

Supplemental Information

The Use of Whole Hawaiian Macroalgae to Engineer Bioplastics and Adhesives for Wood-Particleboards

Ian R. Campbell^{*a}, Ty Shitanaka^{*b}, Hannah Egan^c, Manpreet Kaur^b,
Samir Kumar Khanal^{‡b,d}, and Eleftheria Roumeli^{‡a}

March 13, 2026

Contents of this document:

1. Table S1: Halymenia compositional ThOD breakdown	2-3
2. Table S2: Douglas fir compositional ThOD breakdown	3
3. Table S3: HPAEC-Pad Sugar standard peak location and width	3
4. Table S4: Elemental composition	4
5. Table S5: Complete mechanical performance data	4
6. Figure S1: HPAEC-Pad Sugar Standard callibration curves	5
7. Figure S2: HPAEC-PAD sugar standard chromatograms	6
8. Figure S3: Particle size distributions	7
9. Figure S4: SEM images of inorganic impurities in macroalgal bioplastics ...	8
10. Figure S5: SEM images of wood-algae biocomposite microstructure	8
11. Figure S6: The biodegradation of bioplastics and wood-algae biocomposites	9

^a School of Materials Science and Engineering, The University of Washington, WA 98105, USA. Email: er-roumeli@uw.edu

^b Department of Molecular Biosciences and Bioengineering, University of Hawai'i at Mānoa, Honolulu, HI 96822, USA. Email: khanal@hawaii.edu

^c Department of Bio, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA.

^d Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon 999077, Hong Kong. Email: cekhanal@ust.hk

* These authors contributed equally to this work

‡ Corresponding Authors

Supplementary Tables

Table S1: Summation of individual ThODs for the molecular components of Halymenia

Material	Composition	Formula	H	C	N	O	S	Mr	ThOD (mg/g)	ThOD _i (mg/g)
Carbohydrates	0.500									
Glucose	0.379	C ₆ H ₁₂ O ₆	12	6	0	6	0	180	1066.7	404.6
Galactose	0.097	C ₆ H ₁₂ O ₆	12	6	0	6	0	180	1066.7	103.1
Xylose	0.024	C ₅ H ₁₀ O ₅	10	5	0	5	0	150	1066.7	25.6
Protein ¹	0.120									
Aspartic Acid	0.005	C ₄ H ₇ NO ₄	7	4	1	4	0	133	1203.0	5.8
Glutamic Acid	0.001	C ₅ H ₉ NO ₄	9	5	1	4	0	147	1415.0	0.9
Asparagine	0.010	C ₄ H ₈ N ₂ O ₃	8	4	2	3	0	132	1697.0	16.4
Serine	0.009	C ₃ H ₇ NO ₃	7	3	1	3	0	105	1371.4	12.4
Glutamine	0.012	C ₅ H ₁₀ N ₂ O ₃	10	5	2	3	0	146	1863.0	22.8
Glycine	0.006	C ₂ H ₅ NO ₂	5	2	1	2	0	75	1493.3	8.6
Threonine	0.004	C ₄ H ₉ NO ₃	9	4	1	3	0	119	1613.4	6.7
Arginine	0.002	C ₆ H ₁₄ N ₄ O ₂	14	6	4	2	0	174	2482.8	4.8
Alanine	0.002	C ₃ H ₇ NO ₂	7	3	1	2	0	89	1797.8	4.0
Cysteine	0.006	C ₃ H ₇ NO ₂ S	7	3	1	2	1	121	1719.0	11.1
Tyrosine	0.005	C ₉ H ₁₁ NO ₃	11	9	1	3	0	181	2033.1	11.1
Histidine	0.006	C ₆ H ₉ N ₃ O ₂	9	6	3	2	0	155	2271.0	13.2
Valine	0.007	C ₅ H ₁₁ NO ₂	11	5	1	2	0	117	2188.0	16.2
Methionine	0.009	C ₅ H ₁₁ NO ₂ S	11	5	1	2	1	149	2040.3	17.7
Isoleucine	0.005	C ₆ H ₁₃ NO ₂	13	6	1	2	0	131	2320.6	11.9
Phenylalanine	0.011	C ₉ H ₁₁ NO ₂	11	9	1	2	0	165	2327.3	24.7
Leucine	0.005	C ₆ H ₁₃ NO ₂	13	6	1	2	0	131	2320.6	11.9
Lysine	0.004	C ₆ H ₁₄ N ₂ O ₂	14	6	2	2	0	146	2411.0	9.3
Proline	0.005	C ₅ H ₉ NO ₂	9	5	1	2	0	115	2087.0	11.4
Tryptophan	0.005	C ₁₁ H ₁₂ N ₂ O ₂	12	11	2	2	0	204	2431.4	13.3
Lipids	0.046									
Lauric acid	0.005	C ₁₂ H ₂₄ O ₂	24	12	0	2	0	200	2720.0	14.0
Myristic acid	0.002	C ₁₄ H ₂₈ O ₂	28	14	0	2	0	228	2807.0	4.5
Palmitic acid	0.025	C ₁₆ H ₃₂ O ₂	32	16	0	2	0	256	2875.0	72.7
Stearic acid	0.003	C ₁₈ H ₃₆ O ₂	36	18	0	2	0	284	2929.6	9.3
Oleic acid	0.009	C ₁₈ H ₃₄ O ₂	34	18	0	2	0	282	2893.6	27.3
Linoleic acid	0.000	C ₁₈ H ₃₂ O ₂	32	18	0	2	0	280	2857.1	0.3
Arachidic acid	0.000	C ₂₀ H ₄₀ O ₂	40	20	0	2	0	312	2974.4	0.3
C20:3	0.001	C ₂₀ H ₃₄ O ₂	34	20	0	2	0	306	2875.8	2.7
C20:5	0.000	C ₂₀ H ₃₀ O ₂	30	20	0	2	0	302	2807.9	0.5
Sulfates	0.170									

