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A Comparison of Multiple Macroalgae Cultivation Systems and End-Use Strategies of *Saccharina latissima* and *Gracilaria tikvahiae* Based on Techno-Economic Analysis and Life Cycle Assessment

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Abstract: Macroalgae can be processed into various products with the potential to substitute land-based crops; their cultivation can bioextract nutrients from coastal waters. This study investigated the economic cost and environmental impacts of multiple seaweed cultivation platforms, cultivation strategies, and processing/end-use strategies through techno-economic analysis (TEA) and life cycle assessment (LCA) with a focus on *Saccharina latissima* and *Gracilaria tikvahiae*. Cultivation platforms included single-layer longline, dual-layer longline, single-layer strip, and dual-layer strip systems. Processing/end-use products included seaweed to biofuel, dried sea vegetables, marketable commercial fertilizer, and animal feed. Economic and environmental costs decreased with dual-layer and strip cultivation systems. Cultivation costs were highest using the common single-layer longline system (\$4.44 kg^{-1} dry weight (dw) *S. latissima* and \$6.73 kg^{-1} dw *G. tikvahiae* when cultivated on rotation). The use of the dual-layer strip system reduced cultivation costs to \$2.19 kg^{-1} dw for *S. latissima* and \$3.43 kg^{-1} dw for *G. tikvahiae*. Seaweed drying was the major contributor to economic and environmental costs for macroalgae processing. Yet, all scenarios achieved environmental benefits for marine eutrophication. The best environmental performance was observed when biomass was processed to dry sea vegetables, assuming the offset of land-based vegetable production, or used as biofeedstock for anaerobic digestion for combined heat and power.

Keywords: macroalgae; cultivation methods; life cycle assessment; techno-economic assessment; *Saccharina latissima*; *Gracilaria tikvahiae*

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1. Introduction

Our society currently faces challenges of food, energy, and water security and will continue to do so in the coming decades [1–4]. These challenges are associated with rapid global human population growth and increasing resource demand [2,5,6]. According to a recent United Nations report, the world's population is expected to reach 8.5 billion by 2030 and 9.7 billion by 2050 [7]. To meet this rise in food and energy demand, increased land-based agriculture occupation will be required, with associated demands for nutrients, clean water, and energy resources.

Our limited terrestrial resources are overburdened. Sea-based biomass alternatives such as macroalgae aquaculture provide a promising approach to improve our ability to meet future demands for food, feed, fertilizers, and biofeedstock for a variety of products [8–11]. In contrast to land-based fertilized agriculture, macroalgae extracts existing inorganic nutrients including nitrogen and phosphorus from the ocean during growth, thereby reducing, rather than increasing, both chemical fertilizer requirements for biomass and marine eutrophication potential [12,13]. According to the FAO (2018), global seaweed production exceeded 30 million metric tons of fresh weight in 2016; more than 99% of seaweed was still produced by low-technology and high-manual-labor means in Asian/Pacific Rim countries [14]. Even though seaweed in North America only accounted for less than 0.1% of global seaweed production, seaweed cultivation is gaining increased interest with aquaculture technology and seaweed product development; the size of the seaweed market is expanding rapidly [14,15].

Saccharina latissima (*S. latissima*) and *Gracilaria tikvahiae* (*G. tikvahiae*) are edible seaweeds that have been successfully cultivated in northern American and European coastlines with relatively high growth rates and well-described life cycles [16–18]. *S. latissima* is a brown algal (Phaeophyceae) species, which had the highest world aquaculture production among all aquatic algae in 2018 (greater than 11.4 million tons of fresh weight; [19]). *S. latissima* is a winter crop that can be deployed on global northern coastlines from mid-September to early February, and harvested from May through June in northern Europe and North America [18,20,21]. *G. tikvahiae* is a red algal (Rhodophyta) species with the third-highest world aquaculture production in 2018 (>3.4 million tons of fresh weight [19]). Kim et al. (2014) and Johnson et al. (2014) reported that the *G. tikvahiae* growing season is from July through October in Long Island Sound (CT, U.S.) and from July through November in the Bronx River Estuary (NY, U.S.). Samocha et al. (2015) deployed *G. tikvahiae* on the Texas coast (U.S.) from August through October [22–24]. Notably, both *S. latissima* and *G. tikvahiae* have been successfully cultivated in Long Island Sound (CT, U.S.) and the Bronx River Estuary (NY, U.S.), indicating that the rotational aquaculture of both species is feasible [23–25].

Net cultivation and line cultivation platforms, including off-bottom submerged hanging line and longline methods, are commonly used globally for macroalgae aquaculture [12,26,27]. The popularity of these platforms can be attributed to low installation and maintenance costs, and ease of use [28]. Other offshore cultivation platforms include floating raft cultivation, ring cultivation, and rock-based farming [12]. Dual-layer cultivation was designed by Sharma et al. (2018) and van Oirschot et al. (2017) for *S. latissima* aquaculture in Europe [29,30], with an increased biomass yield compared to the single-layer configuration. In addition, van Oirschot et al. (2017) modified the traditional longline system by replacing the longline with a "cultivation strip" infrastructure. In this system, each strip consisted of four longlines deployed in parallel, with 1 m of space between longlines. In North America, the traditional longline system is the dominant cultivation platform; the use of other cultivation platforms remains limited [21,24,25,30,31].

Seaweed has long been consumed as sea vegetables in Asian countries, and the market of edible seaweed in the U.S. and European countries is expanding [15,32,33]. Red seaweeds, including *Gracilaria*, are also the main sources of commercial agar extraction [34]. Other common uses include animal feed and fertilizer [33,35–38]. Additionally, seaweeds have been investigated as bioenergy feedstocks to produce biogas considering their rapid growth rate, high biomass yield, and non-competitive nature of macroalgae for arable land with terrestrial crops [28,39–46]. However, limited research has considered the use of cultivated macroalgae as high-value seaweed fertilizer or has compared the environmental impacts of edible macroalgae versus land-based vegetables (e.g., lettuce).

Existing studies that compare trade-offs of cultivation platforms, cultivation strategies, and processing/end-use products are limited in scope. The currently available data facilitates comparison between platforms, processing, and end-use products with side-by-side techno-economic analysis (TEA) and life cycle assessment (LCA) [39,46–50]. Improved synthesis information is needed to support decision making by seaweed growers to best balance environmental sustainability, marketing of their products, and optimizing revenue streams while reducing capital and operational costs. In this study, we focus on macroalgae cultivation platforms grounded in the common longline technology used globally, including a single longline platform, a dual-layer longline platform, and a "cultivation strip" platform. We evaluate both widely used and emerging end-use macroalgae products. These include sea vegetables, biofeedstock for combined heat and power via anaerobic digestion, marketable seaweed fertilizer, and animal feed. The objective of this study is to investigate trade-offs between macroalgae cultivation platforms and end-use strategies on both environmental and economic performance, with a particular focus on the commonly cultivated seaweed species *S. latissima* and *G. tikvahiae*.

2. Methods

2.1. Seaweed Cultivation Platforms

For scalability, a unit (one-hectare) aquaculture site (250 m long and 40 m wide) was used for modeling purposes, with a lifespan of 25 years to allow for the reuse and replacement of cultivation platform infrastructure over time [30,39,50]. Two cultivation strategies were modeled, including (C1) a singular annual grow-out of *S. latissima* and (C2) a singular annual grow-out each of *S. latissima* and *G. tikvahiae* on rotation sharing a common seaweed cultivation platform. Cultivation platforms modeled in this study are reported in Figure 1 as platform configurations S1 through S4. These include longlines in either a single-layer (S1) or dual-layer (S2) platform and cultivation strips in either a single-layer (S3) or dual-layer (S4) platform. The framework for each cultivation platform is presented in Figure 2 and includes ten 248 m spans of longlines or cultivation strips set four meters from one another on the center [51]. For dual-layer platforms, a second longline or cultivation strip on each run was placed two meters below the top longline or cultivation strip.

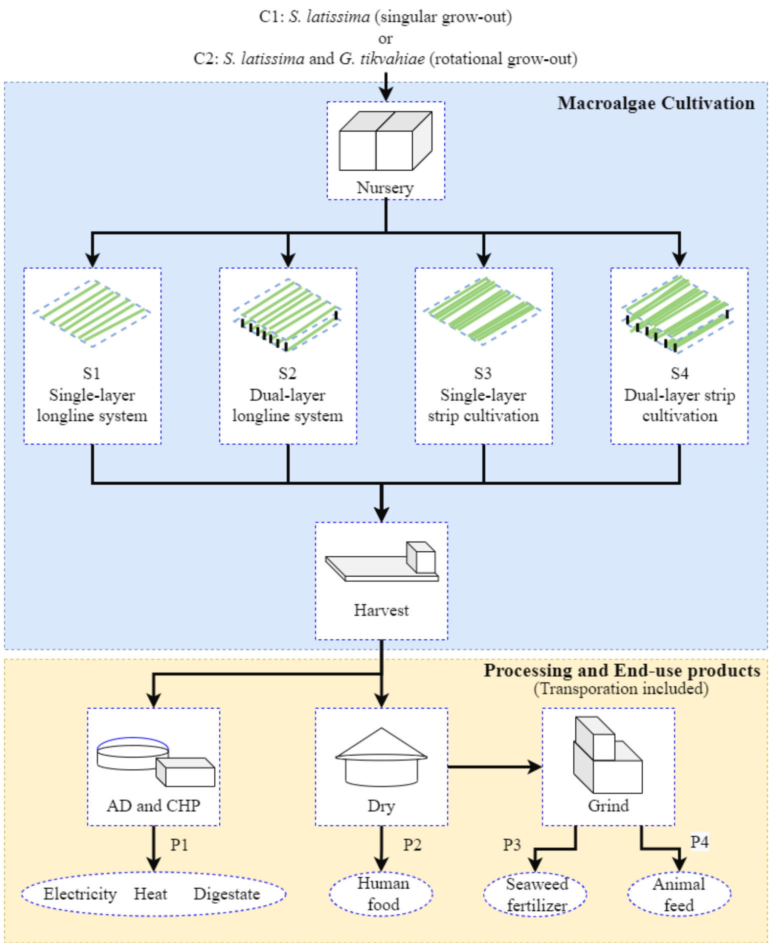

Figure 1. Schematic representation of processes considered in the techno-economic analysis and life cycle assessment. Thirty-two different scenarios were established and evaluated in total, including four cultivation platforms (S1–S4), two cultivation strategies (either (C1) singular grow-out of *S. latissima* or (C2) rotational grow-out of *S. latissima* and *G. tikvahiae*), and four seaweed products (P1–P4). AD: anaerobic digester; CHP: combined heat and power gas engine.

