



Review

Agar production and potential application in CO₂ capture and sequestrationYuling Yang^{a,b,c}, Siwei Tang^c, Wenhao Wu^c, Chengji Wang^d, Guang Gao^{b,c,*}^a College of Life and Environmental Sciences, Huangshan University, Huangshan, 245021, China^b Ocean Decade International Cooperation Center, Qingdao, 266000, China^c State Key Laboratory of Marine Environmental Science, College of Ocean and Earth Sciences, Xiamen University, Xiamen, 361005, China^d Institute of Resources, Environment and Soil Fertilizer, Fujian Academy of Agricultural Sciences, Fujian Province Key Laboratory of Agro-Ecological Processes in Hilly Red Soil, Fuzhou, Fujian, 350013, China

ARTICLE INFO

Keywords:

Agar
Macroalgae
Sustainable production
Carbon capture
Carbon sequestration

ABSTRACT

Agar, a polysaccharide abundant in red macroalgae, has been extensively used in the fields of food, chemical and biomedical industries due to its unique physicochemical properties. However, current understanding of its production potential and application in carbon capture and sequestration remains fragmented. This review comprehensively compiles and analyzes the agar content in red macroalgae (43 species from 29 studies), revealing a wide interspecific variation ranging from as low as 3.5% to up to 62.3% of dry weight, which is also significantly influenced by different extraction methods. Notably, alkali treatment commonly reduces agar recovery compared with traditional water extraction. Global biomass trends of *Gracilaria* and *Gelidium*, two key agar-production genera, are further analyzed noting a distinct shift in their supply mode from wild harvest to aquaculture, particularly for *Gracilaria*. Based on suitable area for seaweed cultivation worldwide, the agar production could reach $61.25 \times 10^9 \text{ t yr}^{-1}$. Due to its structural complexity and bacterial metabolic constraints, agar exhibits the potential to sequester CO₂ in the oceans, with a theoretical carbon sequestration of $19.29 \times 10^9 \text{ t yr}^{-1}$. The latest agar-based green technology in CO₂ capture and current research challenges is also reviewed. Finally, a model of agar's sustainable utilization in carbon capture and sequestration is proposed, integrating high-value biomedicine and large-volume carbon sequestration. By synthesizing production dynamics and green technologies, this study provides novel insights into unlocking agar's potential as a sustainable biopolymer for blue bioeconomy and carbon-neutral initiatives.

1. Introduction

Agar is a complex hydrophilic polysaccharide predominantly extracted from the cell walls of red macroalgae (Rhodophyta), particularly species of *Gracilaria* and *Gelidium* [1]. Agar has a documented history of human use dating back to 1658, when it was extracted from the agarophyte seaweed *Gracilaria* for culinary purposes. Originating in the Far East, its cultivation and application later expanded to other agarophyte-producing nations [2]. After Japan pioneered numerous novel uses for agar, the material gained attention in Europe and was introduced there in 1859 [3]. Agarose, the principal functional component accounting for 58–97% of agar (Table 1), is a linear unbranched polysaccharide composed of repeating disaccharide units of β -D-galactopyranose and 3,6-anhydro- α -L-galactopyranose, linked by α -(1 $\rightarrow$ 3) and β -(1 $\rightarrow$ 4) glycosidic bonds [4]. Within red macroalgal cells, agar/agarose serves critical physiological roles: it forms a rigid

structural network that maintains cell turgor pressure and structural integrity, enabling algae to withstand mechanical stress and osmotic fluctuations in marine environments; additionally, it functions as a storage polysaccharide to reserve energy and carbon, and participates in cell signaling pathways regulating growth and stress responses [5,6].

The unique physicochemical and biological properties of agar, including excellent gelling ability, thermal stability, biocompatibility, biodegradability, and non-toxicity, have endowed it with widespread applications across multiple industries [7]. In the food industry, it is widely used as a gelling agent, thickener, and stabilizer in products such as jellies, dairy desserts, and canned foods [8]. In the biomedical and pharmaceutical fields, agarose is a key material for preparing cell culture media, drug delivery carriers, and biosensors, owing to its ability to mimic the extracellular matrix and support cell proliferation [9]. In the chemical industry, it serves as a template for nanomaterial synthesis and a coagulant in wastewater treatment [10].

* Corresponding author at: Ocean Decade International Cooperation Center, Qingdao, 266000, China.

E-mail address: guang.gao@xmu.edu.cn (G. Gao).<https://doi.org/10.1016/j.ijbiomac.2026.152532>

Received 18 March 2026; Received in revised form 30 April 2026; Accepted 12 May 2026

Available online 14 May 2026

0141-8130/© 2026 Elsevier B.V. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

Table 1

Overview of agar content, gel strengthen, extraction method, composition and molecular weight (MW) in different red seaweed species. Slash means data unavailable, and % DW means % algal dry weight.

Species	Location	Extraction method	Agar yield (% DW)	Agarose (% agar)	3,6-Anhydrogalactose (% agar)	Gel strength (g cm ⁻²)	Sulfate (%DW)	Reference
<i>Agarophyton chilensis</i>	Burgos, Spain	Hot water	26.0 ± 1.1	82			2.1 ± 0.014	[19]
<i>Agarophyton chilensis</i>	Burgos, Spain	NaOH	6.8 ± 0.7	77			0.4 ± 0.007	[19]
<i>Gelidiella acerosa</i>	San Juan de los Cayos, Venezuela	Hot water	21			561		[99]
<i>Gelidiella acerosa</i>	Bolinao, Pangasinan, Philippines	Hot water	24.0 ± 3.2			33 ± 13		[100]
<i>Gelidiella acerosa</i>	Bolinao, Pangasinan, Philippines	NaOH	12.7 ± 2.5			189 ± 26		[100]
<i>Gelidiella acerosa</i>	Oahu, USA	Hot water	37.21		38.34	493	1.64	[101]
<i>Gelidium canariensis</i>	Agate, Mexico	Autoclaved	17.3 ± 0.7–31.7 ± 0.7			532 ± 17–840 ± 74		[102]
<i>Gelidium canariensis</i>	Bocabarranco, Mexico	Autoclaved	17.8 ± 0.9–29.0 ± 1.0			527 ± 34–846 ± 27		[102]
<i>Gelidium corneum</i>	Burgos, Spain	Hot water	10.9 ± 0.3	97			3.2 ± 0.02	[19]
<i>Gelidium corneum</i>	Burgos, Spain	NaOH	3.5 ± 0.3	94			0.3 ± 0.05	[19]
<i>Gelidium floridanum</i>	Isla de Margarita, Venezuela	Autoclaved	31.7		35.8	1030.0	2.4	[103]
<i>Gelidium pluma</i>	Hawaii Island	Hot water	36.30		35.45	930	4.10	[101]
<i>Gelidium pusillum</i>	Kauai, USA	Hot water	27.78		36.99	554	1.41	[101]
<i>Gelidium rex</i>	Pupuya, Chile	Hot water	15.7–36.0		29.0–36.9	460–590	2.2–4.2	[104]
<i>Gelidium rex</i>	Pupuya, Chile	NaOH			39.7–45.4	750–890	0.5–1.6	[104]
<i>Gelidium robustum</i>	Punta Prieta, Mexico	Na ₂ CO ₃	17.5 ± 0.0–44.2 ± 0.2			515 ± 6–665 ± 13	2.12 ± 0.03–2.74 ± 0.04	[105]
<i>Gelidium serrulatum</i>	Playa Bordonas, Venezuela	Autoclaved	33.0		38.1	380.0	2.6	[103]
<i>Gelidium serrulatum</i>	Trinidad	Autoclaved	40.8		34.7	385.0	2.8	[103]
<i>Gracilaria abbottiana</i>	Oahu, USA	NaOH/ Ca(OH) ₂	14.75			17	16.17	[101]
<i>Gracilaria arcuata</i>	San Luis, Batangas, Philippines	Native	17.2 ± 0.9		28.5 ± 0.24	161 ± 4	4.17 ± 0.26	[106]
<i>Gracilaria arcuata</i>	San Luis, Batangas, Philippines	NaOH	18.8 ± 3.1		30.6 ± 0.65	278 ± 2	3.79 ± 0.23	[106]
<i>Gracilaria blodgettii</i>	Dzilam de Bravo, Mexico	Hot water	36.3 ± 1.0		33.3 ± 0.6	760 ± 100	3.0 ± 0.1	[107]
<i>Gracilaria blodgettii</i>	Dzilam de Bravo, Mexico	3%NaOH	26.1 ± 0.7		37.7 ± 0.6	582 ± 66	3.5 ± 0.3	[107]
<i>Gracilaria blodgettii</i>	Dzilam de Bravo, Mexico	5%NaOH	24.5 ± 0.9		41.3 ± 3.6	490 ± 25	3.4 ± 0.2	[107]
<i>Gracilaria blodgettii</i>	Dzilam de Bravo, Mexico	7%NaOH	23.5 ± 0.4		33.1 ± 0.6	557 ± 183	3.4 ± 0.2	[107]
<i>Gracilaria bursa-pastoris</i>	Thau lagoon, France	Autoclaved	34.8 ± 0.28		1.70	22.2 ± 3.6		[108]
<i>Gracilaria bursa-pastoris</i>	Thau lagoon, France	Autoclaved	36.5–38.3			22.4 ± 0.7–41.3 ± 1.2		[109]
<i>Gracilaria bursa-pastoris</i>	Thau lagoon, France	Autoclaved	27.63 ± 4.87		0.76 ± 0.11	101.78 ± 65.28	1.87 ± 0.13	[110]
<i>Gracilaria bursapastoris</i>	Oahu, USA	NaOH/ Ca(OH) ₂	31.94		37.87	181	9.54	[101]
<i>Gracilaria canaliculata</i>	Hawaii Island, USA	NaOH/ Ca(OH) ₂	31.07		29.19	295	4.32	[101]