Continued on next page

Material	Composition	Formula	H	C	N	O	S	Mr	ThOD (mg/g)	ThOD _i (mg/g)
<i>ι</i> -Carrageenan ²	0.170	C ₁₄ H ₁₄ O ₁₁ S ₂	14	14	0	11	2	422	1137.4	193.4
Total ThOD										1092.7

Table S2: Summation of individual ThODs for the molecular components of Douglas fir wood.

Material	Composition	Formula	H	C	N	O	S	Mr	ThOD (mg/g)	ThOD _i (mg/g)
Hemi/Cellulose ³	0.675									
Glucose	0.478	C ₆ H ₁₂ O ₆	12	6	0	6	0	180	1066.7	510.0
Galactose	0.033	C ₆ H ₁₂ O ₆	12	6	0	6	0	180	1066.7	35.2
Xylose/Mannose	0.151	C ₅ H ₁₀ O ₅	10	5	0	5	0	150	1066.7	161.3
Arabinose	0.0128	C ₅ H ₁₀ O ₅	10	5	0	5	0	150	1066.7	13.7
Lignin ⁴	0.258									
Guaiacyl	0.232	C ₇ H ₆ O ₂	6	7	0	2	0	122	1967.2	457.3
Hydroxyphenyl	0.026	C ₆ H ₄ O	4	6	0	1	0	92	2260.9	58.4
Total ThOD										1235.8

Table S3: Average retention times and eluted peak widths of sugar standards during HPAEC-PAD. Values are means \pm standard deviation of at least four concentrations.