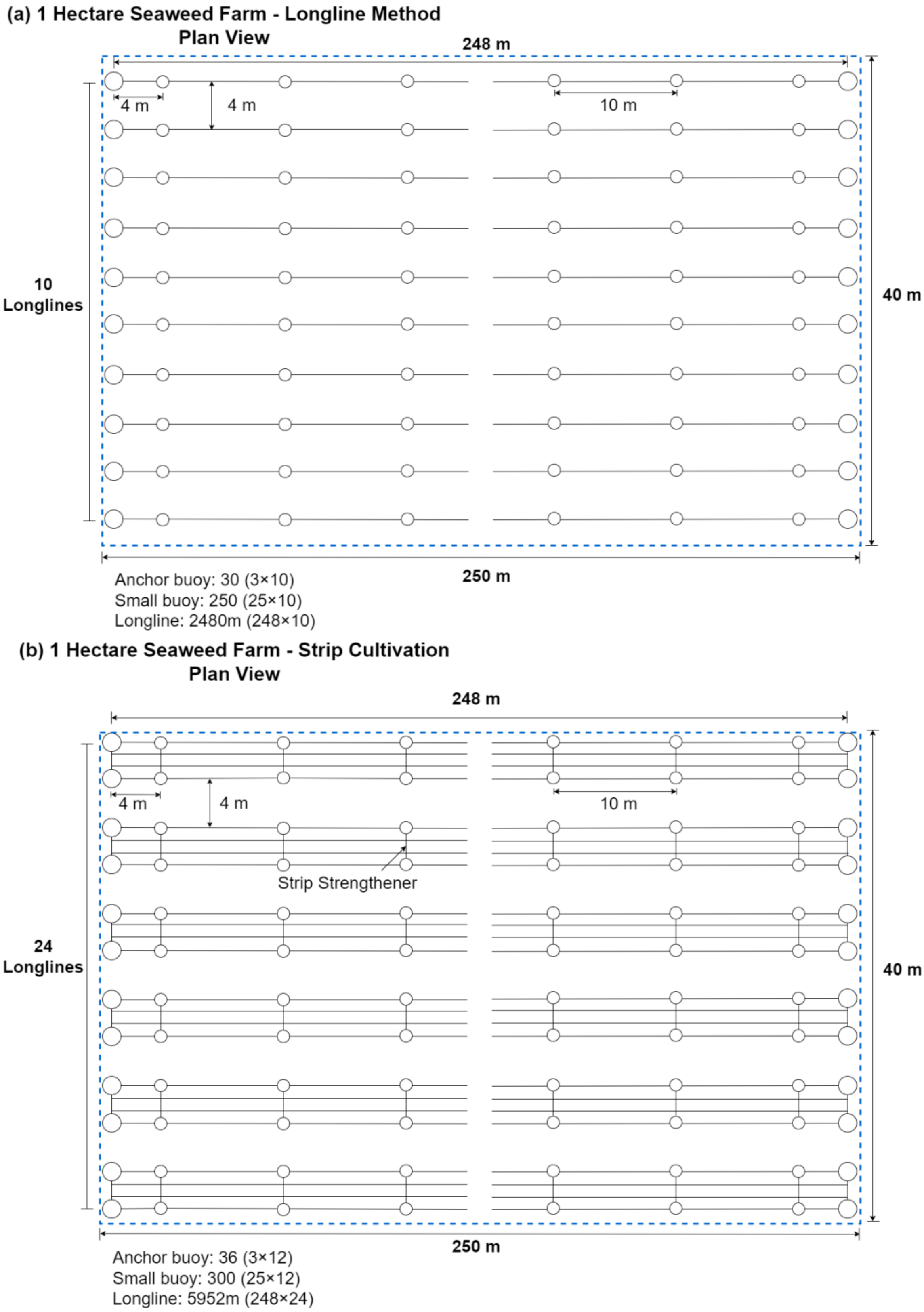

Figure 2. *Cont.*

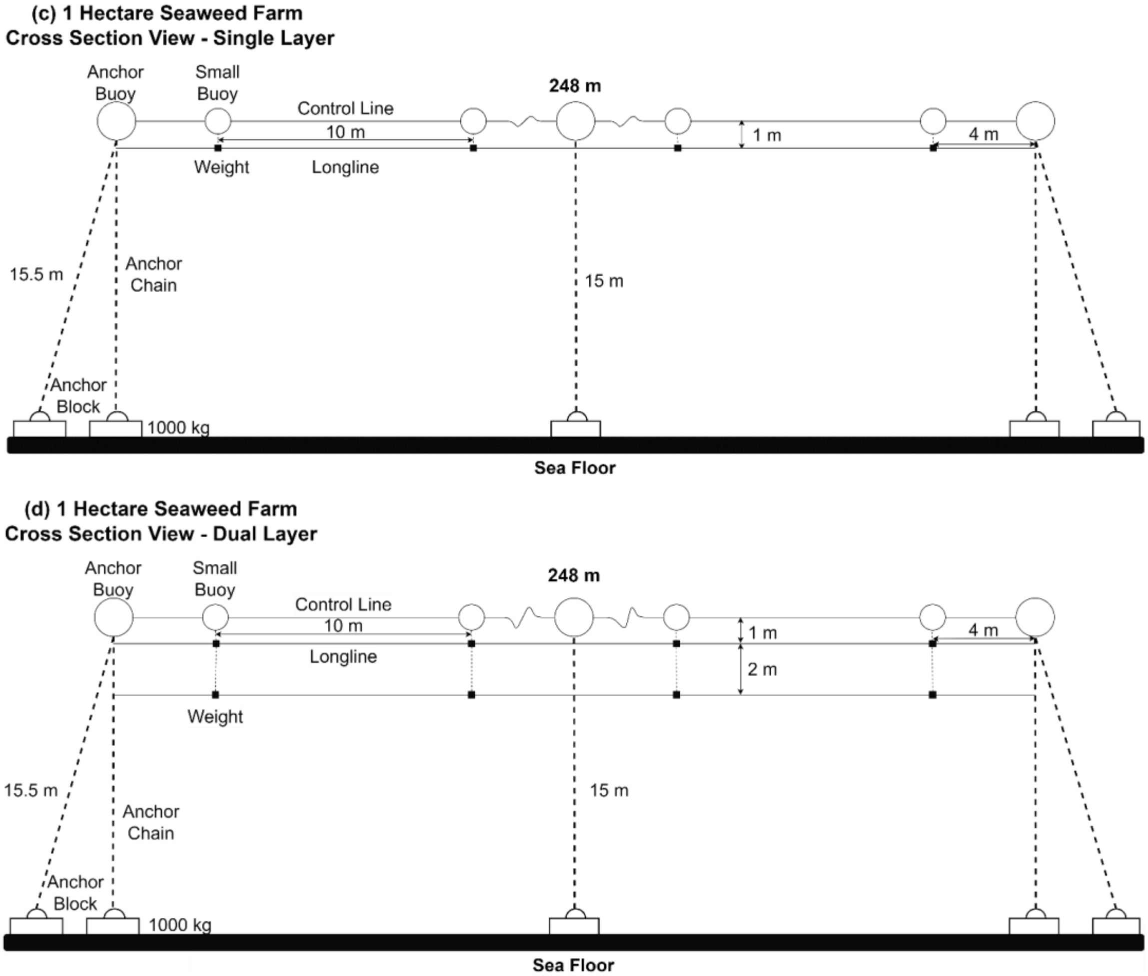

Figure 2. Plan and section views of modeled one-hectare seaweed aquaculture site configurations. Site configuration details are provided for both (**a**) longline cultivation platforms and (**b**) strip cultivation platforms. Cross-sections show configurations of the (**c**) single-layer cultivation platforms and (**d**) dual-layer cultivation platforms. Details of the materials used for modeled site configurations are available in Table S10.

2.2. Seaweed Biomass Production and Utilization

S. latissima and *G. tikvahiae* biomass production characteristics were acquired from the published literature and are presented in Table S1. Median values were used for the TEA and LCA, while the reported range was used for sensitivity analysis of the models. Consistent with prior reports, biomass yield of the upper longlines or cultivation strips on dual-layer platforms was assumed to be the same as the single-layer platforms, while biomass yield on the lower longline or cultivation strips was assumed to be 50% of that of the upper layer [30]. While the difference has previously been attributed to shading from the upper layer of seaweed growth, it is almost certain that the dissipation of photon flux with depth in the water column and reduced nutrient availability with greater biomass density also affect growth rates on the deeper line or strip in dual-layer platforms [30].

This study explored four seaweed product alternatives, including dried food, feed, fertilizer, and bioenergy, as reported in Figure 1. Bioenergy (product P1) was assumed to be produced off-site via the anaerobic co-digestion of fresh seaweed biomass in an existing anaerobic digester (i.e., livestock waste or food waste anaerobic digester). Our model used produced methane to generate heat and electricity in a combined heat and power biogas engine. All heat generated was assumed to balance the heating requirement of the anaerobic digester [46]. Even though excess heat is common, especially in the summer months, and could be used for other purposes such as heating water or attached infrastructure, its use is design-specific, and thus we did not consider this potential in the model. Stabilized anaerobic digestion byproducts were used in the model to offset chemical fertilizers for land-based crops. For P2, harvested seaweed was dried and sold as sea vegetables. We assumed a 1:1 substitution rate of cultivated seaweed for lettuce based on solid contents. For P3 and P4, seaweed was dried and milled before selling as seaweed fertilizer or animal feed [37,52].

Macroalgae cultivation and processing modeled in this study were assumed to occur on the northeastern coast of the U.S., while the results can also provide information for the macroalgae aquaculture and usage in extended coastal areas, especially in North America and Europe.

2.3. Techno-Economic Analysis

The capital costs of seaweed aquaculture site infrastructure, operation and maintenance (O&M) costs of the nursery, sea farm, processing and transportation, and economic value of produced seaweed as a function of the end-use product were included in the study. A 24-foot working boat was assumed for all cultivation scenarios. Cost data, including material and energy usage, costs, and economic values for various seaweed products, were acquired from the published literature, interviews with macroalgae farmers and experts in Maine, and retail prices of required components where necessary [15,30,46,49,53,54] (a list of the online resources is available in Table S10). The annual insurance cost was assumed to be 3% of the capital cost; annual barge maintenance costs were assumed to be 5% of the barge price. Buoy maintenance costs were assumed to be 1% of the capital cost per grow-out; maintenance costs of other equipment were assumed to total 5% of the capital costs per grow-out [49]. This study assumed the purchase of seeded sporeling line from an established nursery supplying multiple aquaculture operations. The capital costs of setting up a nursery have previously been reported to be negligible versus the O&M costs of seeded spore line production over a nursery lifespan, and thus were not included in this study [55].