(continued on next page)

Table 1 (continued)

Species	Location	Extraction method	Agar yield (% DW)	Agarose (% agar)	3,6-Anhydrogalactose (% agar)	Gel strength (g cm ⁻²)	Sulfate (%DW)	Reference
<i>Gracilaria cervicornis</i>	Sian Ka'an, Mexico	Hot water	39.3 ± 0.6		38.3 ± 0.8	46 ± 0	5.3 ± 0.3	[107]
<i>Gracilaria cervicornis</i>	Sian Ka'an, Mexico	3%NaOH	24.4 ± 2.7		36.9 ± 0.2	46 ± 0	5.7 ± 0.1	[107]
<i>Gracilaria cervicornis</i>	Sian Ka'an, Mexico	5%NaOH	25.4 ± 1.1		37.7 ± 1.4	46 ± 0	5.5 ± 0.1	[107]
<i>Gracilaria cervicornis</i>	Sian Ka'an, Mexico	7%NaOH	25.7 ± 0.9		39.7 ± 1.2	46 ± 0	5.6 ± 0.1	[107]
<i>Gracilaria cervicornis</i>	Buzios beach, Brazil	Autoclaved	10.9 ± 1.1–20.5 ± 0.3					[111]
<i>Gracilaria changii</i>	Morib, Malaysia	Autoclaved	10.9 ± 1.2–25.1 ± 5.5			293.7 ± 57.7–562.5 ± 60.4		[112]
<i>Gracilaria changii</i>	Morib, Malaysia	Autoclaved	22.56 ± 0.59			360.33 ± 22.46		[113]
<i>Gracilaria changii</i>	Batu Besar, Malaysia	Autoclaved	20.5			283.51		[113]
<i>Gracilaria changii</i>	Teluk Pelanduk, Malaysia	Autoclaved	18.77 ± 0.93			205.85		[113]
<i>Gracilaria coronopifolia</i>	Oahu, USA	NaOH/ Ca(OH) ₂	47.42		34.49	53	11.79	[101]
<i>Gracilaria cliftonii</i>	Perth, Australia	Hot water	38.2 ± 1.3–62.3 ± 0.7			109 ± 2–246.7 ± 28.0	4.8 ± 0.9–8.2 ± 0.9	[114]
<i>Gracilaria cliftonii</i>	Perth, Australia	NaOH	11.2 ± 0.7–19.8 ± 1.1			131.2 ± 5.1–235.7 ± 4.1	2.2 ± 0.2–3.1 ± 0.2	[114]
<i>Gracilaria corticata</i>	Gulf of Mannar, India	Autoclaved	16 ± 0.77			100 ± 6.19	6.8 ± 0.23	[115]
<i>Gracilaria corticata</i>	Gulf of Mannar, India	3%NaOH	14 ± 0.81			100 ± 8.06	6.0 ± 0.15	[115]
<i>Gracilaria corticata</i>	Gulf of Mannar, India	4% NaOH	13 ± 0.77			100 ± 8.85	5.6 ± 0.17	[115]
<i>Gracilaria corticata</i>	Gulf of Mannar, India	6% NaOH	12 ± 0.85			100 ± 7.72	4.7 ± 0.08	[115]
<i>Gracilaria corticata</i>	Gulf of Mannar, India	8% NaOH	11 ± 0.72			110 ± 6.29	4.2 ± 0.08	[115]
<i>Gracilaria corticata</i>	Gulf of Mannar, India	10% NaOH	10 ± 0.85			110 ± 7.93	4.2 ± 0.08	[115]
<i>Gracilaria corticata</i>	Gulf of Mannar, India	15% NaOH	9.5 ± 0.5			110 ± 8.94	4.2 ± 0.07	[115]
<i>Gracilaria crassa</i>	Gulf of Mannar, India	Autoclaved	23 ± 0.86			250 ± 15.20	3.2 ± 0.15	[115]
<i>Gracilaria crassa</i>	Gulf of Mannar, India	3% NaOH	22 ± 0.73			330 ± 12.65	2.9 ± 0.23	[115]
<i>Gracilaria crassa</i>	Gulf of Mannar, India	4% NaOH	21 ± 0.93			420 ± 17.12	2.4 ± 0.15	[115]
<i>Gracilaria crassa</i>	Gulf of Mannar, India	6% NaOH	18 ± 0.75			640 ± 16.68	2.0 ± 0.08	[115]
<i>Gracilaria crassa</i>	Gulf of Mannar, India	8% NaOH	16 ± 0.86			800 ± 15.40	1.8 ± 0.08	[115]
<i>Gracilaria crassa</i>	Gulf of Mannar, India	10% NaOH	15 ± 0.80			800 ± 15.43	1.6 ± 0.07	[115]
<i>Gracilaria crassa</i>	Gulf of Mannar, India	15% NaOH	12 ± 0.84			800 ± 16.12	1.5 ± 0.04	[115]
<i>Gracilaria crassissima</i>	Sian Ka'an, Mexico	Hot water	29.9 ± 2.8		34.9 ± 0.8	178 ± 25	4.2 ± 0.3	[107]
<i>Gracilaria crassissima</i>	Sian Ka'an, Mexico	3%NaOH	18.4 ± 0.4		37.1 ± 2.4	1176 ± 33	1.3 ± 0.0	[107]
<i>Gracilaria crassissima</i>	Sian Ka'an, Mexico	5%NaOH	15.4 ± 0.5		43.7 ± 3.2	1313 ± 29	1.3 ± 0.3	[107]
<i>Gracilaria crassissima</i>	Sian Ka'an, Mexico	7%NaOH	13.0 ± 2.1		41.9 ± 2.4	1392 ± 54	1.2 ± 0.2	[107]
<i>Gracilaria debilis</i>	West Coast of India	Autoclaved	14.8 ± 0.5		28.7 ± 1.0	490 ± 25	0.76 ± 0.08	[116]
<i>Gracilaria debilis</i>	West Coast of India	NaOH	13.1 ± 0.5		33.1 ± 1.0	650 ± 25	0.21 ± 0.06	[116]
<i>Gracilaria dura</i>	Thau lagoon, France	Autoclaved	33.5 ± 0.50		0.71	318 ± 49		[108]
<i>Gracilaria dura</i>	Thau lagoon, France	Autoclaved	34 ± 1.00		0.73 ± 0.05	455 ± 97.85	1.02 ± 0.03	[117]
<i>Gracilaria edulis</i>	Morib, Malaysia	Autoclaved	28.37 ± 0.12			166.66 ± 8.62		[113]
<i>Gracilaria edulis</i>	Batu Besar, Malaysia	Autoclaved	23.11			78.05		[113]

