

Carbon dioxide removal capacity of converting harmful macroalgal blooms in South Korea to biochar: a Monte Carlo assessment

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Abstract

Blooms of the drifting brown alga *Sargassum horneri* (golden tides) and of green-tide *Ulva* spp. strand on the coasts of South Korea every year and are collected by local governments. Pyrolysing this biomass to biochar has been proposed as a way to store carbon, but its carbon dioxide removal (CDR) capacity has not been quantified. We built a Monte Carlo model (100,000 draws) of the technical 100-year net CDR of slow pyrolysis at about 600 °C, defined as the carbon stored in biochar minus life-cycle emissions from haulage, four drying routes, process energy, kiln methane and soil application, for officially collected biomass (Tier 1) and all biomass stranded on the coast (Tier 2). With open-air pre-drying, net CDR per dry tonne was 0.156 t CO₂e (90% interval 0.061 to 0.253) for *S. horneri* and 0.056 t CO₂e (−0.088 to 0.159) for *Ulva*. Every route without open-air pre-drying was a net emitter (medians −0.168 to −1.471 t CO₂e per dry tonne). National net CDR under open-air drying was 155 t CO₂e yr^{−1} (49 to 280) for Tier 1 and 176 t CO₂e yr^{−1} (−20 to 393) for Tier 2. With renewable electricity and process heat, Tier 2 rose to 364 t CO₂e yr^{−1}, and the gross storage of all stranded biomass, before any emissions, was 624 t CO₂ yr^{−1}. Sand carried with beach-cast *Ulva* diluted the product to a median carbon content of 6%, far below the 40% minimum of the Korean biochar fertiliser standard. The most influential inputs, biochar carbon content, sand content and plant electricity, lack Korean measurements. The CDR capacity of Korean bloom biomass is marginal; its value lies in waste management rather than climate mitigation.

Keywords: biochar; carbon dioxide removal; golden tide; green tide; life-cycle assessment; Monte Carlo; *Sargassum horneri*; *Ulva*

1. Introduction

Floating seaweed blooms have expanded in the East China Sea and the Yellow Sea over the past two decades (Qi et al., 2022). Two kinds reach the coasts of South Korea in large amounts. Rafts of the brown alga *Sargassum horneri* drift north in winter and spring and strand on Jeju Island and the south-western coast; the 2015 event alone left thousands of tonnes on the shores of Shinan and Jeju (Hwang et al., 2016; Seo et al., 2025). Green tides formed by *Ulva* spp. develop in summer in shallow bays on the eastern coast of Jeju, where nutrient-rich submarine groundwater discharge supports them (Choi Y et al., 2023; Choi SK et al., 2024; Moon et al., 2026); the free-floating blooms there are formed mainly by *U. ohnoi* and *U. pseudo-ohnoi* (Lee et al., 2019; Sunwoo et al., 2025). Both blooms foul beaches and aquaculture facilities, and decaying macroalgae release methane and nitrous oxide (Björk et al., 2023; Li et al., 2026).

Local governments collect the stranded biomass. National collection of *S. horneri* reported by the Ministry of Oceans and Fisheries ranged from 314 t (wet) in 2016 to 15,987 t in 2021, and Jeju Province collected 1,812 to 8,885 t of *Ulva* per year between 2017 and 2025 (Table 1). Removal is costly: one large event required the removal of about 33×10^3 t (fresh weight) of *S. horneri* at an estimated cost of about ₩2.8 billion (Choi et al., 2020).

Pyrolysis of biomass to biochar is one of the carbon dioxide removal (CDR) pathways recognised by carbon-crediting standards. The share of biochar carbon that persists in soil for a century is commonly estimated from the molar ratio of hydrogen to organic carbon (H/C_{org}) (Woolf et al., 2021; IPCC, 2019). Algal feedstocks are accepted by several certification schemes (Verra, 2025; EBC, 2025). However, seaweed biochar is unusual: it is rich in ash and salts and poor in carbon (Roberts et al., 2015; Roberts and de Nys, 2016), and fresh seaweed is about 90% water, so drying can consume more energy than the product stores (Thomas et al., 2021; Wen et al., 2022). In Korea, a biochar fertiliser standard was introduced in 2024 (RDA, 2024), a biochar methodology exists in the voluntary agricultural greenhouse-gas reduction programme (MAFRA, 2021), and a 2026 agreement between the Korea Marine Environment Management Corporation and a private firm proposes desalting *S. horneri* and pyrolysing it into a fertiliser (Haesa News, 2026). Whether such a pathway would store a meaningful amount of carbon has not been assessed.

This study estimates the technical CDR capacity of converting Korean bloom biomass to biochar, that is, the net removal the pathway could deliver if all collected or stranded biomass were processed. It does not estimate creditable removals, which would also depend on the baseline use of the biomass under a particular standard. We ask three questions. (i) How much CO₂ could be removed, net of life-cycle emissions, per tonne and per year, and what is the upper bound if process energy is renewable? (ii) Which process choices decide whether the balance is positive? (iii) Would the product meet the carbon and

stability criteria of Korean and international biochar standards? We answer them with a transparent Monte Carlo model whose code and inputs are openly available.

2. Methods

2.1 Biomass inventory

We defined two biomass tiers. Tier 1 is the biomass officially collected from Korean coasts. Tier 2 is all biomass stranded on Korean coasts, that is, collected plus uncollected biomass. Biomass floating offshore in the Korean exclusive economic zone was excluded, because no study quantifies the share of the regional floating biomass (Qi et al., 2022) that reaches Korean waters.

