the ease of implementation into daily life. For example, although the paper straw is far more sustainable than its plastic counterpart, it is widely disliked for its tendency to turn mushy and lose structural integrity while in use.[12] Though more sustainable, the paper straw would score low on the marketability criteria.

Table 4.

Descriptions of Marketability Criteria

Score	**Marketability Criteria**
1	The product is difficult to use or does not fit into consumers'

	everyday routines or lifestyles.
2	Somewhat challenging to use or integrate into everyday life; consumers may need extra motivation or education to switch to this product.
3	The product fits into everyday life reasonably well, though it may require minor behavior changes or adaptations from consumers.
4	Easy to use and integrates seamlessly into consumers' daily routines with minimal behavior change required.
5	The product is highly convenient, familiar, and fits perfectly into consumers' lives without requiring any behavior change.

By applying this framework, the study aimed to identify the seaweed-based products with the highest potential for commercialization, balancing environmental benefits, cost-effectiveness, and consumer appeal.

Evaluation of Seaweed Products

After creating the framework, the next step was to apply it to selected seaweed-based products and materials. Each product was rated in all three categories using data from existing research and predictions about how consumers would respond. The importance of each category was weighted, with sustainability making up 30% of the score, costs 35%, and marketability 35%. This reflects the growing focus on environmental impact while still considering the importance of affordability and consumer demand. Using this framework, some seaweed-based products were identified as the most promising for further development and commercialization. This allowed the identification of the product/source/material that is the most promising for future investment and growth.

Results

Scores were based on data points collected from a literature review of research papers, company websites, and articles.

Table 5.

Summary of CO_2 emissions from the production of algae-based and traditional products[13–18] and their derived CO_2 score.

Product	Base Material	Carbon dioxide emission of algae-based product (kg carbon/ kg	Carbon emission of traditional products (kg	CO_2 score

		product)	carbon/ kg material)	
Cups	Algae Bioplastic	2.2-3.7 kg CO_2/kg plastic	4.523-6 CO_2/kg plastic	**3**
Straws	Algae Bioplastic	2.2-3.7 kg CO_2/kg plastic	4.523-6 CO_2/kg plastic	**3**
Silverware	Algae Bioplastic	2.2-3.7 kg CO_2/kg plastic	4.523-6 CO_2/kg plastic	**3**
Bottles	Algae Bioplastic	2.2-3.7 kg CO_2/kg plastic	4.523-6 CO_2/kg plastic	**3**
Food Wrapper Coating	Algae Bioplastic	2.2-3.7 kg CO_2/kg plastic	4.523-6 CO_2/kg plastic	**3**
Paper	Algae-based papers	.25-2.5 kg CO_2 /Kg paper	1.047kg CO2/kg paper	**1**
Paper bags	Algae-based papers	.25-2.5 kg CO_2 /Kg paper bag	4.523-6 CO2/kg plastic bag	**4**
Paper containers	Algae-based papers	.25-2.5 kg CO_2 /Kg paper container	4.523-6 CO_2/kg plastic container	**4**
Biodiesel	Algae Biofuel	Approx. 0	2.6 CO_2/kg	**5**
Bioethanol	Algae Biofuel	Approx. 0	1.1kg CO_2/kg	**5**
Biogasoline	Algae Biofuel	Approx. 0	2.34 kg CO_2/kg	**5**

The CO_2 Score was determined based on how much less carbon dioxide the seaweed-based products emitted than traditional materials. Products were given higher scores if they significantly reduced CO2 emissions during production, use, and disposal compared to their current market counterparts.

Most seaweed-based products scored well in this category, with reductions in CO_2 emissions ranging from 40% to 99%. The biofuel products even approached carbon neutrality due to the CO_2 absorption during seaweed growth. [19]

Most seaweed-based materials received scores between 3 and 5, reflecting substantial reductions in carbon emissions, thus contributing positively to the overall sustainability score. Although there are some differences in the CO_2 emissions of the different algae-based bioplastics due to the production stage, the newness of the material alongside the small-scale production results in a similar yield of carbon emissions. Algae-based paper received the lowest carbon score of 1 due to its limited production scale, which leads to higher emissions per unit produced. Since traditional paper already has low carbon emissions, algae-based paper would need to approach carbon neutrality to be competitive.

Table 6.

Algae-based product disposal methods[20,21] and derived waste score.

Product	**Base Material**	**Disposal Process**	**Waste score**
Cups	Algae Bioplastic	Industrial composting	3
Straws	Algae Bioplastic	Industrial composting	3
Silverware	Algae Bioplastic	Industrial composting	3
Bottles	Algae Bioplastic	Industrial composting	3
Food Wrapper Coating	Algae Bioplastic	Industrial composting	3
Paper	Algae-based papers	Biodegrades within weeks	4
Paper bags	Algae-based papers	Biodegrades within weeks	4
Paper containers	Algae-based papers	Biodegrades within weeks	4
Biodiesel	Algae Biofuel	used as fuel	N/A
Bioethanol	Algae Biofuel	used as fuel	N/A
Biogasoline	Algae Biofuel	used as fuel	N/A

The waste score evaluated the end-of-life sustainability of the products, such as whether they were recyclable, compostable, or reusable. Products that were non-recyclable or required energy-intensive waste recovery received lower scores, while those that could be composted at home or prevented waste altogether scored the highest.