(continued on next page)

Table 1 (continued)

Species	Location	Extraction method	Agar yield (% DW)	Agarose (% agar)	3,6-Anhydrogalactose (% agar)	Gel strength (g cm ⁻²)	Sulfate (%DW)	Reference
<i>Gracilaria edulis</i>	Teluk Pelanduk, Malaysia	Autoclaved	19.88 ± 0.65			93.15 ± 11.31		[113]
<i>Gracilaria edulis</i>	Gulf of Mannar, India	Autoclaved	25 ± 0.76			100 ± 7.30	5.4 ± 0.23	[115]
<i>Gracilaria edulis</i>	Gulf of Mannar, India	3% NaOH	23 ± 0.89			135 ± 7.71	3.6 ± 0.15	[115]
<i>Gracilaria edulis</i>	Gulf of Mannar, India	4% NaOH	20 ± 0.86			220 ± 8.50	2.7 ± 0.16	[115]
<i>Gracilaria edulis</i>	Gulf of Mannar, India	6% NaOH	18 ± 0.83			340 ± 8.56	2.1 ± 0.07	[115]
<i>Gracilaria edulis</i>	Gulf of Mannar, India	8% NaOH	16 ± 0.87			490 ± 8.16	1.4 ± 0.07	[115]
<i>Gracilaria edulis</i>	Gulf of Mannar, India	10% NaOH	13 ± 0.73			490 ± 7.72	1.3 ± 0.08	[115]
<i>Gracilaria edulis</i>	Gulf of Mannar, India	15% NaOH	11 ± 0.77			490 ± 8.34	1.3 ± 0.08	[115]
<i>Gracilaria edulis</i>	Ban Ang-Sila, Thailand	Hot water	10.90 ± 0.92		37.03 ± 2.83	197.08 ± 72.87	7.54 ± 0.18	[118]
<i>Gracilaria edulis</i>	Ban Ang-Sila, Thailand	5% NaOH	34.34 ± 1.74		43.06 ± 0.41	239.95 ± 28.35	4.92 ± 0.07	[118]
<i>Gracilaria ephippisor</i>	Hawaii Island	NaOH/ Ca(OH) ₂	30.91		35.80	168	2.55	[101]
<i>Gracilaria fisheri</i>	Samut Songkhram Research Station, Thailand	Hot water	13.33 ± 1.78		35.19 ± 0.00	145.61 ± 34.55	4.56 ± 0.14	[118]
<i>Gracilaria fisheri</i>	Samut Songkhram Research Station, Thailand	5% NaOH	39.55 ± 7.59		38.88 ± 1.88	228.27 ± 48.18	2.80 ± 0.04	[118]
<i>Gracilaria foliifera</i>	Gulf of Mannar, India	Autoclaved	22 ± 0.80			100 ± 8.56	5.7 ± 0.15	[115]
<i>Gracilaria foliifera</i>	Gulf of Mannar, India	3% NaOH	20 ± 0.85			100 ± 8.06	5.2 ± 0.08	[115]
<i>Gracilaria foliifera</i>	Gulf of Mannar, India	4% NaOH	18 ± 0.83			100 ± 8.34	4.6 ± 0.15	[115]
<i>Gracilaria foliifera</i>	Gulf of Mannar, India	6% NaOH	16 ± 0.77			120 ± 8.56	4.1 ± 0.08	[115]
<i>Gracilaria foliifera</i>	Gulf of Mannar, India	8% NaOH	15 ± 0.73			135 ± 7.63	3.8 ± 0.08	[115]
<i>Gracilaria foliifera</i>	Gulf of Mannar, India	10% NaOH	14 ± 0.79			135 ± 7.74	3.7 ± 0.07	[115]
<i>Gracilaria foliifera</i>	Gulf of Mannar, India	15% NaOH	12 ± 0.76			135 ± 8.00	3.7 ± 0.06	[115]
<i>Gracilaria gracilis</i>	Sea of Japan, Russia	Hot water	43.1 ± 1.6			277 ± 10		[119]
<i>Gracilaria gracilis</i>	Sea of Japan, Russia	NaOH/NaBH ₄	25.3 ± 0.7			405 ± 20		[119]
<i>Gracilaria gracilis</i>	Thau lagoon, France	Autoclaved	30.0 ± 0.45		0.71	630 ± 15		[108]
<i>Gracilaria gracilis</i>	Luderitz, Namibia	NaOH	17.08			859 ± 139.5		[21]
<i>Gracilaria gracilis</i>	Patagonic coast, Argentina	Hot water	26.7		42	437	6.8	[23]
<i>Gracilaria gracilis</i>	Tosa Bay, Japan	NaOH/H ₂ SO ₄	8.2–17.1			210 ± 5–859 ± 160		[21]
<i>Gracilaria gracilis</i>	Ganzirri Lagoon, Italy		13.2	57.5		880		[120]
<i>Gracilaria gracilis</i>	Thau lagoon, France	Autoclaved	25.75 ± 4.38		0.71 ± 0.04	543.26 ± 236.29	1.34 ± 0.17	[110]
<i>Gracilaria mammillaris</i>	San Juan de los Cayos, Venezuela	Hot water	27			12		[99]
<i>Gracilaria millardetii</i>	West Coast, India	Autoclaved	9.5 ± 0.3		32.70	<100	4.5 ± 0.12	[121]
<i>Gracilaria millardetii</i>	West Coast, India	NaOH	9.0 ± 0.3		40.90	<100	4.8 ± 0.14	[121]
<i>Gracilaria salicornia</i>	Morib, Malaysia	Autoclaved	13.63 ± 0.86			270.50 ± 23.66		[113]
<i>Gracilaria salicornia</i>	Batu Besar, Malaysia	Autoclaved	13.94			215.98		[113]

(continued on next page)

Table 1 (continued)