For *S. horneri* we used national collection statistics by year and province from the Marine Environment Information System of the Ministry of Oceans and Fisheries (MOF, 2026) for 2015–2022 (eight years; mean 6,346 t wet). Data for 2023 cover January to August only and were excluded. Later statistics exist only for Jeju (Jeju Ilbo, 2025; Kyunghyang Shinmun, 2026) and were not used in the resampling pool. Press reports of Jeju data for 2018–2023 (Kyunghyang Shinmun, 2024) differ from the ministry statistics; we used the ministry statistics throughout. For *Ulva* spp. we used Jeju Province collection totals for 2017–2025 as reported in the press (Jeju Ilbo, 2021; Jeju-ui Sori, 2023; Seoul Shinmun, 2026) (nine years; mean 4,903 t wet). No collection statistics exist for *Ulva* outside Jeju. The records are listed in Table 1.

Table 1. Collected biomass of bloom-forming macroalgae in South Korea used in the model (t wet weight per year).

Year	<i>S. horneri</i> (t wet)	<i>Ulva</i> spp. (t wet)
2015	15,640	–
2016	314	–
2017	6,321	1,812
2018	3,855	3,300
2019	972	2,405
2020	6,338	3,342
2021	15,987	5,106
2022	1,341	8,885
2023	–	3,555
2024	–	7,363
2025	–	8,357
Mean (years used)	6,346	4,903

S. horneri: national collection, Marine Environment Information System (MOF, 2026); 2023 (January–August only) excluded. *Ulva* spp.: Jeju Province collection as reported by Jeju Ilbo (2021) for 2017–2019, Jeju-ui Sori (2023) for 2020–2022 and Seoul Shinmun (2026) for 2023–2025; Jeju Ilbo (2021) gave 3,400 t for 2020.

Tier 2 biomass was derived from Tier 1 with a collection efficiency e , the ratio of collected to stranded biomass. For *S. horneri*, the ratio of collection to inflow was about 0.86 in Jeju in early 2026 (761 of 884 t) (Kyunghyang Shinmun, 2026). For 2015, the removal reported for Shinan (5,180 t) and Jeju (20,000 t) alone (Hwang et al., 2016) exceeds the national statistics (15,640 t), so official records may understate the stranded biomass. We used a triangular distribution Tri(0.45, 0.80, 0.90). For *Ulva*, Jeju clears mainly bathing beaches and tourist sites and does not recover sunken biomass (Seoul Shinmun, 2026), while seasonal surveys in 2013–2015 found annual blooms exceeding 11,000 t, as reported by Moon et al. (2026); we used Tri(0.20, 0.45, 0.80). All biomass quantities are wet mass as collected, which includes sand and debris. Dry algal mass was obtained as $W(1 - i) \cdot DM$, where W is wet collected mass, i the sand and debris fraction and DM the dry-matter fraction of the algae.

2.2 Conversion and permanence

We assumed slow pyrolysis at about 600 °C. This temperature was chosen because unrinsed *Ulva* biochar made at 450 °C has an H/C ratio near 1, above the 0.7 threshold used by most standards, whereas biochar made at 600 °C has a ratio of about 0.5 (Roberts and de Nys, 2016). Gross 100-year storage G per dry tonne of algae (sand-free) was

$$G = Y \cdot C_{tot} \cdot f_{org} \cdot F_{perm} \cdot 44/12$$

where Y is the biochar yield, C_{tot} the total carbon fraction of the biochar, f_{org} the organic share of that carbon and F_{perm} the fraction persisting for 100 years. F_{perm} followed the regression of Woolf et al. (2021) for a mean annual soil temperature of 14.9 °C, $F_{perm} = 1.04 - 0.64 \cdot H/C_{org}$, with an added normal error term (SD 0.05, assumption) and truncation to [0, 1]. As an alternative we used the permanence factor for 450–600 °C biochar given in Appendix 4 of the 2019 Refinement to the IPCC Guidelines, $0.80 \pm 11\%$ (IPCC, 2019). That appendix provides a basis for future methodological development rather than a formal Tier 1 method, and it does not cover algal feedstocks.

2.3 Life-cycle emissions and energy balance

Emissions E per dry tonne of algae comprised haulage of wet biomass (with sand) from beach to plant; diesel for turning and loading during open-air drying; natural gas to cover any process-heat deficit; electricity for heat-pump drying (scenario D only); plant electricity; methane from the kiln; and haulage and spreading of the biochar (Table 2). Grid electricity was assigned $0.4173 \text{ t CO}_2\text{e MWh}^{-1}$, the Korean factor for 2023 (MCEE, 2025); diesel $2.62 \text{ kg CO}_2 \text{ L}^{-1}$; and heat from natural gas $62.3 \text{ kg CO}_2 \text{ GJ}^{-1}$ of useful heat, assuming a 90% boiler efficiency and the IPCC default factor for natural gas. Methane was converted with a 100-year global warming potential of 28.

Process heat was balanced explicitly. The heat demand was the heat of pyrolysis, plus the heat to evaporate the water remaining above 10% moisture in a thermal dryer, plus 0.46 GJ t⁻¹ to heat entrained sand to 600 °C:

$$Q_{demand} = Q_{pyro} + W_{thermal} \cdot e_{dry} + m_{sand} \cdot 0.46$$

The heat supply was the recoverable combustion heat of the pyrolysis volatiles, estimated as the heating value of the feedstock minus that retained in the biochar:

$$Q_{supply} = \eta_{vol} \cdot \max(0, HHV_{feed} - Y \cdot HHV_{char})$$

Any deficit was met with natural gas, and surplus heat was not credited. Sand was assumed to pass through the kiln into the product, adding to its mass, to haulage and electricity demand, and diluting its carbon content.