Sugar Standard	Retention Time (min)	Peak Width (min)
Rhamnose	3.973 \pm 0.012	0.656 \pm 0.182
Arabinose	4.205 \pm 0.009	0.518 \pm 0.108
Galactose	4.869 \pm 0.007	0.652 \pm 0.200
Glucose	5.299 \pm 0.013	0.625 \pm 0.028
Mannose	5.879 \pm 0.005	0.866 \pm 0.066
Xylose	6.072 \pm 0.011	0.724 \pm 0.055
Galacturonic Acid	24.654 \pm 0.005	0.469 \pm 0.005
Guluronic Acid	24.890 \pm 0.037	0.474 \pm 0.020
Glucuronic Acid	25.921 \pm 0.012	0.621 \pm 0.027
Mannuronic Acid	27.335 \pm 0.007	0.725 \pm 0.005

¹The amino acid profile of *Halymenia venusta* is based on work by Perumal et al. [1]. The concentrations of each amino acid reported there were renormalized to match the protein content measured here.

²Carrageenan disaccharide is used as a model for sulfated polysaccharides.

³Monosaccharide concentrations are based on Zhu et al. [2].

⁴Lignin monomer distributions are based on Kathahira et al. [3] and Suota et al. [4].

Table S4: Elemental composition of macroalgae species and Douglas fir wood. Values are percent dry mass. A value of 0.00 indicates <0.01%.

Mat.	H	C	N	Na	Mg	Si	P	S	Cl	K	Ca	Mn	Fe
CL	3.93	23.9	2.31	2.59	0.25	0	0.01	0.91	33.56	1.00	1.15	0.00	0.00
GP	3.81	22.0	2.69	0.59	0	0.32	0.00	3.71	22.25	22.1	0.14	3.08	0.01
HH	3.35	16.5	2.07	1.05	0.04	0	0.02	8.14	11.79	9.12	1.03	0	0.01
US	6.48	29.8	4.09	1.26	2.66	0.30	0.00	10.1	12.97	8.51	0.58	0.49	0.04
Wood ⁵	5.25	46.6	0.0	0	0	0	0	0	0	0	0	0	0.01

Table S5: The average density, flexural modulus, flexural strength, strain-to-break, and toughness of bioplastics and wood–algae composites fabricated using different pressing conditions described in Table 1 of the main text. Error shown for each average value is plus-or-minus 1 standard deviation.

Material	Cond. ⁶	Dens. (g/cm ³)	Flex. Mod. (GPa)	Flex. Str. (MPa)	S2B (%)	Tough. (MJ/m ³)
Caulerpa	1	1.68 ± 0.02	4.19 ± 0.28	33.30 ± 1.96	1.20 ± 0.07	0.31 ± 0.03
	2	1.60 ± 0.06	3.05 ± 0.41	26.28 ± 3.36	1.49 ± 0.13	0.32 ± 0.05
	3	1.50 ± 0.04	5.44 ± 0.86	32.37 ± 4.27	0.68 ± 0.07	0.14 ± 0.01
	4	1.60 ± 0.05	4.77 ± 0.72	32.54 ± 4.86	0.89 ± 0.10	0.19 ± 0.03
Gracilaria	1	1.65 ± 0.08	7.33 ± 1.18	42.05 ± 3.46	0.73 ± 0.13	0.22 ± 0.02
	2	1.67 ± 0.04	7.55 ± 0.62	47.57 ± 4.91	0.75 ± 0.07	0.23 ± 0.03
	3	1.54 ± 0.06	4.81 ± 0.79	29.96 ± 6.78	0.64 ± 0.06	0.13 ± 0.02
	4	1.71 ± 0.04	9.02 ± 1.02	45.77 ± 6.98	0.58 ± 0.07	0.21 ± 0.02
Halymenia	1	1.65 ± 0.05	6.66 ± 0.63	69.37 ± 6.06	1.15 ± 0.11	0.47 ± 0.09
	2	1.58 ± 0.07	5.21 ± 0.56	59.46 ± 4.19	1.30 ± 0.12	0.46 ± 0.06
	3	1.53 ± 0.09	6.39 ± 0.89	64.31 ± 7.58	0.98 ± 0.08	0.34 ± 0.06
	4	1.66 ± 0.04	7.77 ± 1.77	69.80 ± 7.56	0.91 ± 0.31	0.35 ± 0.06
Ulva	1	1.32 ± 0.03	4.88 ± 0.44	29.31 ± 2.86	0.70 ± 0.05	0.16 ± 0.01
	2	1.57 ± 0.05	3.00 ± 0.26	24.15 ± 2.09	1.00 ± 0.10	0.19 ± 0.02
	3	1.35 ± 0.04	6.84 ± 0.46	25.87 ± 2.74	0.38 ± 0.02	0.06 ± 0.01
	4	1.60 ± 0.07	7.10 ± 0.30	6.82 ± 5.42	0.37 ± 0.08	0.06 ± 0.02
Wood:CL	3	1.44 ± 0.03	7.75 ± 1.03	41.25 ± 7.25	0.61 ± 0.02	0.15 ± 0.02
Wood:GP	4	1.53 ± 0.01	9.41 ± 0.90	49.77 ± 6.12	0.59 ± 0.02	0.18 ± 0.02
Wood:HH	4	1.46 ± 0.06	7.94 ± 0.66	49.38 ± 5.74	0.70 ± 0.05	0.21 ± 0.04
Wood:US	1	1.43 ± 0.03	6.26 ± 0.81	29.18 ± 7.60	0.57 ± 0.04	0.12 ± 0.02
Wood	4	1.27 ± 0.04	4.23 ± 0.85	11.22 ± 2.39	0.35 ± 0.02	0.06 ± 0.02