Seaweed processing costs included the capital and O&M costs of a seaweed dryer and hammermill. When used as sea vegetables (P2), seaweed was assumed to be dried at or near the aquaculture site before transportation. When sold as fertilizer or animal feed (P3 or P4), seaweed was assumed to be dried and milled before transportation. When used as biofuel feedstock (P1), we assumed transport of fresh seaweed biomass to an existing off-site anaerobic digester (AD) to produce biogas as described above; thus, capital costs of the AD and combined heat and power (CHP) system were not considered in this study. The efficiency of the CHP system for heat and electricity production was assumed to be 35% [56]. We assumed no tipping fee for an off-site AD. Total transportation distances in each processing/end-use product were assumed to be 80 km to include realistic environmental impacts in the LCA (see below), but not to bias the techno-economic analysis of the different platforms, cultivation strategies, or processing/end-use products. In our sensitivity analysis (see below), we investigated the effects of transportation distances up to 1200 km to determine their influence on model outcomes (LCA and TEA).

TEA results were expressed as the costs or revenues per kg of dry weight (DW) *S. latissima* or *G. tikvahiae* harvested. All costs were converted to 2020 US dollars with an assumed interest rate of 8%. Cultivation and processing costs were calculated based upon the annual project costs of the one-hectare aquaculture site, which were obtained from Equations (S1)–(S4).

A sensitivity analysis was conducted to determine the impact of parameters on the estimated cost of macroalgae cultivation and processing. Considering the similarity of macroalgae cultivation processes of *S. latissima* and *G. tikvahiae*, the capital and O&M costs for each cultivation platform (S1–S4) were adjusted by $\pm$25% to determine their effect on the TEA. Other parameters considered in the sensitivity analysis included the cultivated biomass, seaweed solids content, electricity and gasoline requirements, labor time, and length of anchor chains required. For longline cultivation systems (S1 and S2), a sensitivity analysis was also performed for the total length of longlines and the number of longlines. For dual-layer systems (S2 and S4), the impact of potentially reduced biomass on the bottom layer compared to the upper layer was also included. The range of expected seaweed solid content and cultivated biomass were selected from the literature as presented in Table S1. All other parameters were adjusted by ±25%. Each parameter was assigned a triangular distribution using minimum, mode, and maximum values. The mode values were used in the economic analysis. A sensitivity analysis was performed for the 10th to 90th percentile of each parameter's probability distribution with a 10-percentile interval. Parameters that inflicted more than a 1% increase or decrease in *S. latissima* cultivation costs were considered high-impact parameters and were subsequently used in the Monte Carlo analysis presented below.

A Monte Carlo analysis was performed to reduce the uncertainty of the macroalgae cultivation cost estimation. The Monte Carlo analysis considered the impact and the data uncertainty of the model parameters. High-impact parameters determined via the sensitivity analysis were used for the analysis of aquaculture costs, and the parameter distributions were assigned the same values as for the sensitivity analysis. The Monte Carlo analysis of macroalgae processing costs included transportation, energy, and labor costs. The range of simulated transportation distance of fresh seaweed (P1) was set from 40 km to 120 km, and for dry seaweed (P2–P4) from 40 km to 1200 km, which equals approximately a quarter of the width of the continental U.S. This is because anaerobic digesters usually only receive biofeedstocks from nearby areas, while dry seaweed may be transported for use intercontinentally. The processing capital costs were not included because they were less important, considering their lifespans and biomass processing capacities compared to the O&M cost, and were more affected by the biomass yield, which was mainly determined by the selection of cultivation platforms (S1–S4) and cultivation strategies (C1–C2). The distribution assigned to each parameter was the same as the sensitivity analysis; the details are presented in Table S4. Ten thousand trials were performed for each simulation, with a probability distribution, 50 percentile value, and 90% confidence interval determined for macroalgae cultivation and processing in each scenario. The techno-economic analysis was conducted using Microsoft Excel for Microsoft 365 (version 2307). The sensitivity analysis and Monte Carlo simulation were performed with Argo v4.1.3 (Booz Allen Hamilton Inc., McLean, VA, USA).

2.4. Life Cycle Assessment

The goal of the life cycle assessment (LCA) was to compare the trade-offs of different macroalgae cultivation, processing, and usage strategies. The functional unit was the environmental impact of one dry kg of seaweed (whether *S. latissima* or *G. tikvahiae*).

The system boundary, inputs, and outputs for the LCA are presented in Figure 3. Within the system boundaries were the construction of the offshore cultivation system, the operation and maintenance of the nursery and aquaculture site, and the processing and transportation of the harvested biomass. The detailed life cycle inventories (LCIs) are presented in Tables S5 and S6, and the matched processes in the LCI databases are listed in Table S9.

The sensitivity analysis was conducted for *S. latissima* cultivation using the single-layer longline system to determine the impact of parameters on the environmental costs. The use of barge, anchor block, seeding line, and electricity in the nursery were adjusted by 50% to investigate their influence on environmental impacts [30]. Other parameters considered included the produced biomass and biomass total solids, nitrogen, and phosphorus contents as reported in the published literature and presented in Table S1. Similar to the cost analysis, each parameter was assigned a triangular distribution using minimum, mode, and maximum values. Mode values were used for the LCA. The sensitivity analysis was performed for the 10th to 90th percentile of each parameter's probability distribution at 20-percentile intervals.

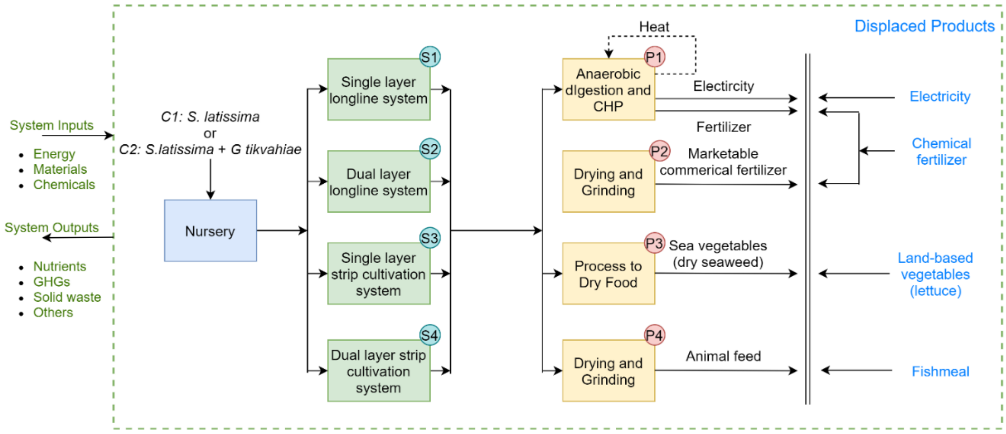

Figure 3. System boundary for the life cycle assessment of the 32 scenarios for *S. latissima* and *G. tikvahiae* cultivation strategies (C1, C2), aquaculture platforms (S1–S4), and processing to end-use products (P1–P4).

The U.S. Life Cycle Inventory Database (USLCI) (NREL, Golden, CO, USA) and EcoInvent 3.7 (EcoInvent, Zurich, Switzerland) were used to construct the life cycle inventory (LCI) for this study. Life cycle impact assessment (LCIA) was conducted using OpenLCA 1.10 (GreenDelta, Berlin, Germany). The LCIA methodology used was the ReCiPe 2016 midpoint (H). The assessed impact categories included human carcinogenic toxicity, human non-carcinogenic toxicity, global warming, marine eutrophication, freshwater eutrophication, fossil resource scarcity, marine ecotoxicity, freshwater ecotoxicity, and terrestrial ecotoxicity.

3. Results

3.1. Sensitivity Analysis

A sensitivity analysis of the TEA model (Figure 4) and LCA model (Figure S1) were conducted to identify model parameters with the greatest impacts on model outcomes, aiding the interpretation of the results. Sensitivity analyses was conducted separately for the cultivation phase and processing phase, and we focus on the single grow-out (*S. latissima*) cultivation scenario (S1). As presented in Figure 4, for the cultivation phase, biomass yield per meter longline was the most important parameter in the TEA model, influencing total costs by as much as ±49.8% of the median cost, depending on the cultivation platform (range: ±43.4% to ±49.8% of the median costs). Biomass solid content (±18.0% to 20.6% of the median costs) and total length of longline (±7.1% to ±11.0% of the median costs) were also important among the four cultivation platforms, as were longline price (±1.5% to ±3.2% of the median cost) and the aquaculture labor cost (±1.9% to ±3.4% of the median cost). For the single and dual-layer longline systems (S1 and S2), increased total length of longlines (S1: ±11.0% of median cost; S2: ±9.9% of median cost) and decreased number of longlines (i.e., longer spacing between anchors; S1: ±3.8% of median cost; S2 = ±3.5% of median cost) reduced cultivation costs. For dual-layer longline (S2) and dual-layer strip (S4) systems, the ratio of second layer to first layer biomass yield impacted cultivation costs by 7.8% and 7.1% of the median costs, respectively (one-sided distribution). Regardless of cultivation platform, the capital cost of the barge was most influential of all the equipment prices (±4.0% to ±6.9% of the median cost) followed by the anchor chain length (±2.6% to ±3.7% of the median cost). Considering the latter, coastal water depth should be considered when determining the seaweed aquaculture site location. All other parameters related to cultivation were common to all cultivation platforms (*n* = 22) and had in sum less than ±2.1% influence on the median costs (±1.4% to ±2.1%); thus, their variability was ignored in the Monte Carlo simulations.