2.4 System boundary and upper bound

Net CDR per dry tonne was defined as $G - E$. Because the aim was the technical capacity of the pathway, no baseline use of the biomass was deducted, and emissions that might be avoided by not leaving the biomass to decay were not counted (Section 4.6). For uncollected Tier 2 biomass, the extra diesel needed to collect it, U(1, 5) L per wet tonne (assumption), was added to its emissions. As an upper bound, scenario A was also run with plant electricity and process heat from renewable sources, which removes their emissions but leaves the diesel for haulage, handling and spreading unchanged. The gross storage G of all stranded biomass, before any emissions, gives the absolute ceiling.

2.5 Drying scenarios

Drying was represented by four scenarios. In scenario A (base case), biomass is spread and turned in the open air until its moisture falls to 15–40%, and a thermal dryer finishes it to 10%; Wen et al. (2022) assumed 20% moisture after open-air drying of beach-cast seaweed. In scenario B, biomass is only drained or dewatered to 60–75% moisture before thermal drying. In scenario C, fresh biomass is dried thermally. In scenario D, fresh biomass is dried in an electric heat-pump dryer powered from the Korean grid; its specific moisture extraction rate was taken from a solar-assisted heat-pump dryer for kelp (Kang et al., 2022), which makes scenario D optimistic. Two further sensitivity cases used the IPCC permanence factor and the methane emissions of a low-technology kiln, U(0.024, 0.054) t CH₄ per tonne of biochar, spanning the mean emission factors measured for retort and traditional kilns (Sparrevik et al., 2015), instead of a modern retort with an afterburner.

2.6 Monte Carlo simulation and sensitivity analysis

All parameters (Table 2) were sampled independently, 100,000 times, with a fixed random seed (20261004). Distributions were triangular where the literature gives a central value and a range, and uniform where only a range is known or the value is an assumption. Results are reported as medians with 90% intervals (5th to 95th percentiles). Annual capacity was computed in two ways: with the mean of the collection records, which reflects parameter uncertainty only, and with a collection year drawn at random for each species, which adds year-to-year variability. Because the two species have records for different years, their years were drawn independently. Tier 1 capacity was the dry algal mass collected times the net CDR per dry tonne of collected biomass; Tier 2 added the uncollected mass times the net CDR per dry tonne of uncollected biomass. Sensitivity was measured with Spearman rank correlations between each input and the net CDR per dry tonne in scenario A. The model was written in Python (NumPy, SciPy, pandas, Matplotlib); an independent JavaScript implementation with a different random number generator reproduced the per-tonne and annual results at the same sample size.

Table 2. Model parameters, distributions and sources.

Parameter	<i>S. horneri</i>	<i>Ulva</i> spp.	Unit	Source [basis]
Collection efficiency, e (collected/stranded)	Tri(0.45, 0.80, 0.90)	Tri(0.20, 0.45, 0.80)	–	(Kyunghyang Shinmun, 2026; Hwang et al., 2016) / (Seoul Shinmun, 2026; Moon et al., 2026); derived [A]
Sand and debris share of wet mass, i	U(0, 0.10)	U(0.05, 0.25)	–	Assumption [A]
Dry-matter fraction, DM	Tri(0.09, 0.12, 0.20)	Tri(0.08, 0.11, 0.17)	–	(Murakami et al., 2016) / (Paiva et al., 2017) (four macroalgae incl. two <i>Ulva</i> spp.); upper bounds [A]
Biochar yield at about 600 °C, Y	Tri(0.36, 0.42, 0.55)	Tri(0.38, 0.43, 0.48)	g g ⁻¹ dw	(Raj et al., 2026; Roberts et al., 2015; Wen et al., 2022) / (Roberts and de Nys, 2016; Niedzbała et al., 2024)
Biochar total carbon, C_{tot}	Tri(0.22, 0.30, 0.35)	Tri(0.23, 0.26, 0.31)	g g ⁻¹	(Roberts et al., 2015) / (Roberts and de Nys, 2016)
Organic share of biochar C, f_{org}	Tri(0.85, 0.92, 1.00)	same	–	(Roberts et al., 2015)
Molar H/C (total C) at 600 °C	Tri(0.45, 0.50, 0.60)	same	–	Mode: un-rinsed flake (Roberts and de Nys, 2016); range [A]
Error of persistence regression	N(0, 0.05)	same	–	[A]
F_{perm} , IPCC alternative	N(0.80, 0.045)	same	–	(IPCC, 2019)
Haul distance, beach to plant	U(5, 50)	same	km	[A]
Truck emission factor	U(0.096, 0.20)	same	kg CO ₂ e t ⁻¹ km ⁻¹	Generic range [A]
Diesel for turning and loading (A, B)	U(0.5, 2.0)	same	L t ⁻¹ wet	[A]
Moisture after open-air drying (A)	Tri(0.15, 0.20, 0.40)	same	–	(Wen et al., 2022); range [A]
Moisture after draining only (B)	Tri(0.60, 0.70, 0.75)	same	–	[A]