⁵For Douglas Fir wood, C and N are from Grandgeorge et al. [5] and H concentration is based on Rowell et al. [6]

⁶For each of the conditions 1-4 specimens are hot-pressed for 5 min at (1) 140 °C and 7 kN, (2) 140 °C and 15 kN, (3) 160 °C and 7 kN, or (4) 160 °C and 15 kN.

Supplementary figures

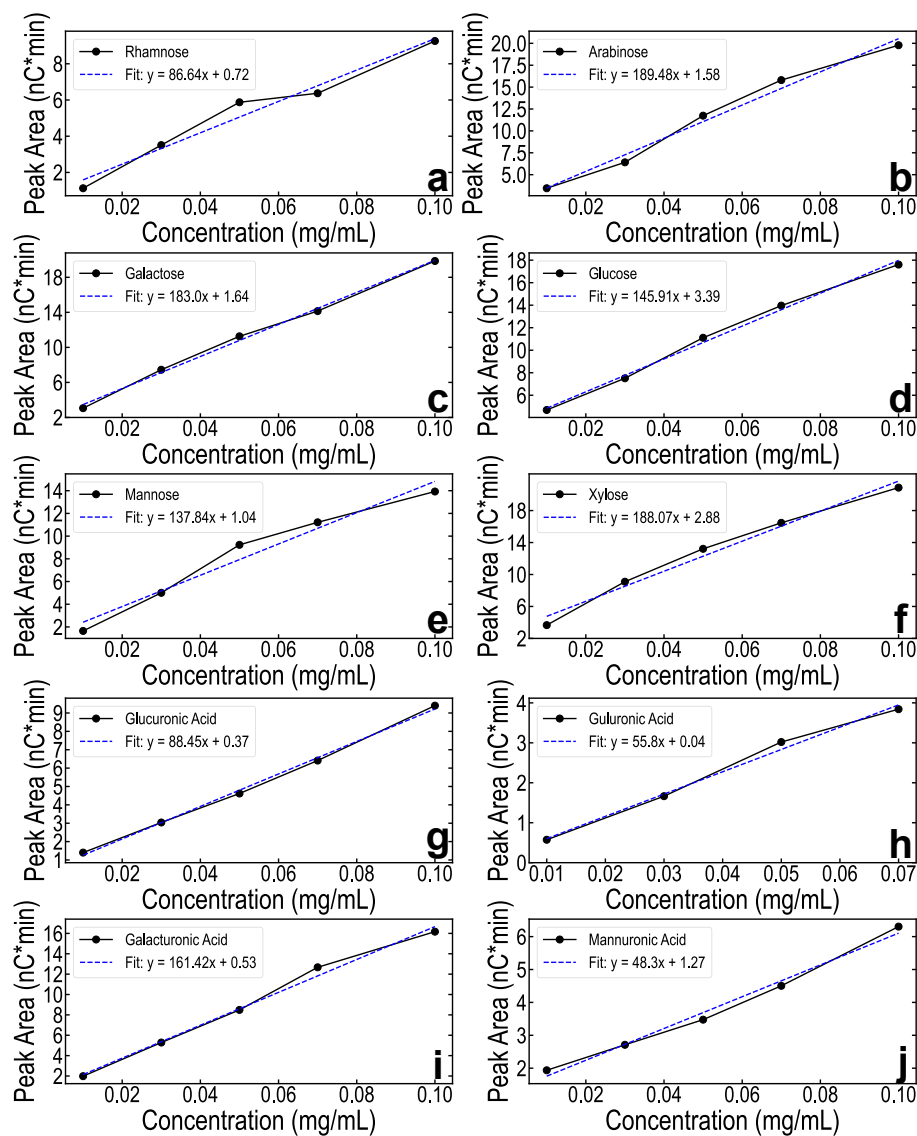


Figure S1: The calibration curves used to identify the concentrations of monosaccharides in macroalgae. The peak areas of standard monosaccharides a) rhamnose, b) arabinose, c) galactose, d) glucose, e) mannose, f) xylose, g) glucuronic