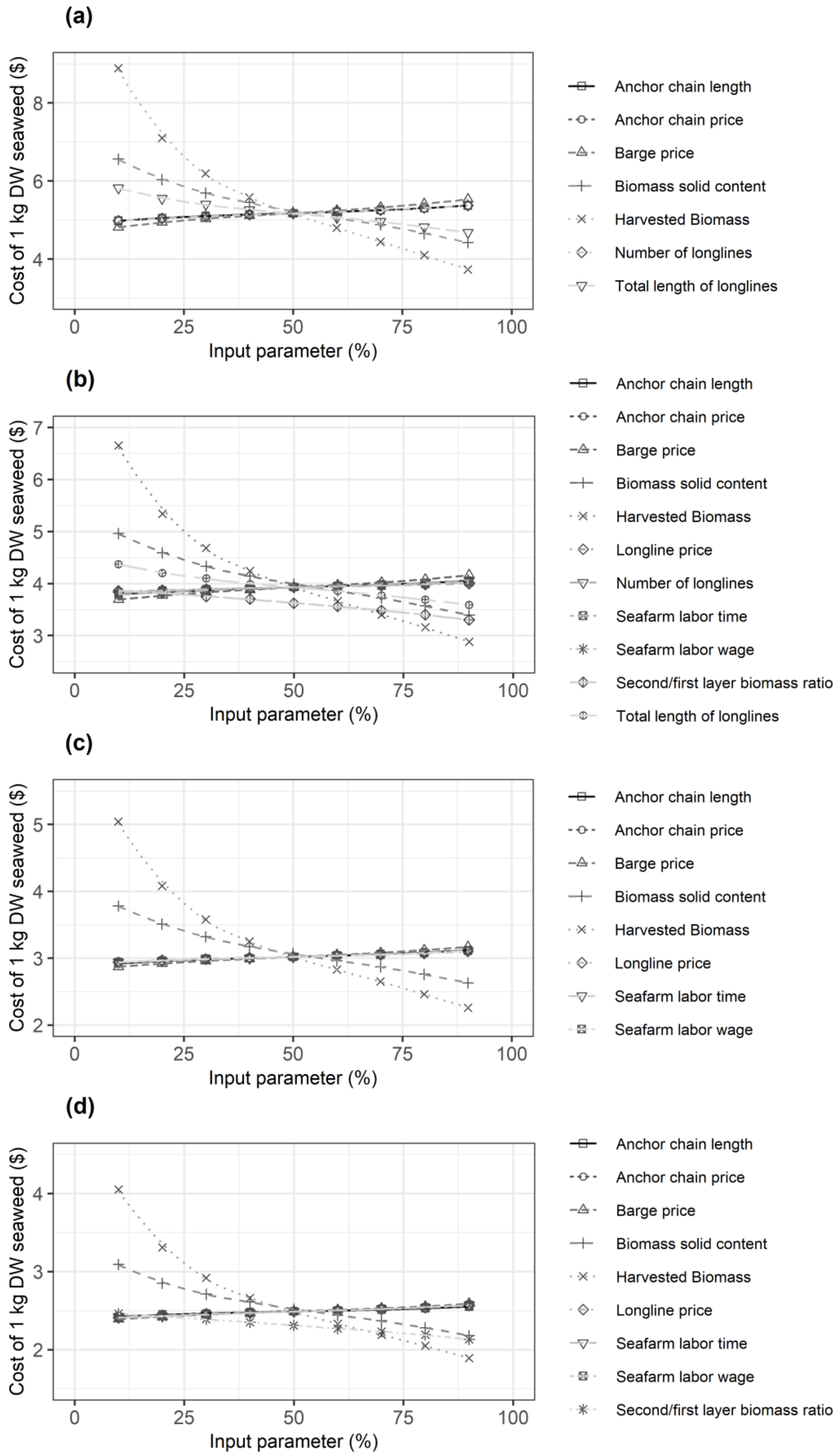

Figure 4. Sensitivity analysis of *S. latissima* cultivation costs for each aquaculture platform ((**a**) platform S1, (**b**) platform S2, (**c**) platform S3, and (**d**) platform S4). The x-axis indicates the percentile of input value in the probability distribution. Only parameters that impact the total costs by more than 2% were plotted. For the second/first layer biomass ratio, the 0 percentile values were used in the techno-economic analysis, and for the other parameters, the 50th percentile values were the values used in the techno-economic analysis.

Factors considered in the processing phase included both dryer and milling equipment capacity, capital cost, operation and maintenance cost, and labor requirements. Also included were transportation costs for wet seaweed (P1: energy biofeedstock) or dry seaweed (P2–P4: all other end uses). The sensitivity of the TEA to factors in the processing phase were dependent upon the biomass production in the cultivation phase. Rather than conflate the sensitivity analyses, we report the range for each factor based upon the median biomass production from each cultivation platform for a singular grow-out scenario (S1). Notably, increasing the transportation to 1200 km only increased the transportation costs by $0.16 per kg dw *S. latissima* and *G. tikvahiae*, 2.4% to 7.3% of the median cultivation costs. The Monte Carlo simulation results of both macroalgae cultivation and processing costs are presented in Table 1; the range of input parameters are presented in Table S4.

Table 1. This table shows the Monte Carlo simulation results for macroalgae cultivation and processing costs in 2020 in USD per kg dw macroalgae cultivation. Capital costs of processing are not included. The lowest cost scenarios for each species are bolded.

Scenario [1]	Seaweed	Mean	SD	Kurtosis	50% Cost	5% to 95% Cost
S1 (C1)	*S. latissima*	$6.17	2.93	9.26	$5.35	$3.28–$11.77
S1 (C2)	*S. latissima*	$5.00	1.79	3.50	$4.57	$2.98–$8.49
	G. tikvahiae	$7.30	1.70	1.88	$7.01	$5.09–$10.51
S2 (C1)	*S. latissima*	$4.29	1.95	10.22	$3.77	$2.36–$8.08
S2 (C2)	*S. latissima*	$3.53	1.21	4.07	$3.25	$2.16–$5.93
	G. tikvahiae	$5.24	1.16	1.74	$5.07	$3.67–$7.41
S3 (C1)	*S. latissima*	$3.60	1.56	7.65	$3.17	$2.07–$6.68
S3 (C2)	*S. latissima*	$2.98	0.96	3.80	$2.75	$1.91–$4.92
	G. tikvahiae	$4.39	0.85	1.77	$4.25	$3.28–$6.00
S4 (C1)	*S. latissima*	$2.72	1.12	6.81	$2.41	$1.60–$4.89
S4 (C2)	*S. latissima*	$2.28	0.70	3.34	$2.12	$1.49–$3.65
	G. tikvahiae	$3.37	0.63	1.33	$3.28	$2.51–$4.56
P1	*S. latissima*	$0.05	0.01	0.40	$0.05	$0.03–$0.08
	G. tikvahiae	$0.07	0.02	−0.32	$0.07	$0.04–$0.10
P2	*S. latissima*	$0.68	0.14	0.44	$0.66	$0.48–$0.94
	G. tikvahiae	$0.87	0.12	−0.20	$0.86	$0.70–$1.08
P3/P4	*S. latissima*	$0.69	0.14	0.44	$0.67	$0.49–$0.95
	G. tikvahiae	$0.88	0.11	−0.20	$0.87	$0.71–$1.09

[1] Scenario constructions include aquaculture platform (S1–S4), cultivation strategy (C1, C2), and processing and end-use product (P1–P4).

Figure S1 depicts the results of the sensitivity analysis of the LCA for *S. latissima* cultivation using the single-layer longline system (cultivation platform S1 and cultivation strategy C1). The environmental impact on marine eutrophication was dominated by the macroalgae total nitrogen (±35.61% of the median impact of seaweed cultivation using platform S1 and strategy C1). The impacts from the other contributors were below ±0.1% of the median impact of seaweed cultivation. For all the other evaluated impact categories using platform S1 and strategy C1, the environmental impacts were most sensitive to the yield of seaweed per meter cultivation line (±80.5% to ±81.0% of the median impact of seaweed cultivation), followed by the biomass solid content (±30.5% to ±30.9% of the median impact). The use of barge and anchor block were also influential parameters, with ±7.67% to ±20.1% and ±6.99% to ±18.7% influence on the median impact, respectively. The influence of the seeding line and nursery electricity usage were negligible (less than ±1.2% of the median impact).

The sensitivity analysis of seaweed processing included seaweed transportation (P1: wet seaweed; P2–P4: dry seaweed) and drying (P2–P4). When cultivated macroalgae were used as anaerobic digester feedstock (P1), only transportation was included in the processing phase. Compared to the environmental impact of macroalgae aquaculture, transportation's highest impact was on global warming (9.20–18.51% of the median impact of seaweed cultivation using platforms S1–S4 and strategy C1), terrestrial ecotoxicity (1.82–4.99% of the median impact), and human non-carcinogenic toxicity (0.51–1.56% of the median impact). The impacts of transportation on other categories were below 1%. Correspondingly, the change of fresh seaweed biofeedstock transportation distance for end-use scenario P1 had the most impact on global warming (4.60–9.26% of the median impact of seaweed cultivation using platform S1–S4 and strategy C1) and terrestrial ecotoxicity (0.91–2.49% of the median impact). The impacts of transportation on other categories were all below 1%.

When harvested macroalgae were dried and used as sea vegetables, seaweed fertilizer, or fishmeal (P2–P4), the environmental impacts of seaweed drying dominated the total environmental impacts of seaweed cultivation and processing across all impact categories except for marine eutrophication (7.16–248 times the median impact of seaweed cultivation using platform S1–S4 and strategy C1). The environmental impact of seaweed drying (marine eutrophication excluded) was sensitive to the seaweed solid content (−21.81–36.48% of the median impact of seaweed drying). Increasing the dry seaweed transportation distance from 80 km to 1200 km increased the environmental impact of seaweed processing on global warming potential by 1.59%. It also increased terrestrial ecotoxicity by 1.10% when harvested seaweed was used as sea vegetables, seaweed fertilizer, or fishmeal (P2–P4). The increased impacts on other impact categories were below 1%.

3.2. Techno-Economic Analysis

Macroalgae cultivation, processing, and transportation costs per kilogram of dry seaweed are presented in Figure 5; a detailed cost inventory is presented in Tables S2 and S3. In general, the cost of seaweed cultivation was most affected by O&M costs (between 50.6% and 73.4% of the annual amortized costs) and dependent on the cultivation platform chosen (S1–S4), with decreasing costs as a function of biomass production potential. For both *S. latissima* and *G. tikvahiae* cultivation, the O&M costs were predominantly maintenance, insurance, and labor.