Species	Location	Extraction method	Agar yield (% DW)	Agarose (% agar)	3,6-Anhydrogalactose (% agar)	Gel strength (g cm ⁻²)	Sulfate (%DW)	Reference
<i>Gracilaria salicornia</i>	Chwaka Bay, Tanzania	Autoclaved	13.7 ± 1.0–28.1 ± 0.3		19.4 ± 3.0–44.0 ± 3.3	215 ± 15–275 ± 8	0.8 ± 0.77–2.55 ± 0.3	[122]
<i>Gracilaria salicornia</i>	Chwaka Bay, Tanzania	NaOH	10.4 ± 1.0–22.3 ± 3.2		23.3 ± 3.2–42.6 ± 3.0	100 ± 1–241 ± 8	0.52 ± 0.5–1.81 ± 1.01	[122]
<i>Gracilaria salicornia</i>	Oyster Bay, Tanzania	Autoclaved	16.3 ± 0.2–30.2 ± 1.6		16.3 ± 1.5–37.4 ± 0.4	127 ± 17–240 ± 15	1.7 ± 0.45–2.8 ± 0.83	[122]
<i>Gracilaria salicornia</i>	Oyster Bay, Tanzania	NaOH	7.0 ± 2.2–26.1 ± 2.1		17.5 ± 1.3–34.2 ± 1	107 ± 17–162 ± 12	0.9 ± 0.78–2.33 ± 0.6	[122]
<i>Gracilaria salicornia</i>	West Coast, India	Autoclaved	15.2 ± 0.5		23.8 ± 1.0	350 ± 25	3.37 ± 0.12	[116]
<i>Gracilaria salicornia</i>	West Coast, India	NaOH	13.2 ± 0.5		28.1 ± 1.0	510 ± 25	0.45 ± 0.06	[116]
<i>Gracilaria</i> sp.	Shimonoseki Sea, Japan	Hot water	39.42 ± 0.71		38.11 ± 2.84	202.31 ± 7.39	3.75 ± 0.06	[118]
<i>Gracilaria</i> sp.	Shimonoseki Sea, Japan	5% NaOH	31.30 ± 1.79		52.55 ± 7.24	334.50 ± 14.1	0.40 ± 0.04	[118]
<i>Gracilaria tenuistipitata</i>	Nha Trang, Vietnam	Hot water	27.9 ± 0.3			130 ± 5		[119]
<i>Gracilaria tenuistipitata</i>	Nha Trang, Vietnam	NaOH/NaBH ₄	15.8 ± 0.1			295 ± 45		[119]
<i>Gracilaria tenuistipitata</i>	Lake of Songkhla, Thailand	Hot water	17.1 ± 1.6		25.1 ± 1.7	97 ± 7	4.3 ± 0.1	[123]
<i>Gracilaria tenuistipitata</i>	Lake of Songkhla, Thailand	3% NaOH	26.1 ± 1.5		45.2 ± 0.7	419 ± 30	2.0 ± 0.2	[123]
<i>Gracilaria tenuistipitata</i>	Lake of Songkhla, Thailand	5% NaOH	25.3 ± 1.3		53.2 ± 0.7	481 ± 31	1.6 ± 0.1	[123]
<i>Gracilaria tenuistipitata</i>	Lake of Songkhla, Thailand	7% NaOH	24.6 ± 0.9		45.6 ± 2.3	451 ± 24	1.7 ± 0.1	[123]
<i>Gracilaria tenuistipitata</i>	Lake of Songkhla, Thailand	3% KOH	24.2 ± 1.2		31.7 ± 1.0	406 ± 31	2.5 ± 0.2	[123]
<i>Gracilaria tenuistipitata</i>	Lake of Songkhla, Thailand	5% KOH	25.2 ± 5.0		32.7 ± 1.0	432 ± 6	2.2 ± 0.3	[123]
<i>Gracilaria tenuistipitata</i>	Lake of Songkhla, Thailand	7% KOH	23.6 ± 1.6		33.0 ± 1.7	445 ± 17	2.3 ± 0.1	[123]
<i>Gracilaria tenuistipitata</i>	Layog, Sorsogon, Philippines	Hot water	32.9 ± 2.4		34.0 ± 0.14	304 ± 23	3.90 ± 0.21	[106]
<i>Gracilaria tenuistipitata</i>	Layog, Sorsogon, Philippines	NaOH	15.7 ± 2.8		42.1 ± 0.37	606 ± 42	3.34 ± 0.08	[106]
<i>Gracilaria textorii</i>	West Coast, India	Autoclaved	10.3 ± 0.3		44.70	<100	2.1 ± 0.09	[121]
<i>Gracilaria textorii</i>	West Coast, India	NaOH	8.8 ± 0.3		31.60	<100	2.3 ± 0.11	[121]
<i>Gracilaria vermiculophylla</i>	Ria de Aveiro, Portugal	6%NaOH+ 3.5 h pretreatment+1.5 h Extraction	24.7 ± 1.7		43.4 ± 0.7	636 ± 149	2.00 ± 0.02	[124]
<i>Gracilaria vermiculophylla</i>	Ria de Aveiro, Portugal	6%NaOH+ 3.5 h pretreatment+2 h Extraction	29.4 ± 0.9		42.5 ± 0.9	614 ± 59	1.86 ± 0.02	[124]
<i>Gracilaria vermiculophylla</i>	Ria de Aveiro, Portugal	6%NaOH+ 3.5 h pretreatment+2.5 h Extraction	24.5 ± 0.5		43.1 ± 1.0	412 ± 41	1.89 ± 0.10	[124]
<i>Gracilaria vermiculophylla</i>	Ria de Aveiro, Portugal	6%NaOH+ 3.5 h pretreatment+3 h Extraction	26.5 ± 1.3		44.2 ± 0.8	394 ± 84	1.92 ± 0.25	[124]
<i>Gracilariopsis bailinae</i>	Cam Ranh, Vietnam	Hot water	29.5 ± 0.4			130 ± 7		[119]

(continued on next page)

Table 1 (continued)

Species	Location	Extraction method	Agar yield (% DW)	Agarose (% agar)	3,6-Anhydrogalactose (% agar)	Gel strength (g cm ⁻²)	Sulfate (%DW)	Reference
<i>Gracilariaopsis balliniae</i>	Cam Ranh, Vietnam	NaOH/NaBH ₄	13.7 ± 0.8			305 ± 1		[119]
<i>Gracilariaopsis longissima</i>	Burgos, Spain	Hot water	25.6 ± 4.1	71			2.1 ± 0.003	[19]
<i>Gracilariaopsis longissima</i>	Burgos, Spain	NaOH	3.9 ± 0.3	75			0.2 ± 0.007	[19]
<i>Hydrodictyon cornea</i>	Maracajau beach, Brazil	Autoclaved	29.2 ± 3.1–41.0 ± 2.6					[111]
<i>Laurencia flexilis</i>	Currimao, Philippines	Hot water	25.7 ± 0.5		31.4 ± 1.2	200 ± 5	1.9 ± 0.2	[125]
<i>Laurencia flexilis</i>	Currimao, Philippines	NaOH	19.3 ± 0.4		29.5 ± 1.5	175 ± 24	2.2 ± 0.1	[125]
<i>Pterocladia caerulea</i>	Oahu, USA	Hot water	41.19		37.72	1174	3.18	[101]
<i>Pterocladia capillacea</i>	Playa Bordonas, Venezuela	Autoclaved	32.1		33.9	735.3	3.7	[103]
<i>Pterocladia capillacea</i>	Hawaii Island, USA	Hot water	44.03		37.50	1137	3.06	[101]

While these traditional and industrial applications have driven agar research for decades, the escalating urgency of global climate change has recently redirected attention toward the previously overlooked CO₂ capture function of this biopolymer (Fig. 1). Traditional industrial CO₂ capture technologies, including chemical absorption, physical adsorption, and membrane separation, currently dominate large-scale carbon control. However, these approaches suffer from high energy consumption, high costs, solvent degradation, and equipment corrosion, limiting their sustainability and large-scale deployment. There is therefore an urgent demand for greener, more cost-effective, and eco-friendly biological alternatives [11,12]. From the perspective of the global carbon cycle, red macroalgae, as important primary producers in marine ecosystems, contribute significantly to biological CO₂ capture by fixing atmospheric CO₂ through photosynthesis; agar, as a major carbon-containing component of red algae, plays a vital role in carbon sequestration, storing fixed carbon in marine environments over long periods and thus regulating the global carbon balance [13]. This biological CO₂ capture process mediated by agar-rich red macroalgae offers a green and sustainable pathway for CCUS, complementing traditional industrial capture technologies. Recent research has focused on the potential of agar in carbon capture, which has emerged as a promising sustainable strategy to mitigate global climate change and advance carbon-neutral initiatives [14–16]. Furthermore, global climate change (e.g., ocean warming and acidification, marine heatwaves) is exerting profound impacts on the growth and physiology of red macroalgae, thereby potentially affecting agar content, structure, and functionality [17,18]. These climate-induced changes may further disrupt the carbon sequestration capacity of agar/agarose and its ecological roles in marine ecosystems, with far-reaching implications for the global carbon cycle and CCUS potential. Despite this rising interest, the ecological functions of agar, including its production, carbon sequestration potential, CO₂ capture technologies and sustainable utilization, remain critically fragmented in the literature.