acid, h) guluronic acid, i) galacturonic acid, and j) mannuronic acid were measured using HPAEC-PAD at different concentrations the macroalgae chromatograms.

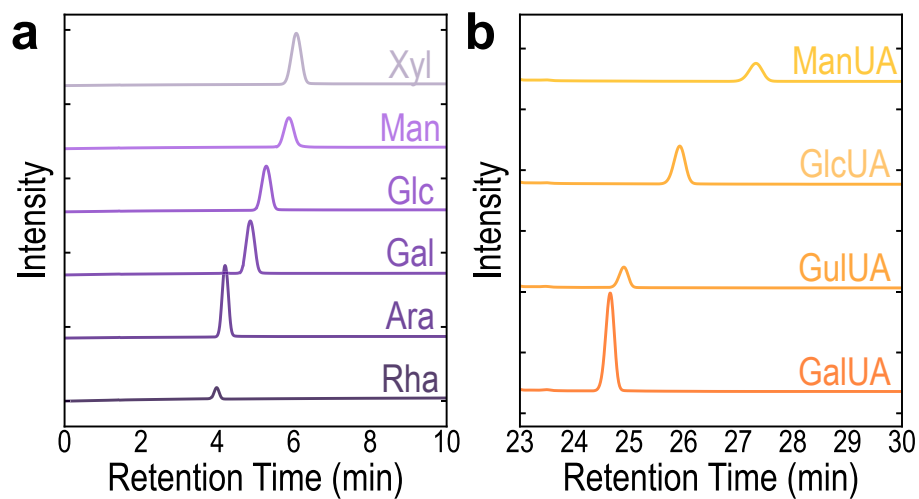


Figure S2: The chromatograms for 0.1 mg/mL concentration sugar standards analyzed using HPAEC-PAD. The a) neutral sugars (rhamnose, arabinose, galactose, glucose, mannose, and xylose) are separated from the b) uronic acids (galacturonic acid, guluronic acid, glucuronic acid, and mannuronic acid) in order to improve clarity.