Figure 5a presents the capital and O&M costs of *S. latissima* cultivation alone. The use of the single-layer longline system (S1) had the highest capital ($2.55 kg^{-1} dw) and O&M ($2.62 kg^{-1} dw) costs as a function of biomass produced among all scenarios (total = $5.17 kg^{-1} dw). Capital and O&M costs decreased as a function of the biomass production potential of the various cultivation platforms (S1 > S2 > S3 > S4). The use of the dual-layer longline system (S2) decreased the capital and O&M costs by $1.26 kg^{-1} dw as compared to a single-layer system. The use of the dual-layer strip system achieved the lowest *S. latissima* cultivation cost ($2.49 kg^{-1} dw). The rotational cultivation of *S. latissima* and *G. tikvahiae* decreased the costs of seaweed cultivation (Figure 5b). For example, *S. latissima* cultivation costs decreased by $0.73 kg^{-1} dw on a single-layer longline system and by $0.30 kg^{-1} dw on a dual-layer strip system when grown on rotation with *G. tikvahiae*. The costs of *G. tikvahiae* cultivation were greater than *S. latissima,* owing to the lower biomass production potential per meter longline ($6.73 kg^{-1} dw for a single-layer longline system and $3.43 kg^{-1} dw for a dual-layer strip system).

The O&M costs of the four seaweed processing/production strategies (P1–P4) are presented in Figure 5c. Figure 5d presents the capital costs associated with a seaweed dryer and hammermill. The most important contributor to processing costs (both capital and O&M) was seaweed drying (capital costs were $0.04–$0.17 kg^{-1} dw depending on the aquaculture platform and cultivation strategy, and O&M cost was $0.64 kg^{-1} dw for *S. latissima* and $0.89 kg^{-1} dw for *G. tikvahiae*). The costs of macroalgae milling (<$0.02 kg^{-1} dw) and transportation (<$0.07 kg^{-1} fw; <$0.01 kg^{-1} dw) were minor. Table S3 presents the details of macroalgae processing costs and end-use product economic values.

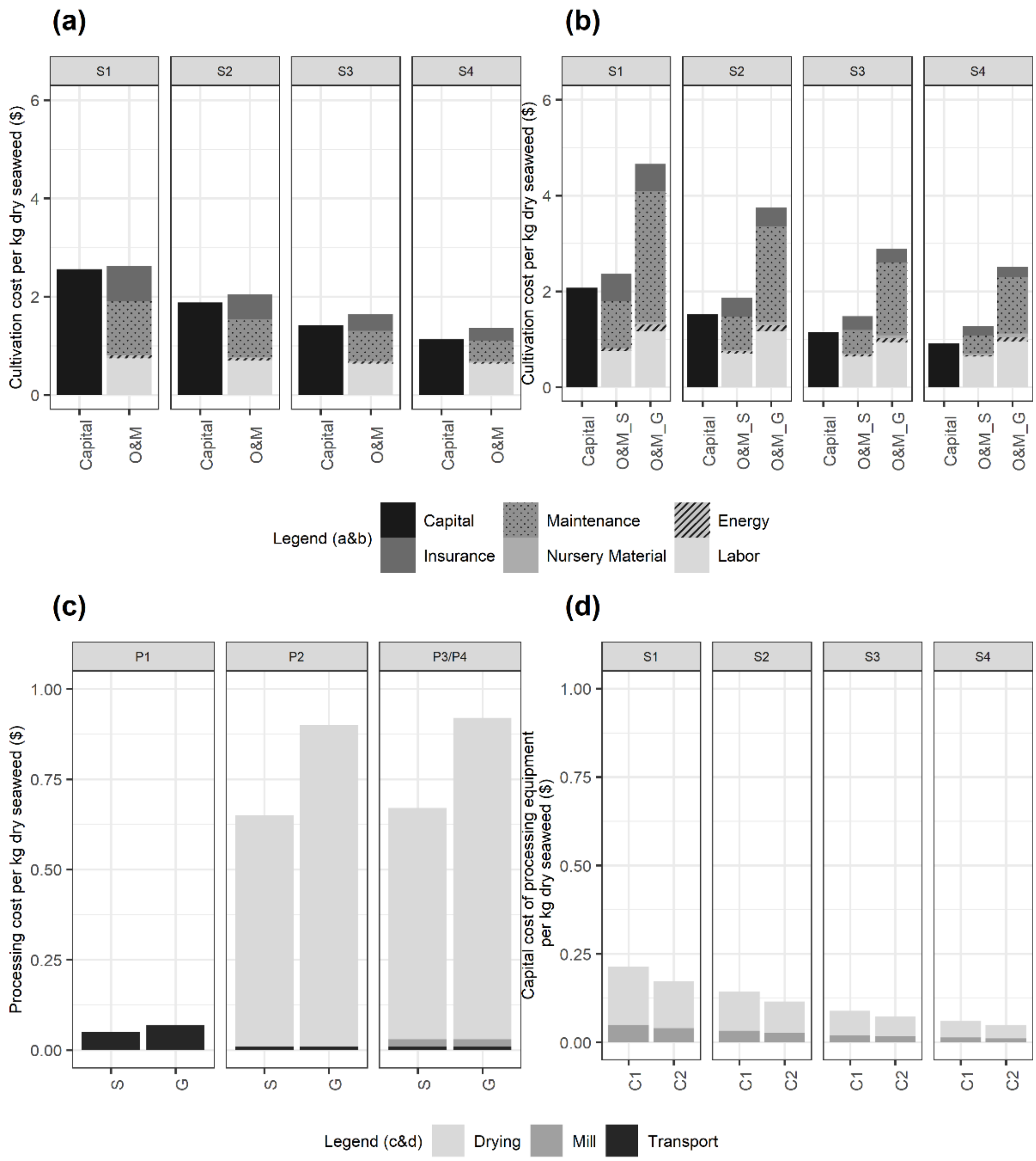

Figure 5. Capital and O&M costs and revenues of macroalgae cultivation reported per kg dry weight seaweed produced: (**a**) cultivation cost of *S. latissima* using cultivation strategy C1 as a function of aquaculture platform (S1–S4); (**b**) cultivation cost of *S. latissima* (S) and *G. tikvahiae* (G) using rotational cultivation (strategy C2) as a function of aquaculture platform (S1–S4); (**c**) processing cost of *S. latissima* (S) and *G. tikvahiae* (G) (independent of cultivation strategy and aquaculture platform); and (**d**) capital cost of processing equipment for cultivation strategies C1 and C2 as a function of aquaculture platform (S1–S4).

Table 2 summarizes the net benefits of the end-use products (P1–P4) of macroalgae cultivated using different cultivation platforms (S1–S4) and strategies (C1–C2) investigated in this study. Harvested biomass was most profitable when sold as sea vegetables, with net benefits between $11.96 and $16.89 among the cultivation platforms and strategies. When processed and sold as fertilizer, the cultivation of *S. latissima* was profitable regardless of cultivation strategy (C1 or C2) when grown on platforms S3 and S4, or on platform S2 if grown on rotation with *G. tikvahiae* (C2). Selling *G. tikvahiae* as fertilizer had net benefits only when the seaweed was cultivated on platform S4. Using macroalgae biomass as biofeedstock for anaerobic digestion or processing it to fishmeal was not economically beneficial, regardless of cultivation platforms or strategies.

Table 2. Net benefits of macroalgae for different aquaculture platforms (S1–S4), cultivation strategies (C1, C2), and processing and end-use products (P1–P4) in 2020 for USD per kg dw macroalgae cultivation. Positive values indicate net benefits and negative values indicate net costs.

Aquaculture Platform	Cultivation Strategy and Seaweed Species		Processing and End-Use Product			
			P1	P2	P3	P4
S1	C1:	*S. latissima*	−\$5.09	\$13.72	−\$1.48	−\$5.31
	C2:	*S. latissima*	−\$4.36	\$14.50	−\$0.68	−\$4.52
		G. tikvahiae	−\$6.66	\$11.96	−\$3.22	−\$7.05
S2	C1:	*S. latissima*	−\$3.85	\$15.05	−\$0.13	−\$3.96
	C2:	*S. latissima*	−\$3.32	\$15.61	\$0.44	−\$3.39
		G. tikvahiae	−\$5.21	\$13.48	−\$1.68	−\$5.52
S3	C1:	*S. latissima*	−\$2.99	\$15.96	\$0.81	−\$3.02
	C2:	*S. latissima*	−\$2.55	\$16.42	\$1.27	−\$2.53
		G. tikvahiae	−\$3.97	\$14.76	−\$0.38	−\$4.22
S4	C1:	*S. latissima*	−\$2.41	\$16.57	\$1.43	−\$2.41
	C2:	*S. latissima*	−\$2.11	\$16.89	\$1.75	−\$2.09
		G. tikvahiae	−\$3.36	\$15.40	\$0.26	−\$3.58

3.3. Life Cycle Assessment

Environmental trade-offs between different aquaculture platforms (S1–S4), cultivation strategies (C1, C2), and processing and end-use strategies (P1–P4) are presented in Figures 6–8. The normalized values of each impact category are presented in Tables S7 and S8.

According to the normalized values of each category presented in Table S7 (construction versus operation and maintenance phases by aquaculture platform), the most significant environmental impact of seaweed cultivation was the environmental service of marine eutrophication mitigation (Figure 6b) owing to the bioextraction of nitrogen during growth. Nitrogen mitigation was 0.023 kg N eq per kg dry weight *S. latissima* produced and 0.035 kg N eq per kg dry weight *G. tikvahiae* produced. Aside from marine eutrophication, the environmental impacts of seaweed cultivation were dominated by platform construction rather than operation and maintenance. The most significant impact during platform construction was on marine ecotoxicity (Figure 7b), followed by carcinogenic toxicity (Figure 8a) and freshwater ecotoxicity (Figure 7a). Environmental impacts stemmed mostly from the barge and anchor blocks (concrete). The environmental impacts of sea farm construction declined as a function of cultivation platform biomass potential (S1 > S2 > S3 > S4) for each impact category, with reductions from S1 to S4 ranging from 60.3% to 69.9%. Furthermore, the cultivation of *G. tikvahiae* on rotation with *S. latissima* reduced construction phase environmental impacts by 15.4% to 19.4%.

Table S8 presents the normalized environmental impacts of seaweed processing and end-use products. When harvested biomass was used as biofuel feedstock (P1), the environmental impacts of seaweed processing were negligible compared to seaweed cultivation and trade-offs by end-use products. Owing to the offset of commercial fertilizer and electricity, the most significant environmental benefits were on marine ecotoxicity and freshwater ecotoxicity. While considering the combined effects of seaweed aquaculture (S1–S4) and processing to end-use products (P1), the net benefits were significantly impacted by the selection of cultivation platform and strategy. The highest net environmental benefits were observed on marine eutrophication throughout all cultivation platforms. The second greatest benefits were observed on marine ecotoxicity for all combinations of cultivation platform and strategy except C1 and S1, in which a net impact was observed. The most significant impact was on human carcinogenic toxicity for all scenarios except those employing a rotational cultivation strategy (C2) using single- or dual-layer strip cultivation platforms (S3 or S4). In these scenarios, net benefits were observed on all impact categories.