Given the above context, this review defines its scope and objective as an integrated synthesis across five interconnected domains. (1) To summarize the distribution patterns of agar in red macroalgae is analyzed. (2) To analyze the production trends of agar by red macroalgae, emphasizing how global change variables (temperature, CO₂, nutrient availability) influence agar yield and quality. (3) To assess the ecological roles of agar in marine carbon sequestration, specifically highlighting the currently fragmented knowledge on its degradation pathways and carbon sequestration potential. (4) To summarize recent advances in agar-based green technology in CO₂ capture. (5) To propose a comprehensive and sustainable utilization strategy for agar that integrates high-value product development, CO₂ capture, bioenergy recovery, and ecological carbon sequestration. By integrating these five perspectives, this review can unlock the potential of agar as a sustainable biopolymer for the blue bioeconomy and carbon-neutral goals, while also identifying priority research directions to fill the identified ecological knowledge gaps.

2. Production of agar

2.1. Agar content in red macroalgae

Agar content exhibits considerable variability, spanning from 3.5 to 62.3% (Table 1). This variation is largely species-specific. Specifically, *Gracilaria cliftonii* displays the highest agar content (62.3%), whereas *Gelidium corneum* shows the lowest (3.5%). Furthermore, extraction methodologies significantly impact the final yield. Alkali treatment typically reduces agar recovery. For example, when compared to hot water extraction (26.0%), alkali treatment decreased the agar yield of *Agarophyton chilensis* to 6.8% [19]. Similarly, the agar yield of *Gelidium corneum* dropped from 10.9% (hot water) to 3.5% following alkali processing [19]. Despite this yield reduction, alkali pretreatment yields agar of superior quality—it is readily water-soluble and leaves minimal

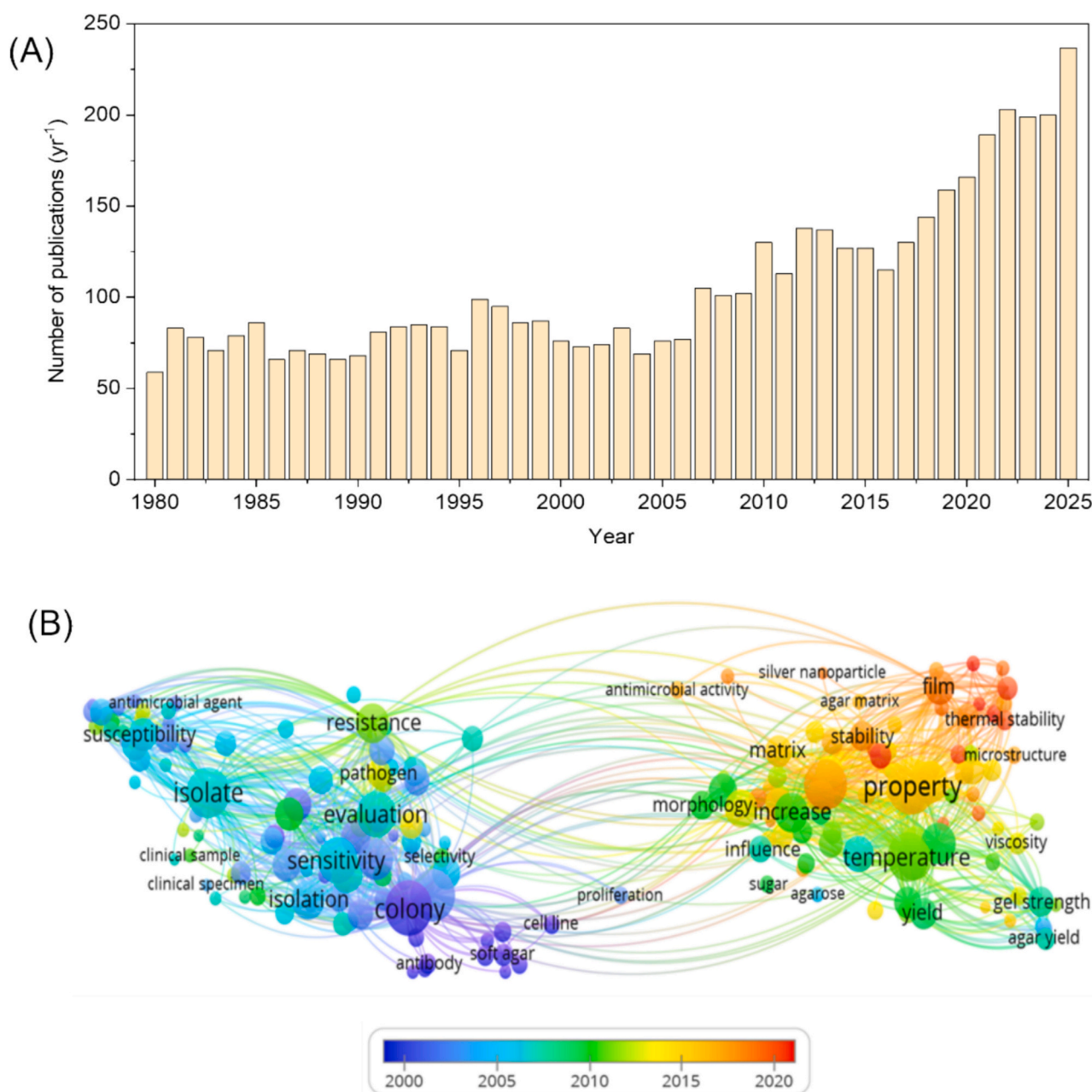


Fig. 1. Publication trends (A) and research hotspots (B) in agar research. Bibliometric analysis was conducted using the Web of Science database, with the search query applied to titles and abstracts containing “Agar” through March 2026. Panel A illustrates the temporal distribution of publications. Panel B presents a network visualization of keyword co-occurrence, where nodes represent individual keywords sized proportionally to their occurrence frequency; edges indicate co-occurrence relationships within the same publication, with thickness reflecting association strength; and node colors denote the year of peak publication frequency for each keyword. The visualization was generated using VOSviewer.

insoluble residue [20]. Seasonal fluctuations also influence agar content. For instance, *Gracilaria gracilis* exhibits its lowest agar content (8.2%) in April and peak content (17.1%) in June [21]. This pattern is likely attributed to the associated increase in ambient temperature, which rose from 17 °C in April to 23 °C in June.

2.2. Agar gel strength

The gel strength of agar ranges from 12 g cm⁻² to 1392 g cm⁻², with the lowest value obtained from *Gracilaria mamillaris* and the highest from *Gracilaria crassissima* (Table 1). Beyond interspecies differences, extraction methodologies also exert a significant influence on agar gel strength. For example, native agar extracted from *Gracilaria manilaensis*

exhibited a very low gel strength (< 60 g cm⁻²), whereas this value increased to 454 g cm⁻² following alkali pretreatment of the thalli [22]. Alkali-modified agar is obtained by subjecting red algae to an alkali pretreatment step prior to extraction. This process converts galactose-6-sulfate (L6S) groups into 3,6-anhydrogalactose, thereby enhancing the gel strength of the polymer [23]. Meanwhile, alkali pretreatment can also reduce sulfate content in agar (Table 1). For instance, alkali pretreatment resulted in the decrease of sulfate content in agar extracted from *Agarophyton chilensis* from 2.1 ± 0.014% to 0.4 ± 0.007% [19].