Heat of pyrolysis, Q_{pyro}	U(0.88, 2.02)	same	GJ t ⁻¹ dw	(Jerzak et al., 2022)
Heating value of feedstock, HHV_{feed}	U(10, 14)	same	GJ t ⁻¹ dw	[A]; cf. (Milledge and Harvey, 2016)
Heating value of biochar, HHV_{char}	U(10, 18)	same	GJ t ⁻¹	(Roberts et al., 2015)
Recovery of volatile energy as heat, η_{vol}	U(0.60, 0.80)	same	–	[A]
Specific energy of thermal drying, e_{dry}	U(2.5, 5.0)	same	GJ t ⁻¹ water	(Thomas et al., 2021) (3 GJ t ⁻¹); range [A]
Heat-pump SMER (D)	U(1.66, 3.725)	same	kg water kWh ⁻¹	(Kang et al., 2022) (solar-assisted)
Plant electricity	U(50, 150)	same	kWh t ⁻¹ dry solids	[A]
Kiln CH ₄ , modern retort	U(0, 0.002)	same	t t ⁻¹ biochar	[A]; low-tech case U(0.024, 0.054) (Sparrevik et al., 2015)
Haul distance, plant to farm	U(10, 50)	same	km	[A]
Diesel for spreading	U(0.5, 2.0)	same	L t ⁻¹ biochar	[A]
Diesel for extra collection (Tier 2)	U(1.0, 5.0)	same	L t ⁻¹ wet	[A]
Fixed factor	Value	Basis		
Grid electricity	0.4173 t CO ₂ e MWh ⁻¹	(MCEE, 2025)		
Diesel	2.62 kg CO ₂ L ⁻¹	35.3 MJ L ⁻¹ × 74.1 kg CO ₂ GJ ⁻¹		
Heat from natural gas	62.3 kg CO ₂ GJ ⁻¹	56.1 kg CO ₂ GJ ⁻¹ ÷ 0.90 boiler efficiency		
Heating sand to 600 °C	0.46 GJ t ⁻¹	$c_p \approx 0.8 \text{ kJ kg}^{-1} \text{ K}^{-1} \times 575 \text{ K}$		
GWP100 of CH ₄	28	IPCC Fifth Assessment Report		

Tri(min, mode, max), triangular; U(min, max), uniform; N(mean, SD), normal. Where two sources are separated by a slash, the first applies to *S. horneri* and the second to *Ulva* spp. [A] marks an assumption without a direct empirical source; all [A] parameters are included in the sensitivity analysis.

3. Results

3.1 Biomass

Collected *S. horneri* varied by a factor of about fifty between years, from 314 t in 2016 to 15,987 t in 2021 (Fig. 1a). Collected *Ulva* in Jeju increased over the record, from 1,812 t in 2017 to 8,357 t in 2025 (Fig. 1b). In scenario A, the record-mean collection corresponded to 1,311 (90% interval 1,071 to 1,617) t of dry algae per year (Tier 1) and 2,225 (90% interval 1,643 to 3,132) t including uncollected stranded biomass (Tier 2), which in turn corresponded to 19,380 t of wet stranded biomass (median).

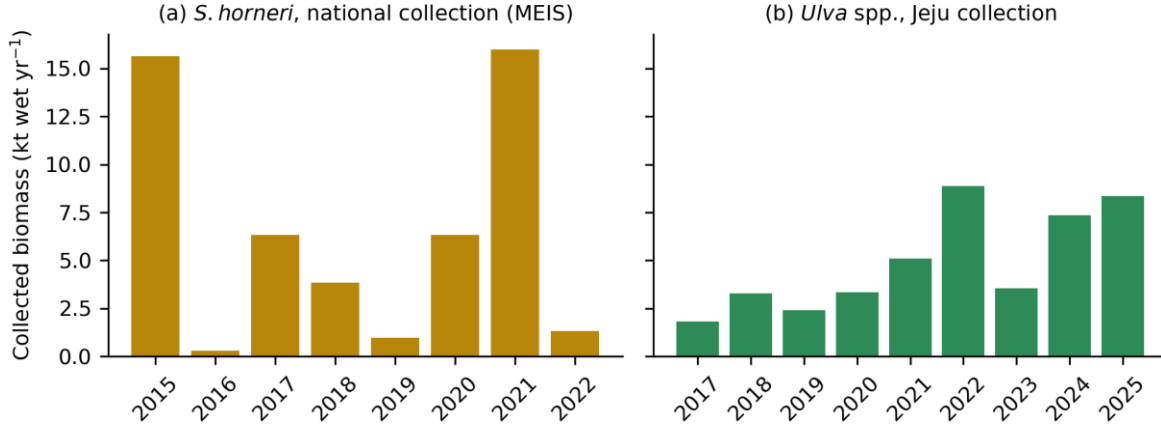


Fig. 1. Collected biomass. (a) *Sargassum horneri*, national collection, 2015–2022 (MOF, 2026). (b) *Ulva* spp., Jeju collection, 2017–2025 (sources in Table 1).

3.2 Carbon balance per tonne

With open-air pre-drying (scenario A), the gross 100-year storage was 0.294 (90% interval 0.224 to 0.380) t CO₂ per dry tonne for *S. horneri* and 0.263 (90% interval 0.214 to 0.321) t CO₂ for *Ulva* (Fig. 2). The median persistence factor was 0.682 and 0.682, nearly identical because the same H/C distribution was used. Life-cycle emissions were 0.136 (90% interval 0.087 to 0.208) and 0.206 (90% interval 0.123 to 0.345) t CO_{2e} per dry tonne. Plant electricity was the largest emission for both species (0.057 and 0.099 t CO_{2e}), followed by haulage to the plant (0.030 and 0.038) and handling during open-air drying (0.025 and 0.032). Combustion of the volatiles usually covered the process heat: a deficit occurred in 12% of draws for *S. horneri* and 19% for *Ulva*, so the median natural-gas emission was zero.