All products scored a three or higher, reflecting their recyclability or industrial compostability, although, no products received a score of five because of their single-use nature.

Currently, seaweed bioplastic needs to be industrially composted, giving all the bioplastic scores of three.[22] The paper products scored near-perfect due to their ability to biodegrade within weeks but did not receive a five because of their lack of reusability. Biofuels cannot receive waste scores because they are combusted when used as fuel. This results in carbon emissions which have already been analyzed.

Table 7.

Cost of algae-based products compared to traditional products[23–41] with derived cost score.

Product	Base Material	Market Price($/unit)	Cost of the traditional product ($/unit) (plastic if applicable)	Cost Score
Cups	Algae Bioplastic	.16-.30$/cup	.03-.06 $/unit	1
Straws	Algae Bioplastic	.05-.10$/straw	.02-.04$/unit	2
Silverware	Algae Bioplastic	.10-.20$/untensil	.06-.10$/unit	3
Bottles	Algae Bioplastic	.47-.7$/unit	.26-.35$/unit	3
Food Wrapper Coating	Algae Bioplastic	.44-1.10$/kg	.80-1.60$/kg	5
Paper	Algae-based papers	.1875-.385$/sheet	.01-.03$/sheet (printer paper)	1
Paper bags	Algae-based papers	.50-1.5$/bag	.03-.30 $/unit	1
Paper containers	Algae-based papers	.2-.5$/unit	.05-.34$/unit	2
Biodiesel	Algae Biofuel	2.22-5.45/ gallon	3.584$/gallon	2
Bioethanol	Algae Biofuel	2.24-3.73$/gallon	1.57$/gallon	3
Biogasoline	Algae Biofuel	5.70-13.25/gallon	3.205$/gallon	2

The cost score reflected how economically competitive seaweed-based products were compared to traditional materials. Products were evaluated based on their market price relative to conventional alternatives, with higher scores awarded to products within 50% of the traditional product’s cost.

The results showed a mix of scores, with some products being significantly more expensive due to the high cost of seaweed cultivation and processing. These productsreceived scores of 1 or 2. However, scoring a 5 was the food wrapper coating, the only product to score above a 3.

A majority of the products scored low due to their novelty, leading to smaller-scale production and increasing costs. The prices of paper products were priced at five times the cost of the traditional product. Though the cost scores were relatively low for most products, in the future, if the production scale for the products can increase, it would result in a lower-end market price.

Marketability Score

The marketability score assessed how easily consumers would adopt seaweed-based products based on their usability and fit into daily life. Products that were easy to use, familiar, or seamlessly integrated into existing consumer habits scored the highest.

Seaweed-based plastics scored well in this category, indicating that they are relatively easy to implement into consumers' growing demand for sustainable products. The seaweed-based plastics all scored 5 because of their almost identical nature to traditional plastic in texture and strength.

Those that required significant changes in behavior or were unfamiliar to consumers received lower scores, such as the biofuels. The biofuels received a score of 2 because of their lower energy density, which would result in larger fuel tanks to accommodate current needs.[42] Algae-based papers received middle-range scores of 2-4 and 3 due to their lack of structural strength compared to that of normal paper.[43]

Weighted Score

Table 8.

Overall Scoring table for all 11 identified products.

Base Material	**Product**	**CO_2 score**	**Waste score**	**Sustainability Score (Avg. of CO_2 and Waste Score)**	**Cost Score**	**Marketability Score**	**Weighted Score**	**Average by base material**
	Cups	3	3	3	1	5	3	
	Straws	3	3	3	2	5	3.35	
Algae Bioplastic	Silverware	3	3	3	3	5	3.7	**3.63**
	Bottles	3	3	3	3	5	3.7	

	Food Wrapper Coating	3	3	3	5	5	4.4	
	paper	1	4	2.5	1	4	2.5	**2.80**
Algae-based papers	Paper bags	4	4	4	1	4	2.95	
	Paper containers	4	4	4	2	3	2.95	
	Biodiesel	5	N/A	5	2	2	2.9	**3.02**
Algae Biofuel	Bioethanol	5	N/A	5	3	2	3.25	
	Biogasoline	5	N/A	5	2	2	2.9	

The final weighted score was calculated using the following formula:

Total score = (sustainability score * 0.3) + (cost * 0.35) + (marketability * 0.35)

This formula balanced environmental impact, cost-effectiveness, and market readiness, reflecting the importance of all three factors. Products with high sustainability scores but poor cost competitiveness or marketability tended to score lower overall. In contrast, those who balanced sustainability with economic feasibility and ease of adoption scored the highest. The criteria that created the most significant difference in the overall score was the cost.