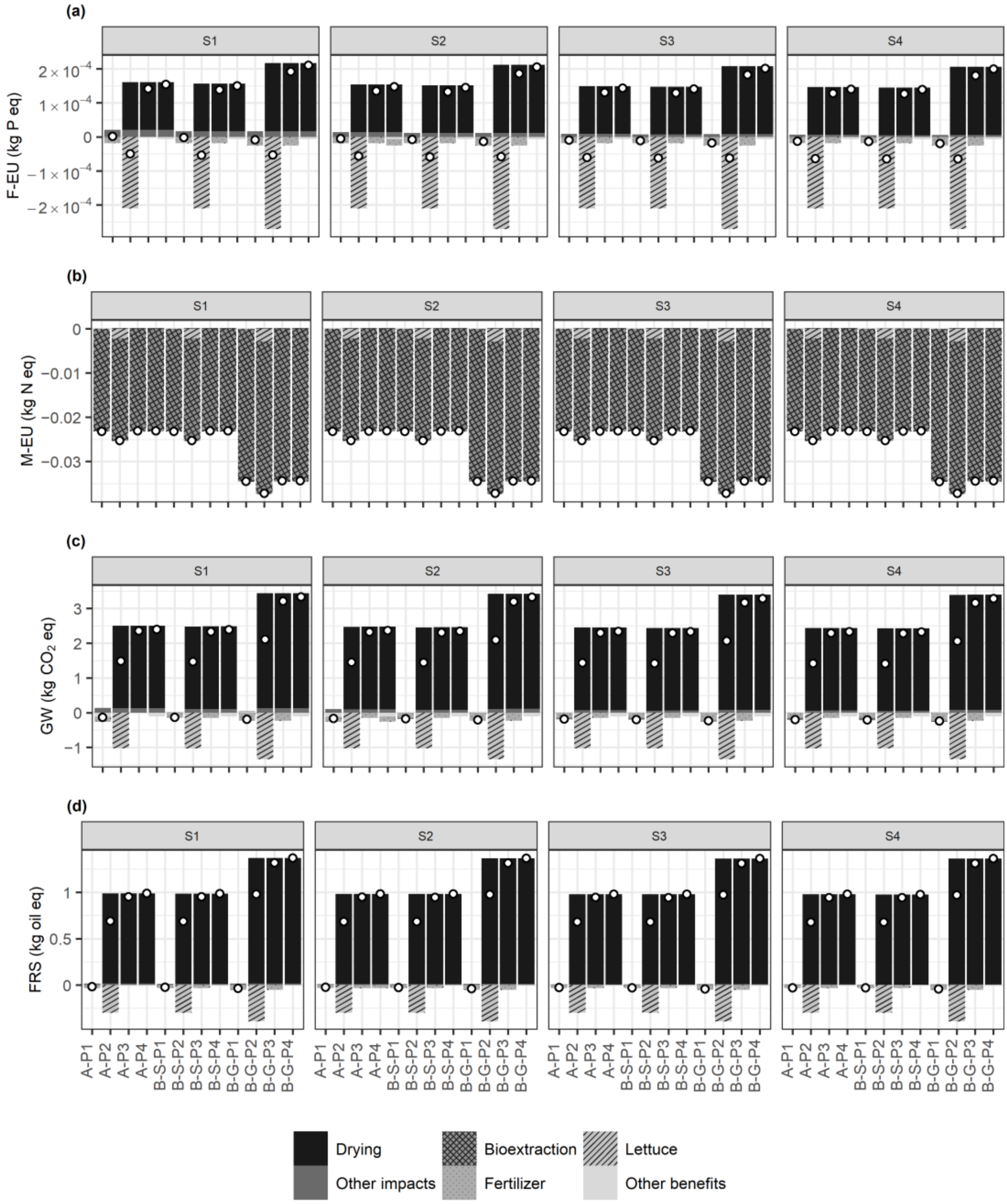

Figure 6. Comparison of (**a**) freshwater eutrophication, (**b**) marine eutrophication, (**c**) global warming potential, and (**d**) fossil resource scarcity of macroalgae cultivation for each aquaculture platform (S1–S4), processing and end-use product (P1–P4), and cultivation strategy (C1, C2). Positive values indicate environmental impacts while negative values indicate environmental benefits. The "other benefits" categories included the substitution of electricity and fishmeal for seaweed end-use products. LCI items (listed in Tables S5 and S6) not presented separately in the figure were summarized in the "other impacts" category. The items included in the "other benefits" and "other impacts" categories only contributed to a small amount of the total impact. White dots indicate net benefits or impacts. S: environmental impact of *S. latissima* cultivation; G: environmental impact of *G. tikvahiae* cultivation.

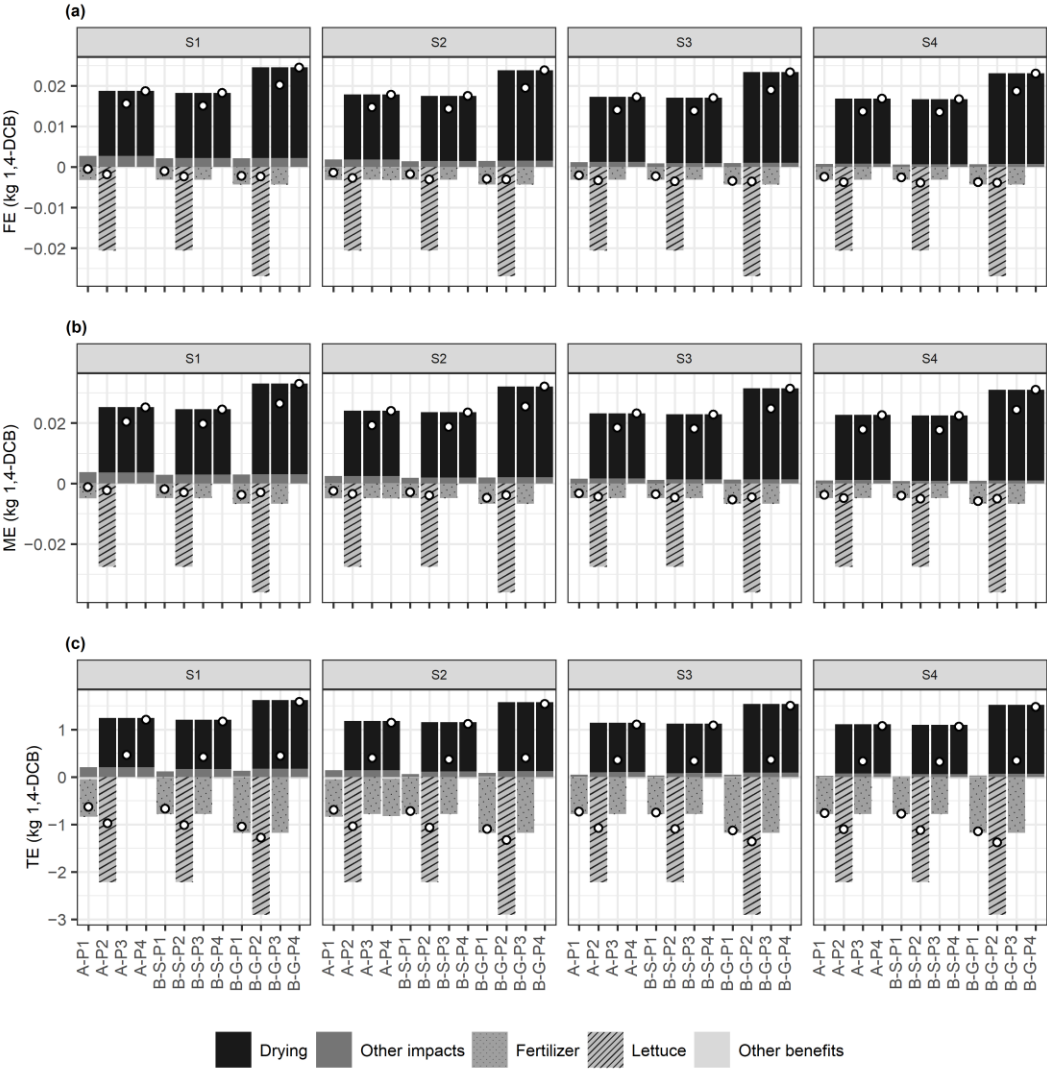

Figure 7. Comparison of (**a**) freshwater ecotoxicity, (**b**) marine ecotoxicity, and (**c**) terrestrial ecotoxicity of macroalgae cultivation for each aquaculture platform (S1–S4), processing and end-use product (P1–P4), and cultivation strategy (C1, C2). The "other benefits" categories included the substitution of electricity and fishmeal for seaweed end-use products. LCI items (listed in Tables S5 and S6) not presented separately in the figure were summarized in the "other impacts" category. The items included in the "other benefits" and "other impacts" categories only contributed to a small amount of the total impact. White dots indicate the net impacts. S: environmental impact of *S. latissima* cultivation; G: environmental impact of *G. tikvahiae* cultivation.

When used as human food, fertilizer, or fishmeal, seaweed drying during the processing phase (P2–P4) drove the environmental impacts across all impact categories. Furthermore, the environmental impacts from seaweed drying in the processing phase greatly exceeded those derived from the seaweed cultivation phase, except for marine eutrophication, regardless of cultivation platform or end-use product. The most significant environmental impact was observed on human carcinogenic toxicity, followed by freshwater ecotoxicity and marine ecotoxicity. The displacement of lettuce by sea vegetables (seaweed) (P2) offered environmental services to freshwater eutrophication, human non-carcinogenic toxicity, and marine, freshwater, and terrestrial ecotoxicity. The substitution of seaweed as food for lettuce also slightly improved nitrogen mitigation (0.0002 kg N eq for *S. latissima* and 0.0003 kg N eq for *G. tikvahiae*). Using harvested biomass as seaweed fertilizer or fishmeal did not yield similar net environmental benefits.