2.3. Global agar production patterns

Agar production largely depends on the biomass of red macroalgae that contain high agar content, e.g., *Gracilaria* and *Gelidium* species. Here the production of *Gracilaria* and *Gelidium* seaweeds from both wild capture and aquaculture was analyzed.

Chile dominated global *Gracilaria* capture production (Fig. 2A). From 1950 to 1970, capture volumes remained low ($< 1 \times 10^3$ t), but surged sharply in the middle 1980s (peaking at 113×10^3 t). Volumes fluctuated thereafter but remained elevated through 2020; contributions from “Others” were negligible across the period. *Gracilaria* aquaculture production (Fig. 2B) was negligible globally until the 1990s, after which China emerged as the primary producer: its output grew exponentially from 442×10^3 t (2003) to 6108×10^3 t (2021). “Others” contributed modestly but were dwarfed by China’s expansion. The proportion of *Gracilaria* from aquaculture (Fig. 2C) remained $< 10\%$ before 1985, then rose rapidly to $> 50\%$ (i.e., aquaculture exceeded capture) by 2003, reflecting China’s dominance in cultivated production (consistent with Fig. 2B).

Gelidium capture production (Fig. 2D) involved multiple regions: Taiwan (China) had low, stable volumes pre-1970; Chile and Spain expanded modestly in the 1980s–1990s. All regions’ capture volumes show a declined trend toward 2020. *Gelidium* aquaculture (Fig. 2E) was minimal until the 1990s: North Korea had small, transient production in the 1990s, which was then replaced with China after 2002.

The proportion of *Gelidium* from aquaculture (Fig. 2F) remained near 0% before 1990, then increased intermittently (peaking at 65% in 2006) and rose sharply again after 2010, aligned with China’s aquaculture expansion (Fig. 2E).

2.4. Agar production in future

Anthropogenic activities have driven continuous increases in atmospheric CO_2 , leading to ocean acidification and warming [24]. These environmental changes significantly affect algal physiology, community structure, and ecological functions [25,26]. Concurrently, the sustained discharge of nitrogen and phosphorus from terrestrial sources and aquaculture operations has caused widespread coastal eutrophication [27,28], triggering increased algal blooms and ecosystem regime shifts [29].

Agar production depends fundamentally on two parameters: the agar content within seaweed thalli and the total biomass of agar-containing red macroalgae. Despite the persistent anthropogenic pressures of eutrophication, ocean warming, and acidification, their direct impacts on agar content remain poorly understood due to limited empirical data. Current understanding relies largely on surrogate indicators such as carbohydrate content.

Ocean warming or acidification individually increased carbohydrate content in *Gracilaria lemaneiformis*, with combined treatments producing further enhancement, whereas elevated nitrogen availability showed no significant effect [30]. By contrast, carbohydrate content in *Gracilaria manilaensis* exhibited seasonal variation, reaching higher levels in winter ($39.56 \pm 0.26\%$) than in summer ($35.30 \pm 0.34\%$) [31]. Similar results were found in *Gelidium crinale* that commonly had higher agar content in winter and in summer [32]. This discrepancy likely stems from differences in experimental temperatures: Liu et al. [30] applied a 4°C increase from 20 to 24°C for *G. lemaneiformis*, whereas field temperatures ranged from 25.0°C (winter) to 30.5°C (summer) for *Gracilaria manilaensis* [31] and 18.0°C (winter) to 29.3°C (summer) for *Gelidium crinale*. These findings suggest that carbohydrate content in *Gracilaria* follows a unimodal pattern, initially increasing and subsequently

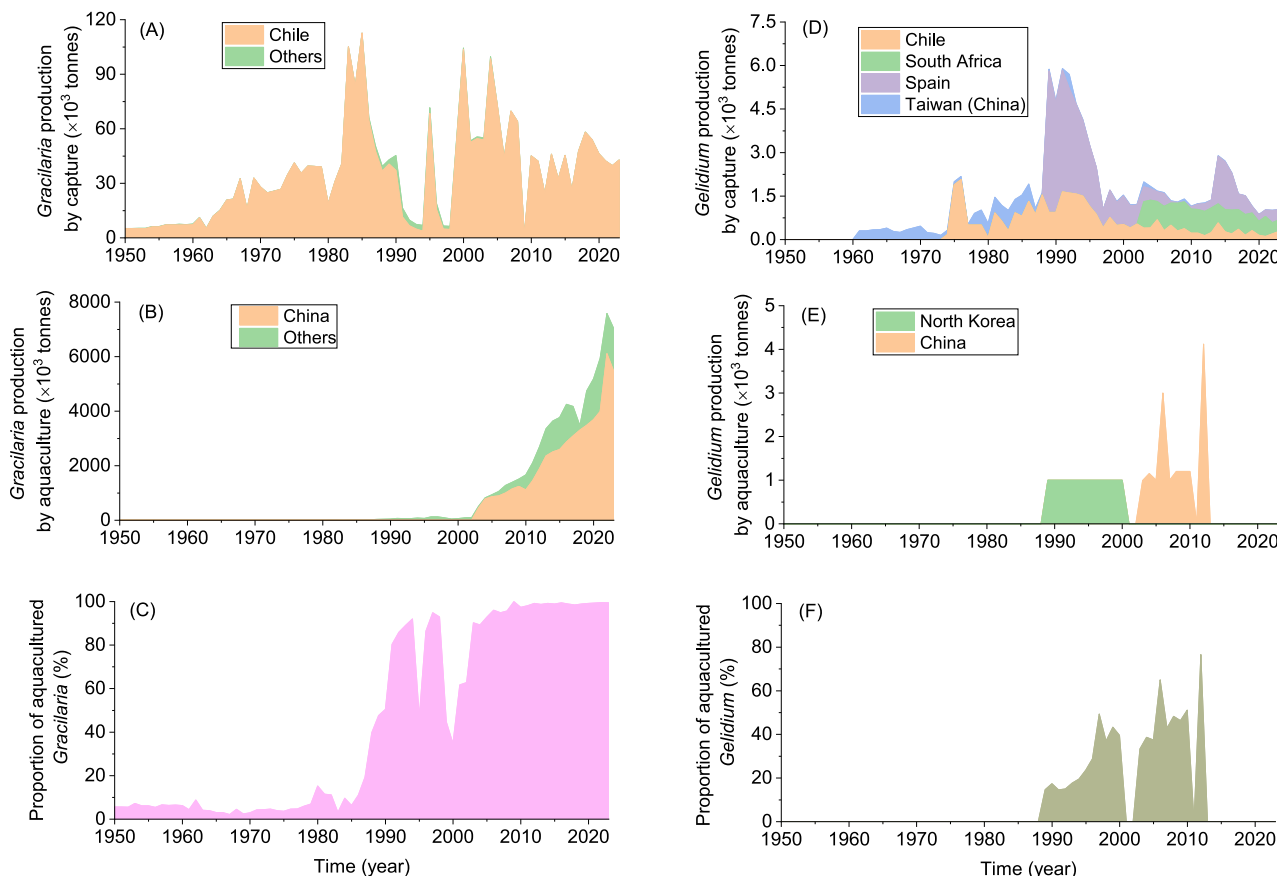


Fig. 2. Global production (fresh weight) of *Gracilaria* (A, B, C) and *Gelidium* (D, E, F) by wild harvesting and aquaculture. Data sources are FAO database (FishStatJ).

decreasing with rising temperature. In terms of eutrophication, carbohydrate content in *G. manilaensis* declined under eutrophic conditions (N/P concentrations increased from 50/5 $\mu\text{mol/L}$ to 500/50 $\mu\text{mol/L}$) compared to control treatments (10/1 $\mu\text{mol/L}$) [33], presumably due to enhanced protein synthesis under elevated nitrogen availability. On the other hand, agar content of *Gelidium crinale*s increased initially and then declined, with the tipping point at 500 $\mu\text{mol/L}$ nitrogen [32]. Collectively, while ocean warming and acidification may enhance carbohydrate accumulation, eutrophication appears unfavorable for carbohydrate storage in *G. manilaensis*.