The algae-based coating for food wrappers ranked the highest of the 11 products, with a weighted score of 4.4. The product that scored the lowest was the paper, with a weighted score of 2.5. Per material, in order, the algae-based plastic scored the highest overall, with biofuel second and paper last.

Discussion

This study showed that seaweed-based products offer promising sustainability improvements compared to traditional materials, particularly in reducing carbon emissions and waste. However, cost competitiveness remains a significant hurdle for these products to achieve widespread adoption. For example, while offering lower CO_2 emissions (approximately 40% to 60% less than conventional plastics), seaweed-based bioplastics are currently 2 to 5 times more expensive than traditional plastics, limiting their marketability despite their environmental benefits.

Cost is a critical factor in the development and success of bioplastics. For seaweed-based bioplastics to become more viable alternatives, their production costs need to decrease significantly. This reduction could be achieved through economies of scale, as production volumes increase, the cost per unit is expected to fall. This has been observed in other industries where innovations and scaling production processes reduce costs. For instance, as seaweed farming methods become more efficient and automated, the initial high costs associated with cultivating and processing seaweed should decrease. This is especially important for bioplastics, as their current higher costs make it challenging for consumers and businesses to switch from cheaper, petroleum-based plastics.

The higher price of these materials makes them less accessible to mainstream consumers, slowing their adoption. This could be mitigated by government policies, such as banning traditional plastics or making them more expensive through taxes, to make seaweed-based products more competitive. Additionally, if governments or organizations invest in infrastructure to increase seaweed production and provide subsidies for bioplastics, this could further reduce costs, making them more affordable for consumers.

In the case of biofuels, seaweed-based biodiesel, bioethanol, and biogasoline show significant promise in reducing carbon emissions, often approaching carbon neutrality due to the CO_2 absorbed by seaweed during cultivation. However, seaweed-based biofuels still face stiff competition from electric vehicles and other renewable energy sources like solar and wind power. Seaweed-based biofuels could be mixed with traditional fuels in a blend, allowing them to be used with existing fuel infrastructure. This makes them more attractive in the short term compared to transitioning to electric vehicles, which require new infrastructure.

The products with the highest weighted scores, such as the algae-based food wrapper coating (score of 4.4), are particularly promising. This product combines high sustainability and marketability with cost competitiveness. The higher-scoring products are already being sold in niche markets, but their scalability remains a challenge. The seaweed bioplastic market, for example, is growing, but it is still a fraction of the global plastics market, which is valued at over $600 billion annually.[44] The environmental benefits could be significant if the seaweed bioplastic market grows and costs are reduced.

Reducing the carbon footprint of materials like bioplastics is crucial for sustainability. The lower CO_2 emissions associated with seaweed-based products scale well with increased production and market share. If seaweed-based products become more widespread, the potential CO_2 savings would grow exponentially, amplifying their environmental benefits. For example, bioplastic has a carbon footprint up to 42 percent less than that of traditional plastic, not even to mention the carbon sequestered from the algae growth.[45] If seaweed-based products capture a larger share of the market, the environmental impact could be transformative.

While seaweed-based products present many environmental advantages, the feasibility of bringing them to market depends on overcoming cost barriers and improving consumer awareness. Governments, businesses, and consumers must collaborate to foster demand for sustainable materials. Additionally, while there are limitations to single-use products (even sustainable ones), these products remain essential for consumers and are unlikely to disappear from the market anytime soon. Therefore, making these products more sustainable is crucial to reducing environmental harm without disrupting consumer habits.

Conclusion

This study highlighted the significant potential of seaweed-based products to contribute to sustainable material solutions. By assessing seaweed products across multiple dimensions–namely CO2 emissions, waste generation, production costs, and marketability–it became evident that seaweed-based bioplastics, biofuels, and packaging materials offer significant environmental benefits, particularly in reducing carbon emissions and waste. However, the economic feasibility of these products remains a challenge, with many being considerably more expensive than their traditional counterparts. The seaweed-based food wrapper coating, which emerged as the top-performing product in terms of sustainability and marketability, showcases the promise of seaweed-based materials but also underscores the need for cost-reduction strategies to achieve widespread adoption.

Future research should focus on improving the scalability and cost-efficiency of seaweed cultivation and bioproduct manufacturing processes. Innovations in seaweed farming techniques, such as automation and energy-efficient processing, will be key to reducing production costs. Additionally, exploring new market applications for seaweed-based materials, alongside policy interventions to limit the use of traditional plastics, could accelerate their adoption. As the demand for sustainable materials continues to grow, seaweed-based products hold the potential to make a significant impact, not only in reducing the global carbon footprint but also in transforming various industries dependent on fossil-fuel-based products.

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