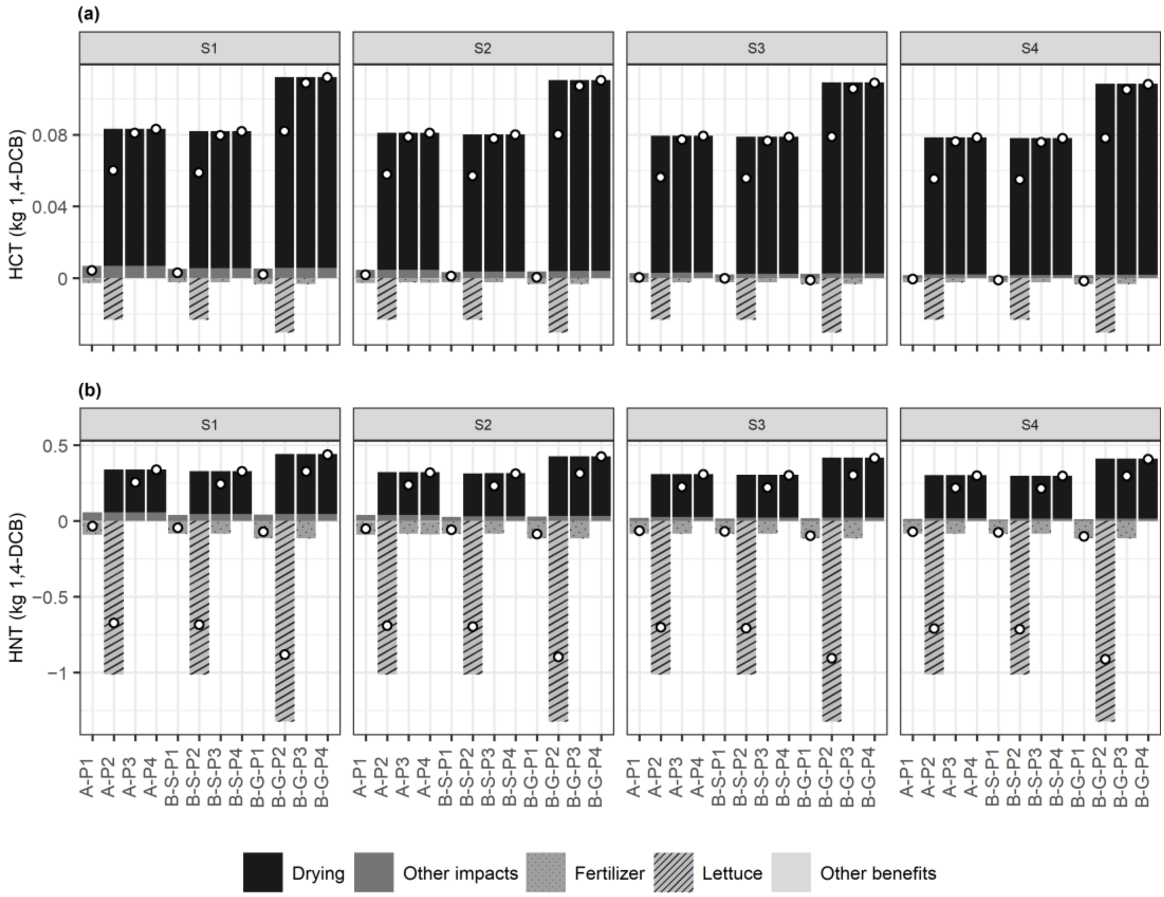

Figure 8. Comparison of (**a**) human carcinogenic toxicity and (**b**) human non-carcinogenic toxicity of macroalgae cultivation for each aquaculture platform (S1–S4), processing and end-use product (P1–P4), and cultivation strategy (C1, C2). The "other benefits" categories included the substitution of electricity and fishmeal for seaweed end-use products. LCI items (listed in Tables S5 and S6) not presented separately in the figure were summarized in the "other impacts" category. The items included in the "other benefits" and "other impacts" categories only contributed to a small amount of the total impact. White dots indicate the net impacts. S: environmental impact of *S. latissima* cultivation; G: environmental impact of *G. tikvahiae* cultivation.

4. Discussion

This study investigated economic and environmental trade-offs between different macroalgae cultivation platforms, processing, and end-use strategies for the single annual grow-out of *S. latissima* or rotational annual grow-out of *S. latissima* and *G. tikvahiae*. Our study builds significantly upon prior studies to answer several outstanding questions, including (i) the differences between the traditional longline cultivation platform and novel platforms such as the strip cultivation systems from economic and environmental perspectives; (ii) the distinctions between the singular annual grow-out of one species versus the bi-annual grow-out (on rotation) of two complementary species of macroalgae during warm and cold seasons sharing the same platform; and (iii) the effect of decisions regarding end-use products on economic and environmental costs.

Compared to the single-layer longline platform (S1), the use of dual-layer and strip cultivation platforms (S2–S4) greatly decreased the costs of platform construction, sea farm insurance, and maintenance. These categories total 67.3–84.4% of the total seaweed cultivation costs. Changing the cultivation platform from S1 to S4 reduced the breakpoint price of harvested seaweed by \$2.25–\$3.29 kg^{-1} dw, due to the cultivation costs being much greater than the processing costs. The estimated cost of *S. latissima* cultivation (C1) using the S1 platform (\$5.17 kg^{-1} dw) was within the range of previously reported costs of *S. latissima* cultivation using single-layer longlines [57,58]. Our sensitivity analysis indicated that cultivation costs were most sensitive to the seaweed density at harvest, which is also consistent with the study conducted by Yarish et al. (2017) [57]. In addition, our results are comparable to the results of a cost analysis of *S. latissima* aquaculture using multiple systems (cultivation costs between \$1.11 and \$7.30 kg^{-1} dw) [59].

Particularly, the breakpoint price is crucial where macroalgae is sold as seaweed fertilizer. The only processing and end-use strategies with the potential to be profitable were sea vegetables (P2) and fertilizer (P3). Using a rotational cultivation strategy (C2), the selection of a dual-layer strip cultivation platform (S4) at greater capital cost over a single longline system (S1) could reduce the payback period from two years to one while also providing long-term increased revenue owing to greater biomass density. Considering fertilizer as an end-use product (P3), the payback period could be reduced from 15 years to 3 years by choosing a dual-layer strip cultivation platform over a single-layer longline system.

The net environmental impacts on marine eutrophication were dominated by the macroalgae biomass in all the scenarios. The net impacts on other categories were affected by the selection of cultivation platform and strategy, and dependent on the intended macroalgae product. When harvested biomass was used as biofuel feedstock (P1); the net impact decreased from C1 to C2 and from S1 to S4. When processed to other end-use products (P2–P4), environmental impacts associated with macroalgae cultivation were overwhelmed by those associated with seaweed drying. While freshwater and marine ecotoxicity were among the most noteworthy impact categories when seaweed was processed to fertilizer and fishmeal (P3–P4), significant net environmental benefits were observed when it was used as biofuel feedstock (P1).

The selection of cultivation platform and strategy affected the environmental impacts by altering the biomass yield. Changing the cultivation platform from S1 to S4 and adding *G. tikvahiae* cultivation on rotation increased the total annual biomass yield by as much as 4.4 times (from 6.7 tons dw per hectare using cultivation strategy C1 and platform S1 to 29.8 tons dw per hectare using cultivation strategy C2 and platform S4), resulting in decreased net economic and environmental costs. The important influence of platform choice on environmental impacts of macroalgae cultivation was also reported by van Oirschot et al. (2017), indicating that the aquaculture system can be more environmentally friendly with the reduced use of steel chain and rope for infrastructure and increased productivity density [30]. Notably, both this study and previously published research about the economic costs and environmental impacts of macroalgae aquaculture are mainly focused on the longline and longline-based platforms, which may be associated with the widespread use of the longline system and data availability [12,30,39,43,47,58,60,61]. Future investigations of TEA and LCA on macroalgae aquaculture can be expanded to other platforms such as net cultivation, floating raft cultivation, ring cultivation, and oil rig platforms—aquaculture platforms that may yield increased economic and environmental benefits [12,62].

The comparison of the economic costs and environmental impacts of C1 and C2 highlight the benefits that can be achieved using rotational grow-out on shared aquaculture infrastructure. While our results focus on *S. latissima* and *G. tikvahiae* on rotation, the results imply that other species could also share similar benefits when grown on rotation. Carefully considering factors such as demand, growing season, and the biogeographic distribution pattern of seaweed species when designing macroalgae aquaculture platforms and grow-out strategies could lead to economic and environmental benefits at other locations.

Our LCA results evidence the marine eutrophication mitigation potential of seaweed aquaculture. This benefit, primarily due to nitrogen uptake during seaweed biomass growth, was increased with increased biomass density of the operation. The nutrient bioextraction potential of seaweed aquaculture has been reported in multiple prior studies, including the possibility of using seaweed aquaculture to trade-off nutrient discharge from wastewater resource recovery facilities (WRRF) for nutrient management in coastal areas [24,47,51,59,61,63]. This study estimated the nitrogen uptake of *S. latissima* and *G.*

tikvahiae based on the data in the literature relating to harvested biomass tissue nitrogen content. However, the nitrogen concentrations and composition in coastal areas vary in space and time. For example, there can be seasonal changes in the flowrate, total nitrogen, and nitrogen speciation (e.g., nitrate vs. ammonium nitrogen) of WRRF effluent discharged to coastal areas; in turn, this can impact nitrogen concentration and composition of the resulting nutrient plume [51]. Previous studies have demonstrated that environmental nitrogen can impact the physiological characteristics of seaweed grown in the area, including the growth rate and the total nitrogen content [64,65]. However, data are still lacking to quantitatively model the impact of environmental nitrogen on seaweed growth and characteristics. Future work should leverage emerging information to better maximize the placement of aquaculture platforms relative to nutrient sources and optimize harvest periods to advantage higher macroalgae nutrient contents and associated nutrient bioextraction from coastal areas.

TEA revealed that *S. latissima* and *G. tikvahiae* used as seaweed fertilizer can be economically profitable when the dual-layer strip cultivation platform (S4) is used for cultivation. However, the LCA indicates significant environmental impacts on all the categories except for marine eutrophication, owing to the energy-intensive drying process. Significant impacts of seaweed drying on the environment were previously reported in other studies of the LCA of seaweed cultivation and processing [30,66,67]. Nevertheless, others have compared multiple *S. latissima* preservation options and reported that using air (hung) drying can dramatically decrease the environmental impacts [68]. Using renewable energy instead of fossil energy may also reduce the impacts of drying, which can improve the environmental outlook of using cultivated macroalgae as seaweed fertilizer to achieve economic benefits with minimal environmental impacts. Freezing may also be used to preserve fresh seaweed for human consumption. Even though the fresh seaweed food product value may be greater, freezing is energy-intensive relative to drying and leads to greater environmental and economic costs of shipping relative to dry seaweed [68]. Considering the limited data on the average time of freezing and storage, we did not explore it in this study. In addition, even though the available data is still limited for quantitative analysis, there have been studies investigating the potential for the passive carbon sequestration of farmed seaweeds naturally sloughing tissues during growth, enhance the environmental benefits of climate change [69–71].