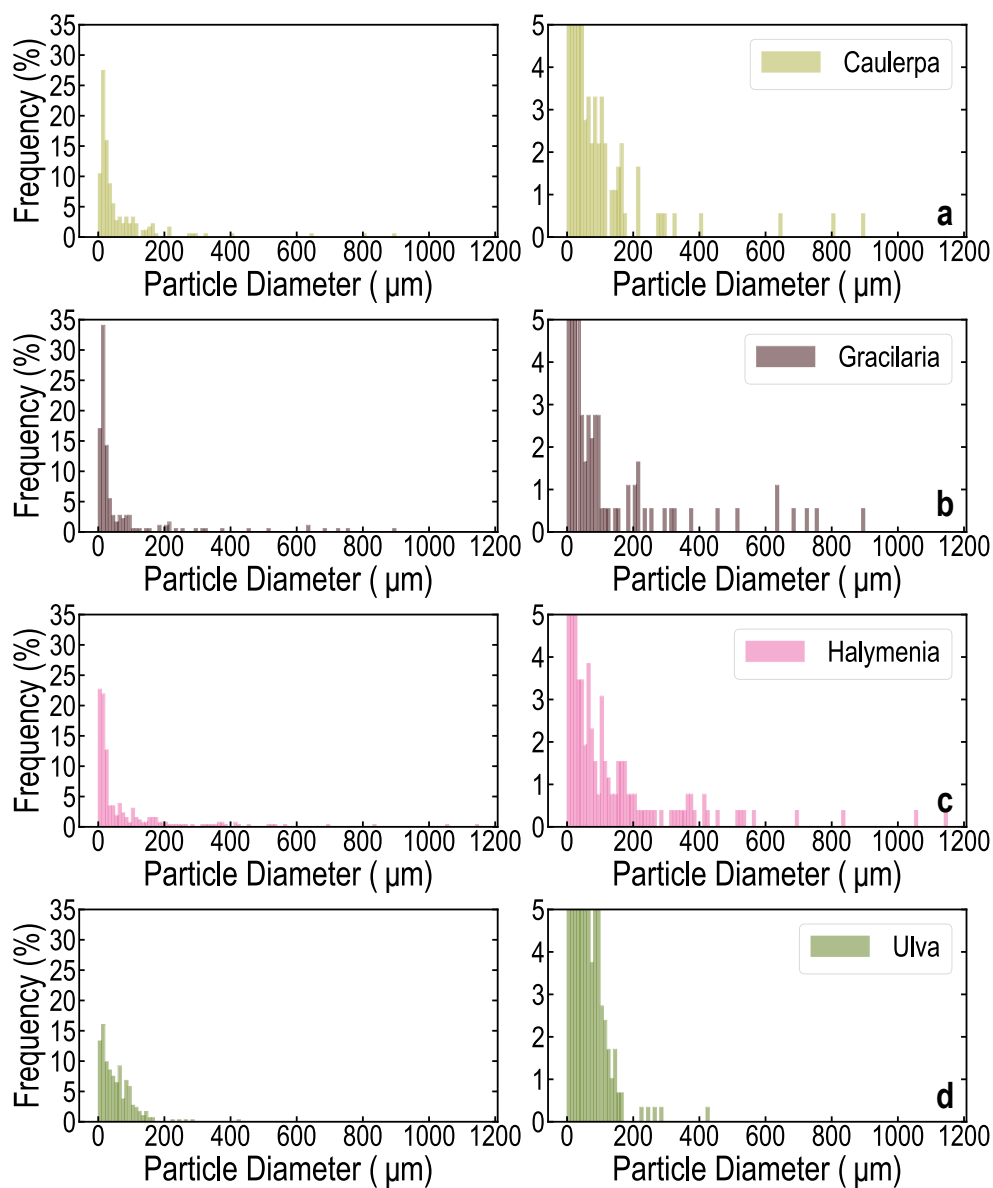


Figure S3: The particle size distributions, expressed using Feret's diameter, for ground a) *Caulerpa*, b) *Gracilaria*, c) *Halymenia*, and d) *Ulva* powders.