Net CDR was 0.156 (90% interval 0.061 to 0.253) t CO_{2e} per dry tonne for *S. horneri*, with a 0.4% probability of a net emission, and 0.056 (90% interval –0.088 to 0.159) t CO_{2e} for *Ulva*, with a 24.0% probability. Per wet tonne as collected, the corresponding values were 0.020 (90% interval 0.007 to 0.037) and 0.006 (90% interval –0.008 to 0.019) t CO_{2e}. Sand was the main reason for the difference between species: it added to the mass hauled and processed, so *Ulva* carried higher electricity and transport burdens per tonne of algae.

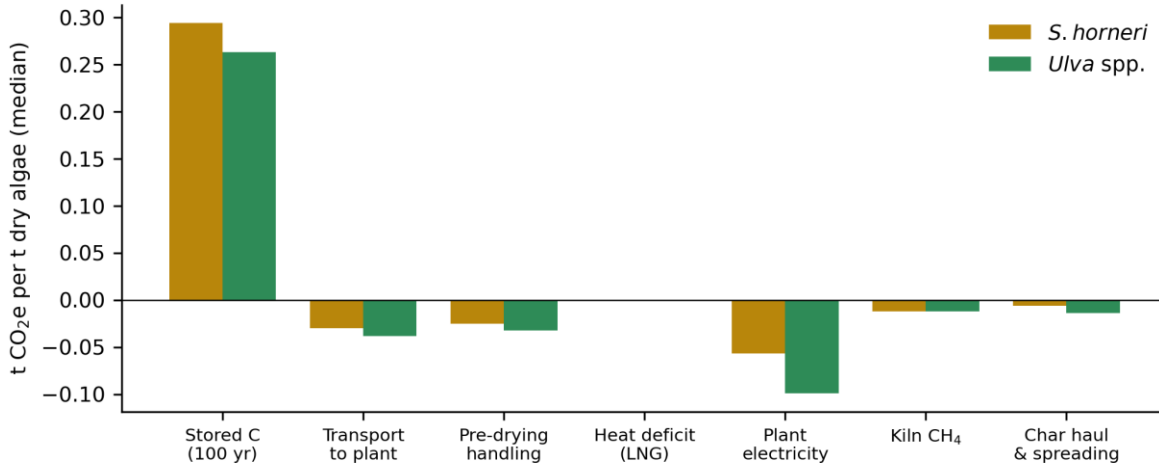


Fig. 2. Components of the carbon balance per dry tonne of algae in scenario A (medians). Storage is positive and emissions are negative. The median heat deficit is zero for both species.

3.3 Drying scenarios

The drying route decided the sign of the result (Fig. 3). Without open-air drying, the remaining water had to be removed with fuel or electricity, and the volatiles no longer covered the heat demand. In scenario B (drained only), net CDR was -0.168 (90% interval -0.430 to 0.064) t CO₂e per dry tonne for *S. horneri* and -0.297 (90% interval -0.583 to -0.044) for *Ulva*, with net-emission probabilities of 87.6% and 97.6%. Thermal drying of fresh biomass (scenario C) gave -1.116 (90% interval -1.943 to -0.526) and -1.471 (90% interval -2.406 to -0.798), and heat-pump drying (scenario D) gave -0.808 (90% interval -1.505 to -0.402) and -1.064 (90% interval -1.851 to -0.606); in both cases every draw was a net emission. Heat-pump drying performed better than thermal drying, but the electricity it used on the Korean grid (0.992 t CO₂e per dry tonne of *S. horneri*, median) still exceeded the gross storage.

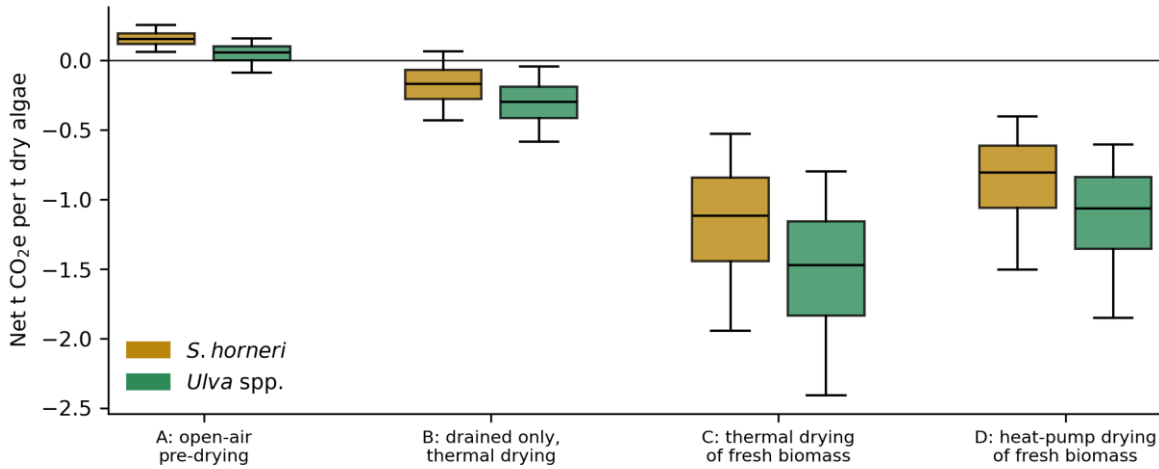


Fig. 3. Net CDR per dry tonne of algae under the four drying scenarios. Boxes show the interquartile range and median; whiskers show the 5th and 95th percentiles.