While global environmental changes may alter agar content, shifts in *Gracilaria* productivity and biomass can also substantially influence agar production. Ocean acidification alone did not affect the growth rate of *G. lemaneiformis*; however, warming (from 20 to 24 °C) significantly enhanced growth, particularly under concurrent elevated CO₂ levels (700 ppm), indicating synergistic effects of ocean acidification and warming [34]. Conversely, growth rates declined when temperatures exceeded 25 °C, with complete growth cessation at 30 °C and negative growth at 35 °C [35], suggesting that the thermal threshold for *G. lemaneiformis* lies near 30 °C. Regarding eutrophication effects, *G. lemaneiformis* exhibited increased growth rates when N/P concentrations rose from 50/3.13 $\mu\text{mol/L}$ to 400/25 $\mu\text{mol/L}$; however, growth declined significantly when N/P concentrations exceeded 400/25 $\mu\text{mol/L}$. [36] Collectively, these findings suggest that *G. lemaneiformis* productivity will likely increase under future environmental conditions (warming, acidification, and moderate eutrophication), except in tropical regions where temperatures approach the species' upper thermal limit. Combined with observed trends in carbohydrate content, carbohydrate productivity in *G. lemaneiformis* will likely increase in future ocean scenarios, suggesting an enhanced supply of agar. However, given the reliance on surrogate indicators and the aforementioned limitations of extrapolation, future projections of agar production remain subject to considerable uncertainty and require direct measurements of agar content for validation. Specifically, total carbohydrates comprise a broad mixture of soluble sugars, starch, cellulose, and other cell wall polysaccharides, and do not perfectly represent agar concentration. Changes in total carbohydrate content therefore cannot be simply equated with changes in agar yield, as the relative proportion of agar within total carbohydrates can shift significantly under environmental stressors. Furthermore, the regulatory mechanisms underlying agar biosynthesis differ from those governing general carbohydrate metabolism, meaning environmental effects on bulk carbohydrates may not reflect true effects on agar.

3. Carbon sequestration of agar

3.1. Degradation of agar

Agar, a complex galactan from red algal cell walls, can be degraded by marine bacteria, e.g., *Alteromonas marina*, *Vibrio alginolyticus*, *Zobellia galactanivorans*, *Saccharophagus degradans* 2–40 [37,38]. These bacteria secrete extracellular agarases to break down the agar polymer through a coordinated enzymatic cascade, primarily involving three key pathways and carbohydrate-active enzymes (CAZymes) encoded in polysaccharide utilization loci (PULs) [37,39]: (1) β -agarolytic pathway (dominant): β -agarases (EC 3.2.1.81) from glycoside hydrolase (GH) families 16, 50, 86, and 118 cleave the β -(1,4) glycosidic linkages between D-galactose (G) and 3,6-anhydro-L-galactose (LA) in agarose. This produces neoagar-oligosaccharides (e.g., neoagarobiose, neoagarotetraose, neoagarooctaose). Subsequent hydrolysis by α -neoagarobiose hydrolases (GH117) breaks these oligosaccharides into monomers (G and LA) for bacterial metabolism. (2) α -agarolytic pathway: α -agarases (EC 3.2.1.158, GH96) target the α -(1,3) linkages of neoagarose moieties, generating agarotetraose and agarohexaose. Further degradation of these intermediates requires uncharacterized hydrolases (e.g., agarotetraose hydrolase), which remain a research gap.

(3) β -porphyranolytic pathway: β -porphyranases (GH16) hydrolyze the β -(1,4) linkages in porphyran (a sulfated agar variant with G-L6S repeating units), producing neoporphyrobiose (L6S-G). Additional enzymes (e.g., α -neoporphyrobiose hydrolase, arylsulfatases) are needed to remove sulfate groups and convert intermediates into G and L6S/LA [37,39].

Agar degradation is biochemically challenging due to its structural complexity and bacterial metabolic constraints, supported by the following evidence: (1) Structural barriers: Agar's hybrid structure (alternating G-LA and G-L6S units) and modifications (sulfate, methyl groups) require specialized enzymes for each unique linkage. For example, sulfate groups on L6S block CAZyme binding, necessitating sulfatases for efficient degradation. Methylated residues further demand energy-consuming demethylases (e.g., P450 monooxygenases) before hydrolysis [40]. (2) Enzymatic specificity and redundancy: Bacteria require a minimum number of CAZymes proportional to agar's structural complexity ($R^2 = 0.89$). Specialist bacteria (e.g., *Zobellia galactanivorans*) encode up to 9 agar/porphyran-specific enzymes, while generalist marine bacteria often lack complete PULs for agar degradation [39]. (3) Nutrient and energy constraints: Expressing and secreting multiple CAZymes consumes nitrogen and energy, limiting degradation efficiency in nutrient-poor marine environments. Immobilization of agar-degrading bacteria (e.g., via sodium alginate-calcium chloride) further reduces accessibility between enzymes and substrates, inhibiting degradation. (4) Persistence in the ocean: Agar-derived glycans have a residence time of 1–3 years in surface waters, with some fractions persisting for millennia. This persistence confirms that bacterial degradation cannot keep pace with agar synthesis in many marine ecosystems [41]. Notably, agar degradation by bacteria is severely environment-dependent. For instance, the oligosaccharide yield from agar degradation by *Flammeovirga pacifica* WPAGA1 increased from 1.05 to 1.27 g/L when the N:P ratio in the medium was raised from 3:1 to 5:1, and then decreased to 1.19 g/L as the N:P ratio further increased to 7:1. Meanwhile, the oligosaccharide yield rose from 1.06 to 1.52 g/L with the temperature increasing from 30 to 37 °C, but declined from 1.56 to 1.31 g/L when the medium pH was enhanced from 7.0 to 8.5 [42].

3.2. Carbon sequestration potential by agar

As mentioned above, the degradation of agar in the ocean is a complex, enzyme-dependent process. Its resistance to degradation arises from its structural complexity, the substrate specificity of carbohydrate-active enzymes (CAZymes), and various environmental constraints, making agar a promising candidate for ocean carbon sequestration.

In 2023, the biomass of wild and cultivated *Gracilaria* was 442.78×10^3 and 7021.57×10^3 t (fresh weight), respectively. Assuming agar accounts for 40% of cellular dry weight (Table 1) and fresh to dry weight ratio is 10 [43], *Gracilaria* was estimated to produce 298.57×10^3 t of agar. Similarly, wild *Gelidium* had a biomass of 1.03×10^3 t (fresh weight). With agar comprising 30% of cellular dry weight (Table 1) and fresh to dry weight ratio is 10 [43], *Gelidium* was estimated to yield 0.03×10^3 t of agar. In total, *Gracilaria* and *Gelidium* combined could produce 298.60×10^3 t of agar annually, equivalent to 94.03×10^3 t of sequestered carbon, assuming that carbon content of agar is 47% and the transformation rate of agar to refractory carbon is 67% [17].