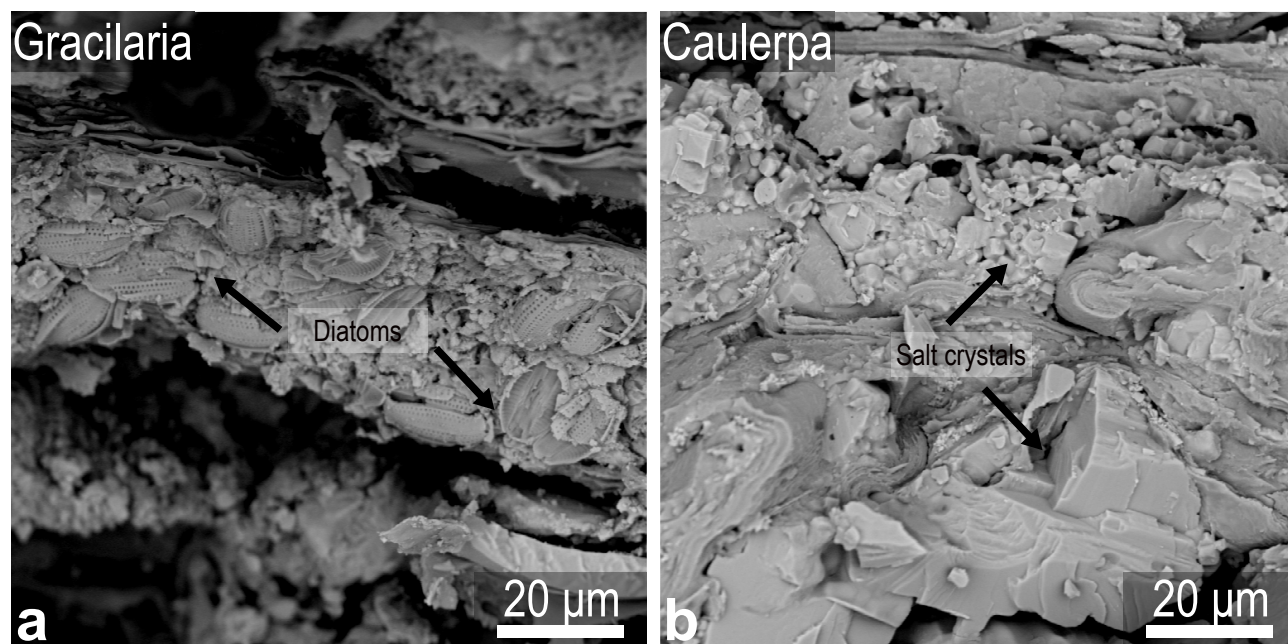


Figure S4: Examples of inorganic impurities identified within macroalgal bioplastics using SEM micrographs. a) Diatoms were observed in Gracilaria and b) salt crystals were observed in Caulerpa