3.4 Annual capacity

With the record-mean collection and open-air drying, Tier 1 net CDR was 155 (90% interval 49 to 280) t CO₂e yr⁻¹ (Table 3). *S. horneri* contributed 126 t CO₂e yr⁻¹ and *Ulva* 28 t CO₂e yr⁻¹ (medians). Adding uncollected stranded biomass raised the total to 176 (90% interval -20 to 393) t CO₂e yr⁻¹ (Tier 2), with a 7% probability of a net emission. Gross storage before emissions was 624 (90% interval 440 to 908) t CO₂ yr⁻¹ for Tier 2, from 2,956 t of product per year (median, including sand). When collection years were resampled, the median fell to 115 t CO₂e yr⁻¹ for Tier 1 and 127 for Tier 2, and the 90% intervals widened (-1 to 476 and -77 to 617), because collection is dominated by a few large years (Fig. 4). The means were nearly unchanged (158 and 180 t CO₂e yr⁻¹). Every other scenario was a net source at the national scale, from -283 t CO₂e yr⁻¹ (scenario B, Tier 1) to -2,910 t CO₂e yr⁻¹ (scenario C, Tier 2).

With renewable plant electricity and process heat, life-cycle emissions in scenario A fell to 0.075 and 0.098 t CO₂e per dry tonne, mostly diesel for haulage and handling, and net CDR rose to 0.217 (90% interval 0.136 to 0.309) t CO₂e per dry tonne for *S. horneri* and 0.164 (90% interval 0.087 to 0.236) for *Ulva*. The national upper bound was 260 (90% interval 166 to 382) t CO₂e yr⁻¹ for Tier 1 and 364 (90% interval 202 to 589) t CO₂e yr⁻¹ for Tier 2 (Table 3), still well below the gross storage of all stranded biomass (624 t CO₂ yr⁻¹).

Table 3. Annual net CDR by drying scenario and biomass tier.

Scenario	Biomass	Tier 1, median (90% interval)	Tier 2, median (90% interval)	Tier 1, mean	Tier 2, mean
A: open-air pre-drying	record mean	155 (49 to 280)	176 (-20 to 393)	159	180
A: open-air pre-drying	years resampled	115	127	158	180

		(-1 to 476)	(-77 to 617)		
A, renewable electricity and heat (upper bound)	record mean	260 (166 to 382)	364 (202 to 589)	266	376
B: drained only	record mean	-283 (-536 to -54)	-573 (-1,100 to -176)	-288	-596
B: drained only	years resampled	-228 (-787 to -27)	-488 (-1,488 to -96)	-290	-599
C: thermal drying	record mean	-1,645 (-2,164 to -1,135)	-2,910 (-4,391 to -1,904)	-1,647	-2,998
C: thermal drying	years resampled	-1,422 (-3,659 to -431)	-2,627 (-6,346 to -823)	-1,646	-2,996
D: heat-pump drying	record mean	-1,202 (-1,678 to -842)	-2,163 (-3,358 to -1,410)	-1,223	-2,243
D: heat-pump drying	years resampled	-1,042 (-2,797 to -316)	-1,962 (-4,830 to -608)	-1,225	-2,247

Net CDR in t CO₂e yr⁻¹. Tier 1, collected biomass; Tier 2, collected plus uncollected stranded biomass.

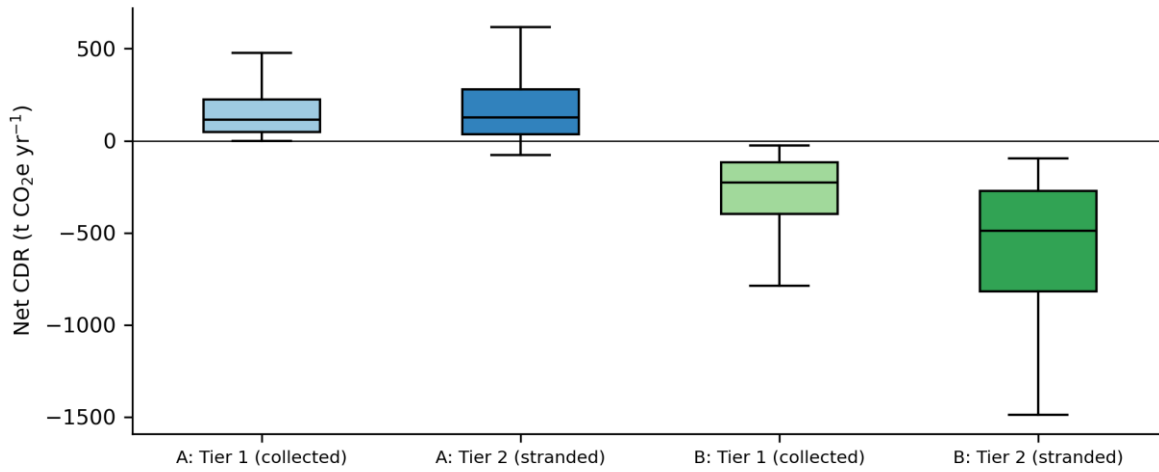


Fig. 4. Annual net CDR for Tier 1 (collected) and Tier 2 (stranded) biomass in scenarios A and B, with collection years resampled. Boxes show the interquartile range and median; whiskers show the 5th and 95th percentiles.

3.5 Sensitivity and alternative assumptions

For *S. horneri*, net CDR was most sensitive to the carbon content of the biochar (Spearman $\rho = 0.46$), its yield (0.36), the error term of the persistence model (0.36) and plant electricity (-0.29) (Fig. 5a). For *Ulva*, the sand fraction (-0.57), plant electricity (-0.41) and the dry-matter fraction (0.31) ranked highest (Fig. 5b). None of these leading inputs has been measured for Korean bloom biomass: biochar yield and carbon content come from cultivated or foreign seaweed, and the sand fraction and plant electricity are assumptions or generic values.