The substitution of land-based lettuce for sea vegetables (seaweed) reduced freshwater eutrophication, human non-carcinogenic toxicity, and freshwater, marine and terrestrial ecotoxicities (Table 3). The breakpoints of substitution decreased when using dual-layer and strip cultivation platforms. A breakpoint less than 100% indicates that the substitution for lettuce can be environmentally favorable even if 100% substitution is not achieved. To achieve zero impact on freshwater and marine ecotoxicity, 1000 g of macroalgae were needed to substitute between 885 g to 919 g of lettuce when grown on platform S1. This was reduced to between 811 g and 862 g of lettuce when grown on platform S4.

While harvested seaweed may be fully used as biofuel feedstock, fertilizer, or fishmeal, when processed to dry human food (P2), the experience shows that harvested macroalgae would not be 100% utilized. The results presented herein yield the possibility of evaluating the economic costs and environmental impacts of macroalgae aquaculture, with harvested biomass being processed to multiple end-use products. For example, as shown in Figure 9a, we estimate that even at 30% utilization of harvested biomass as sea vegetables when *S. latissima* and *G. tikvahiae* are cultivated on rotation on a dual-layer strip platform, the operation would still be profitable with a net benefit between \$3.30 and \$6.05 per kg dw, which is dependent on the selection of the alternative disposition of remaining biomass (biofuel feedstock, seaweed fertilizer, or fishmeal). Figure 9b–f provides the adjusted environmental impacts or ecosystem services for major impact categories associated with macroalgae cultivation as a function of the alternative disposition of seaweed biomass for 30% to 70% utilization as sea vegetables.

Table 3. Breakpoints of macroalgae to lettuce substitution rate to achieve zero environmental impact on F-EU: freshwater eutrophication, HNT: human non-carcinogenic toxicity, FE: freshwater ecotoxicity, ME: marine ecotoxicity, and TE: terrestrial ecotoxicity.

Aquaculture Platform	Cultivation Strategy	Seaweed Species	F-EU	HNT	FE	ME	TE
S1	C1	*S. latissima*	78.48%	33.54%	90.94%	91.75%	56.06%
S1	C2	*S. latissima*	76.61%	32.48%	88.46%	89.21%	54.33%
		G. tikvahiae	78.92%	33.33%	91.19%	91.90%	55.91%
S2	C1	*S. latissima*	75.31%	31.76%	86.68%	87.40%	53.23%
S2	C2	*S. latissima*	74.06%	31.05%	84.98%	85.66%	52.05%
		G. tikvahiae	76.97%	32.26%	88.55%	89.22%	54.25%
S3	C1	*S. latissima*	73.15%	30.58%	83.70%	84.37%	51.47%
S3	C2	*S. latissima*	72.31%	30.09%	82.58%	83.24%	50.62%
		G. tikvahiae	75.57%	31.50%	86.69%	87.34%	53.07%
S4	C1	*S. latissima*	71.76%	29.79%	81.82%	82.46%	50.16%
S4	C2	*S. latissima*	71.19%	29.45%	81.09%	81.69%	49.56%
		G. tikvahiae	74.74%	31.04%	85.58%	86.18%	52.33%

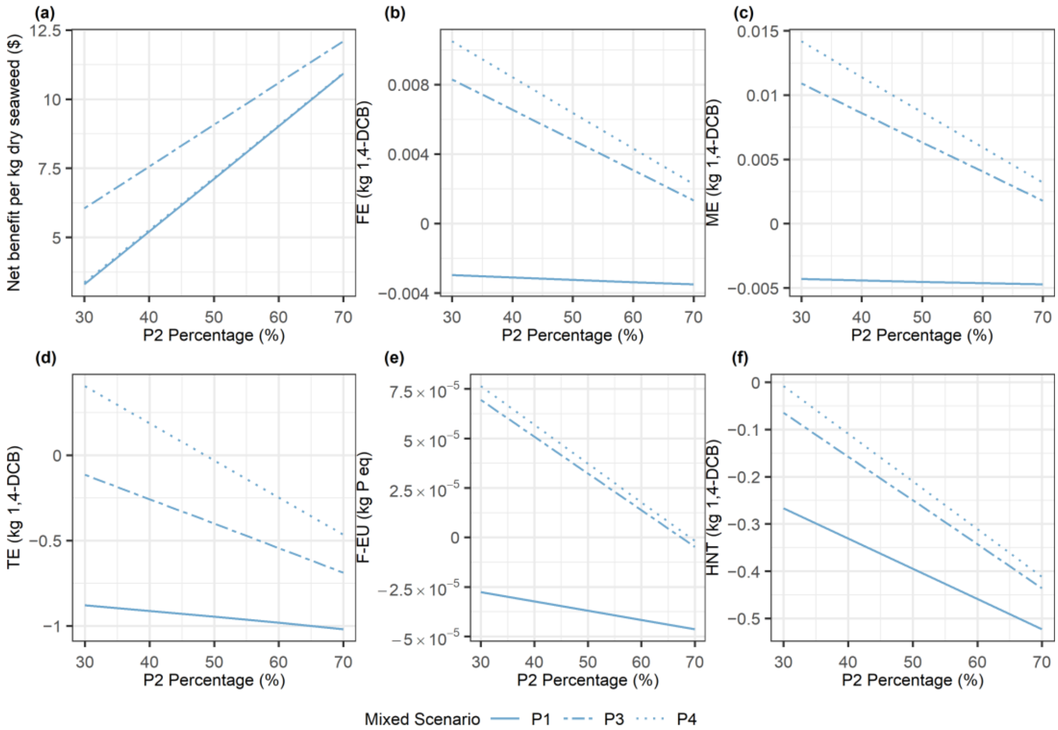

Figure 9. Comparison of (**a**) net economic benefit and environmental impact on (**b**) freshwater ecotoxicity, (**c**) marine ecotoxicity, (**d**) terrestrial ecotoxicity, (**e**) freshwater eutrophication, and (**f**) human non-carcinogenic toxicity when between 30% and 70% of the harvested *S. latissima* (cultivated with platform S4 and cultivation strategy C2) was used as sea vegetables (P2), and the remaining was used as biofuel feedstock (P1), seaweed fertilizer (P3), or fishmeal (P4).

5. Conclusions

In this study, single versus rotational macroalgae cultivation strategies and different cultivation platforms, including single-layer longline, dual-layer longline, single-layer strip, and dual-layer strip systems were assessed in terms of their economic and environmental performance. The findings reveal that dual-layer and strip cultivation systems offer significant cost reductions compared to the common single-layer longline system. Cultivation costs are substantially reduced when utilizing the dual-layer strip system, making it a more economically viable option. For example, when cultivated on rotation, the dual-layer strip cultivation platform reduced *S. latissima* and *G. tikvahiae* cultivation costs by 50.7% and 49.1%, respectively, over traditional longline cultivation. The rotational grow-out of seaweeds reduced the amortized capital costs per kg dw macroalgae by 19.2%. Additionally, this study examined various processing and end-use strategies, such as seaweed-to-biofuel, dried sea vegetables, marketable commercial fertilizer, and animal feed. Seaweed drying was identified as the major contributor to both economic and environmental costs during the processing stage. However, regardless of the specific processing strategy, all scenarios demonstrated environmental benefits in terms of marine eutrophication. This study highlights that the processing of seaweed biomass into dry sea vegetables, assuming the displacement of land-based vegetable production, or its use as biofeedstock for anaerobic digestion for combined heat and power results in the best environmental performance. This suggests the potential for seaweed cultivation to contribute to sustainable food production and energy generation while mitigating environmental impacts. Overall, this research significantly contributes to the academic and commercial/professional context, emphasizing the high market value of the selected macroalgae species and the utilization of shared infrastructure for cultivating multiple algae species. This approach, reminiscent of crop rotation in traditional agriculture, holds promise for the future development of phyconomy—an emerging field that integrates economic growth, environmental sustainability, and the production of valuable biomass from macroalgae.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151512072/s1, Figure S1: Sensitivity analysis of the LCA for *S. latissima* cultivation strategy C1 and cultivation platform S1; Table S1: Biomass production and characteristics of *S. latissima* and *G. tikvahiae* as reported in the literature [21–24,30,39,42,47,60,64,72–86]; Table S2: Cost inventories of *S. latissima* and *G. tikvahiae* cultivation based on a one-hectare sea farm; Table S3: Cost and economic value inventories of *S. latissima* and *G. tikvahiae* processing and end-use products for one-kilogram dry weight of harvested biomass; Table S4: Minimum, mode, and maximum values of the triangle distribution applied to the parameters used in the Monte Carlo simulation of one-kilogram dry weight of *S. latissima* and *G. tikvahiae* cultivation and processing costs; Table S5: Life cycle inventories of one-kilogram dry weight of *S. latissima* and *G. tikvahiae* cultivation through cultivation scenarios S1–S4; Table S6: Life cycle inventories of one-kilogram dry weight of *S. latissima* and *G. tikvahiae* processing and end-use scenarios P1–P4; Table S7: Comparison of normalized amounts of each environmental impact of one-kilogram dry weight of *S. latissima* and *G. tikvahiae* cultivation through cultivation scenarios S1–S4; Table S8: Comparison of normalized amounts of each environmental impact of one-kilogram dry weight of *S. latissima* and *G. tikvahiae* processing and end-use through scenarios P1–P4; Table S9: List of matched processes in the life cycle inventory database; Table S10: List of website addresses of online resources.

Author Contributions: Conceptualization, S.W.R. and J.W.; methodology, J.W. and S.W.R.; validation, S.W.R., N.N.P. and J.W.; investigation, J.W., S.W.R. and R.S.; resources, S.W.R. and N.N.P.; data curation, J.W.; writing—original draft preparation, J.W.; writing—review and editing, S.W.R. and N.N.P.; visualization, S.W.R. and J.W.; supervision, S.W.R.; project administration, S.W.R.; funding acquisition, S.W.R. All authors have read and agreed to the published version of the manuscript.

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