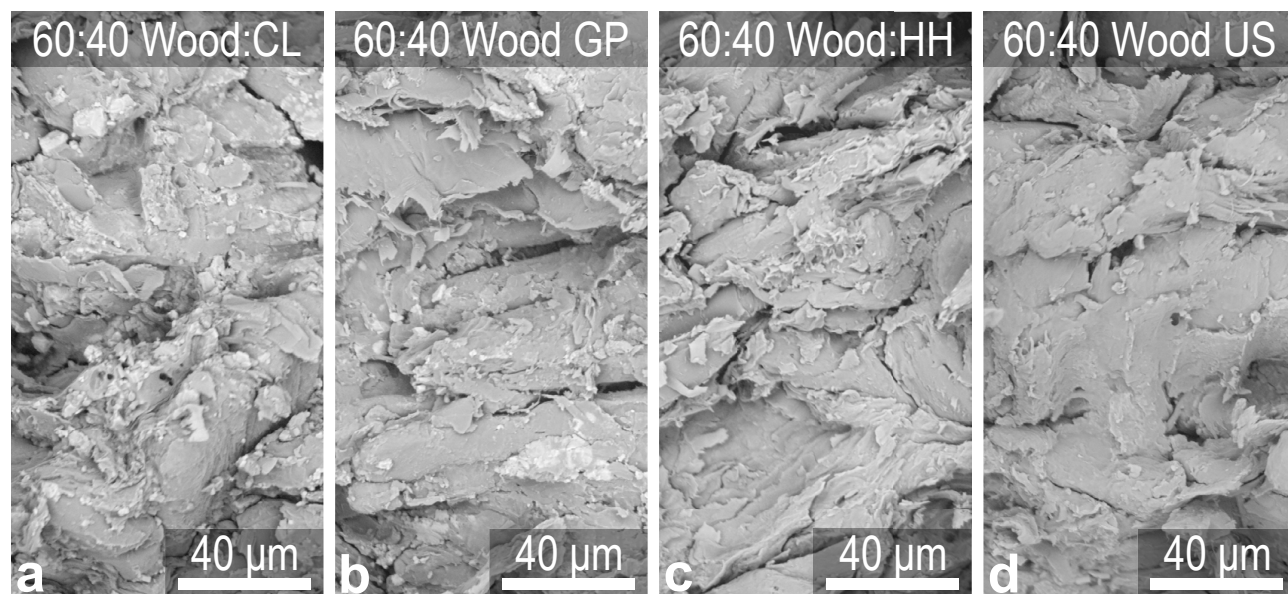


Figure S5: SEM images of wood composites fabricated using 60 wt% Douglas fir and 40 wt% a) Caulerpa, b) Gracilaria, c) Halymenia, and d) Ulva.

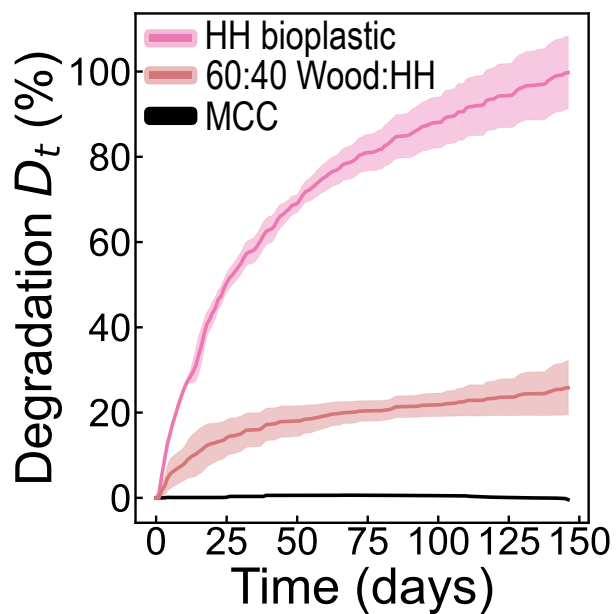


Figure S6: The percentage degradation in sea water of Halymenia bioplastics and 60:40 wood:Halymenia (wood:HH) biocomposites compared to the microcrystalline cellulose (MCC) control. The percentage degradation is calculated by comparing the total oxygen consumption to the theoretical oxygen consumption in aerobic conditions. The shaded regions surrounding each curve represent ± 1 standard deviation of the average degradation at each point.

References

- [1] P. Perumal, A. Aravinth, S. Dhanasundaram, R. Rajaram, P. Santhanam, M. Palanisamy, R. A. James, *Food and Humanity* **2023**, *1*, 1659–1669.
- [2] R. Zhu, V. Yadama, *Biomass and Bioenergy* **2016**, *90*, 78–89.
- [3] R. Kathahira, T. J. Elder, G. T. Beckham, *Lignin Valorization: Emerging Approaches Energy and Environment Series No. 19* **2018**, *19*, 1–20.
- [4] M. J. Suota, T. A. da Silva, S. F. Zawadzki, G. L. Sasaki, F. A. Hansel, M. Paleologou, L. P. Ramos, *Industrial Crops and Products* **2021**, *173*, 114138.
- [5] P. Grandgeorge, I. R. Campbell, H. Nguyen, R. Brain, M. Parker, S. Edmundson, D. Rose, K. Homolke, C. Subban, E. Roumeli, *MRS Bulletin* **2024**, *49*, 787–801.
- [6] R. M. Rowell, R. Pettersen, M. A. Tshabalala, *In: Handbook of Wood Chemistry and Wood Composites 2nd Edition; Chapter 3. pp. 33-72. 2013.* **2012**, *3*, 33–72.