With the IPCC permanence factor instead of the H/C regression, net CDR in scenario A rose to 0.207 (90% interval 0.109 to 0.308) t CO₂e per dry tonne for *S. horneri* and 0.102 (90% interval -0.043 to 0.204) for

Ulva. With the methane emissions of a low-technology kiln, it fell to -0.313 (90% interval -0.516 to -0.123) and -0.407 (90% interval -0.622 to -0.204), a net emission for both species.

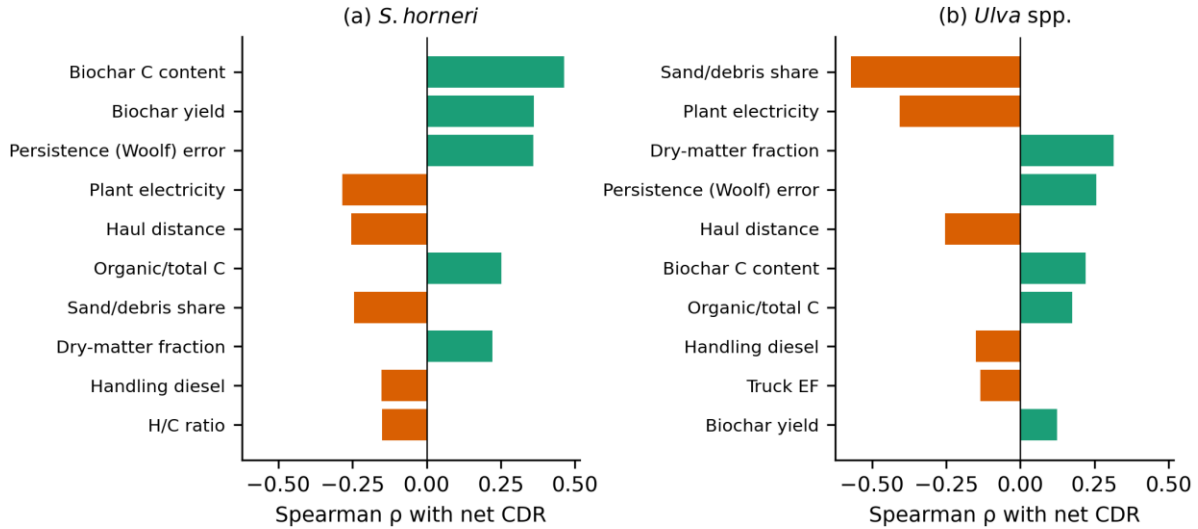


Fig. 5. Spearman rank correlations between the ten most influential inputs and net CDR per dry tonne in scenario A. (a) *S. horneri*; (b) *Ulva* spp.

3.6 Product quality

The modelled H/C_{org} ratio was 0.557 (90% interval 0.501 to 0.628) and below 0.7 in 100% of draws, so the $H/C_{org} \leq 0.7$ criterion of VM0044 and of the Korean voluntary methodology was met by design (Verra, 2025; MAFRA, 2021), as was the molar $H/C < 0.7$ criterion of the Korean fertiliser standard (RDA, 2026). Carbon content was not. Including the entrained sand, the product contained 15% (90% interval 10–27%) carbon for *S. horneri* and 6% (90% interval 3–12%) for *Ulva*. No draw reached the 40% carbon minimum that the Korean fertiliser standard sets for biochar from agricultural and forestry by-products (RDA, 2024) (0% for both species), and only 1.3% of *S. horneri* draws reached the 30% minimum set for manure-based biochar.

4. Discussion

4.1 Scale

The net CDR that Korean bloom biomass could deliver is of the order of 10^2 t CO₂e per year. Even with renewable process energy the upper bound is 364 t CO₂e per year for all stranded biomass, and the gross storage of that biomass, before any emissions, is only 624 t CO₂ per year. At this scale the pathway is not a meaningful national mitigation measure. The small numbers follow directly from the feedstock: about nine-tenths of the wet mass is water, a further share is sand, and the biochar is only a quarter to a third

carbon, of which roughly two-thirds is expected to persist for a century. A wet tonne of collected *S. horneri* therefore yields a median net CDR of only 0.020 t CO₂e.

4.2 Drying decides the sign

The sign of the result depends on how the water is removed. Only open-air pre-drying kept the balance positive, because it uses sun and wind instead of fuel and leaves the volatiles enough energy to run the kiln. This agrees with earlier assessments that identified drying as the dominant energy burden of seaweed processing (Thomas et al., 2021; Wen et al., 2022). Open-air drying is not always available. *Ulva* green tides in Jeju develop in summer, when they can be dispersed by typhoons (Choi SK et al., 2024), and summer is also the monsoon rainy season in Korea; by contrast, the 2015 *S. horneri* event occurred between January and May (Hwang et al., 2016), when drying conditions are likely to be more favourable. Drying space on or near beaches is limited, and leachate and odour from drying piles are local concerns. A realistic system would need covered drying yards or would have to accept that part of the biomass cannot be dried passively, which pushes the balance towards scenarios B–D.

4.3 Sand, salt and washing

Sand affects *Ulva* more than any other factor. It lowers the carbon content of the product, adds to haulage and processing, and absorbs heat in the kiln. Washing would remove sand and salt. Roberts and de Nys (2016) found that rinsing *Ulva* before pyrolysis lowered the ash content of the biomass from 28.6% to 14.7% and raised the carbon content of the biochar, but un-rinsed biomass gave a higher biochar yield and a higher proportion of fixed carbon, so that rinsing had no significant effect on stable carbon per kilogram of seaweed. Washing is therefore mainly a question of product quality, notably for the salt and carbon criteria of fertiliser standards, and is unlikely to increase carbon storage. It also needs fresh water and produces saline effluent, which our model does not include.

4.4 Korean regulatory context

Three Korean frameworks are relevant. First, the biochar fertiliser standard introduced in 2024 lists agricultural and forestry by-products and livestock manure as feedstocks and sets minimum carbon contents of 40% and 30% (dry weight), respectively, together with limits on salt, moisture, HCl-insoluble matter and heavy metals, including 45 mg kg⁻¹ of arsenic. It also requires a molar H/C below 0.7 or a molar O/C below 0.4 (RDA, 2024; RDA, 2026). Seaweed is not among the listed feedstocks (RDA, 2026), and our results suggest that beach-cast seaweed biochar would not meet these carbon minima without washing and blending. Second, the biochar methodology of the voluntary agricultural greenhouse-gas reduction programme accepts plant-based feedstocks pyrolysed at 350 °C or more with H/C below 0.7 (MAFRA, 2021). This programme is separate from the Korean Emissions Trading Scheme, which at the

time of writing recognised afforestation and reforestation as its only carbon-removal activities (Son et al., 2025). Third, international standards such as Verra VM0044 and the European Biochar Certificate accept algal feedstocks (Verra, 2025; EBC, 2025), so certification would be possible in principle, but the expected volume is too small to justify the fixed costs of certification and monitoring.

4.5 Arsenic

Brown algae of the genus *Sargassum* can accumulate arsenic. Pelagic *Sargassum* in the Mexican Caribbean contained 24–172 mg kg⁻¹ (dry weight) (Rodríguez-Martínez et al., 2020) and other pelagic *Sargassum* 49–217 mg kg⁻¹ (Davis et al., 2021), and in *Sargassum* collected in Korea inorganic arsenic made up about 69–85% of total arsenic (Lee et al., 2022). Arsenic in stranded *Sargassum* is mostly inorganic and is partly lost by volatilisation and leaching during decay (Abdool-Ghany et al., 2026). We found no measurements of arsenic in Korean *S. horneri* on a dry basis, so we did not model a distribution. Instead we computed the feedstock concentration at which the biochar would exceed a given limit, assuming that 75–100% of the arsenic remains in the char; thermal treatment of an arsenic-hyperaccumulating fern lost about a quarter of its arsenic at 800 °C (Yan et al., 2008). For the EBC-Agro limit of 13 g t⁻¹ (EBC, 2025), the threshold was 6.6 (90% interval 5.4 to 8.1) mg kg⁻¹ (dry feedstock) for *S. horneri* and 6.4 (90% interval 5.5 to 7.5) mg kg⁻¹ for *Ulva*. For the arsenic limit of 45 mg kg⁻¹ (dry weight) in the Korean biochar fertiliser standard (RDA, 2026), it was 23 (90% interval 19 to 28) and 22 (90% interval 19 to 26) mg kg⁻¹. Both thresholds lie below the concentrations reported for pelagic *Sargassum*, so arsenic screening of Korean feedstock would be a prerequisite for any soil application.

4.6 Avoided emissions

Decaying macroalgae release methane and nitrous oxide (Björk et al., 2023; Li et al., 2026), so processing stranded biomass promptly may also avoid emissions. Such avoided emissions are not carbon removal and were outside the scope of this study; their size depends on how the biomass would otherwise be handled. For a feedstock this wet and this poor in carbon, they may nevertheless matter as much for the climate as the removal itself and deserve a separate assessment.

4.7 Limitations

The study has six main limitations. First, the biomass records are incomplete: national *S. horneri* statistics end in 2022, *Ulva* statistics exist only for Jeju, and some figures come from press reports of provincial data that disagree with each other. Second, collection efficiency, and hence Tier 2, rests on a few ratios. Third, there are no Korean measurements of the dry-matter, sand and carbon contents of beach-cast bloom biomass, of its biochar yield and carbon content, or of its arsenic content; we used values from cultivated or foreign seaweed and assumptions, and the sensitivity analysis shows that these inputs drive the result.

Fourth, parameters were sampled independently, although some are correlated (for example, yield and carbon content). Fifth, the permanence model was developed for terrestrial feedstocks and mineral soils (Woolf et al., 2021; IPCC, 2019), and its validity for high-ash algal biochar is untested (Petersen and Sanei, 2025). Sixth, the estimates are technical capacities; removals credited under a particular standard would be smaller if the standard deducts carbon that the baseline use of the biomass would have retained. Field measurements of the feedstock and product would narrow the uncertainty more than any refinement of the model.

5. Conclusions

Converting harmful macroalgal blooms collected in South Korea to biochar has a technical net CDR capacity of about 155 t CO₂e per year (Tier 1), or 176 t CO₂e per year if all stranded biomass were collected (Tier 2), and only if the biomass is dried in the open air before pyrolysis. Renewable process energy raises the upper bound to 364 t CO₂e per year. Any route that dries the biomass with fuel or electricity is a net source. Sand makes *Ulva* biochar a marginal store and a low-carbon product that falls short of the Korean fertiliser standard. Policy for bloom biomass should therefore be framed as waste management, with attention to drying logistics, product quality and arsenic, rather than as a source of carbon removal credits.

Declarations

Data and code availability. The model code (hab_biochar_mc.py), its independent JavaScript cross-check, input data, results (summary.json and tables) and figures are available at Zenodo, <https://doi.org/10.5281/zenodo.23140955>.

Competing interests. The authors declare no competing interests.

Funding. This research received no external funding.

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