Furthermore, the global area suitable for seaweed cultivation is approximately 48 million km² [44]. If this entire area were used for *Gracilaria* cultivation, with a productivity of $3.19 \text{ kg m}^{-2} \text{ yr}^{-1}$ [28], the annual agar production could reach 61.25×10^9 t, corresponding to 19.29×10^9 t of sequestered carbon. Notably, agar serves not only as a structural component of algal cell walls but can also be released into seawater as dissolved organic carbon (DOC). When DOC contributions are included, the total carbon sequestration via agar would be even higher. Meanwhile, it is worth noting that this estimation carries a certain degree of uncertainty, which arises mainly from two aspects. First, the productivity of *Gracilaria* may vary considerably under

different marine environmental conditions (e.g., temperature, salinity, nutrients, and light), leading to fluctuations in agar production. Second, the transformation rate from agar to refractory carbon (67%) used in this calculation was derived from an average ratio of dissolved organic matter, owing to the lack of species-specific conversion data for agar. Further studies based on long-term in situ observations and agar-specific carbon preservation experiments are needed to constrain these parameters more precisely.

4. Agar-based technology for CO₂ capture

4.1. CO₂ Capture technologies

Under the severe situation of global climate change, CO₂, as the most prominent greenhouse gas, its excessive emission-induced greenhouse effect has triggered a series of environmental issues such as glacier melting, sea-level rise, and frequent extreme weather events, seriously threatening human survival and sustainable development [26,45]. Therefore, Carbon Capture and Storage (CCS) technology, as well as the Carbon Capture, Utilization, and Storage (CCUS) technology developed on this basis, have become key means to mitigate the greenhouse effect and achieve global carbon emission reduction goals, attracting extensive attention from the global scientific and industrial communities.

Currently, CO₂ capture technologies mainly include chemical absorption, physical adsorption, membrane separation, etc. [46] Chemical absorption utilizes chemical solvents to react with CO₂ for selective absorption, featuring high capture efficiency and large absorption capacity. However, it faces problems such as high solvent regeneration energy consumption, severe equipment corrosion, and easy solvent degradation, leading to high operating costs [47]. Physical adsorption achieves CO₂ adsorption under specific conditions based on physical interactions (e.g., van der Waals forces) between adsorbents and CO₂ molecules. This method boasts fast adsorption rate and regenerable adsorbents but suffers from limited adsorption capacity and strict requirements on adsorption conditions [48]. Membrane separation separates CO₂ from mixed gases using the selective permeability of special membrane materials, offering advantages like simple operation, low energy consumption, and compact equipment. Nevertheless, factors such as membrane performance, stability, and cost restrict its large-scale application [46]. These mainstream technologies encounter bottlenecks of high energy consumption, high cost, and low efficiency in practical applications, failing to meet the demands of large-scale industrial CO₂ capture. Thus, the development of novel, efficient, and low-cost CO₂ capture materials and technologies is imminent.

4.2. Physicochemical properties of agar for CO₂ capture

Agar is a natural polysaccharide extracted from red algae (e.g., *Gelidium* and *Gracilaria*), primarily composed of agarose (accounting for approximately 70% of the total mass) and agaropectin—with agarose serving as the core component determining its fundamental properties [20]. Agarose forms a linear molecular skeleton via the alternate linkage of D-galactose and 3,6-anhydro-L-galactose through α -1,3 and β -1,4 glycosidic bonds, while agaropectin features a similar backbone modified with substituted groups such as sulfate ($-\text{OSO}_3^-$), pyruvate, and acetylated hydroxyl groups ($-\text{OCOCH}_3$), rendering agar's chemical structure complex and diverse [49]. Overall, agar molecular chains are rich in highly polar and chemically active functional groups including hydroxyl ($-\text{OH}$) and sulfate ($-\text{OSO}_3^-$), along with ether bonds, which lay the structural foundation for its unique physicochemical properties and interaction with CO₂ molecules [15,50].

Agar exhibits a host of excellent physicochemical and biological properties derived from its special molecular and supramolecular structure. Driven by tight intermolecular hydrogen bonds, it forms a highly cross-linked network structure and displays a reversible thermogelation property: it dissolves in water to form a homogeneous

solution when heated above 85–95 °C (due to hydrogen bond breakage) and reassembles into a stable three-dimensional porous network gel when cooled below -40 °C, with the gel possessing a melting point around 85 °C and good thermal stability [50–52]. Upon cooling, agarose chains form anti-symmetric double helices, which then aggregate into suprafibers via exterior hydroxyl groups, creating a three-dimensional continuous network [53]. This porous structure is characterized by uniformly distributed pores of varying sizes, which, together with the high specific surface area brought by the cross-linked structure, provides abundant channels and surface space for gas molecule diffusion and adsorption; its relatively low density further reduces the overall mass of the material and modulates gas diffusion performance during adsorption [15]. In addition, agar shows good chemical stability, resisting degradation and unwanted chemical reactions under common acid–base conditions (pH 4–10) and temperature ranges (40–85 °C), and maintains structural and performance stability [5]. It also has excellent biocompatibility, being non-toxic to organisms and non-immunogenic, which has underpinned its wide application in biomedicine, food and other fields [54].

The structural characteristics of agar endow it with significant research value and application potential for the development of novel CO₂ capture materials. The abundant hydroxyl and sulfate groups on its molecular chains act as key active sites for CO₂ adsorption: hydroxyl groups can form weak hydrogen bonds with CO₂ molecules, a mechanism supported by density functional theory studies showing that polar functional groups such as hydroxyl and carboxyl improve carbon surface polarity and facilitate CO₂ adsorption through hydrogen bond formation [55]. Meanwhile, sulfate groups engage in electrostatic interactions or chemical reactions with CO₂, thereby achieving effective CO₂ capture [15,50]. On this basis, high-performance CO₂ capture materials can be prepared via agar modification or compounding with other materials. For instance, the prepared Li₄SiO₄ pellets with agar showed higher CO₂ sorption capacities (>0.330 g CO₂/g sorbent) than the corresponding sorbent powder and excellent cyclic durability [15]. Calcined carbide slag pellets containing 15 wt% corncob powder (CCS-15cp) had the largest specific surface area of 15.610 m²/g, 44% higher than that of calcined carbide slag powder without agar or corncob (CCS-p); after 15 cyclic captures, the CO₂ capture capacity of CCS-15cp was 0.336 gCO₂/g sorbent, 20% higher than CCS-p [16] which provides new ideas and technical approaches for breaking through the bottlenecks of existing CO₂ capture technologies.

4.3. Interaction mechanisms with CO₂ molecules

The overall adsorption process follows a sequential event chain, as illustrated below: (1) Approach phase: CO₂ molecules in the gas phase diffuse toward the agar surface, driven by concentration gradients and initial van der Waals attraction; (2) Orientation and polarization: Due to the dipole moment of CO₂ (asymmetric O=C=O structure), molecules gradually align under the influence of local electrostatic fields generated by negatively charged sulfate groups ($-\text{OSO}_3^-$) on agar chains; (3) Hydrogen bond formation: Polar hydroxyl groups ($-\text{OH}$) on agar interact with the oxygen atoms of CO₂, forming multiple weak hydrogen bonds. Although each bond is weak, the abundant hydroxyl groups collectively create a strong binding effect; (4) Electrostatic attraction: The negative charges of sulfate groups electrostatically attract the positively polarized end of CO₂ dipoles, enhancing adsorption selectivity and anchoring CO₂ molecules more firmly; (5) Multi-layer accumulation and saturation: As the surface sites become occupied, additional CO₂ molecules are held by van der Waals forces and further hydrogen bonding in outer layers until equilibrium is reached.

Multiple interaction mechanisms exist between agar and CO₂ molecules, which synergistically contribute to agar's certain adsorption capacity for CO₂.

Hydrogen bonding is one important interaction mode. The numerous hydroxyl groups ($-\text{OH}$) on Agar molecular chains are highly polar, with

hydrogen atoms carrying partial positive charges, while oxygen atoms in CO₂ molecules carry partial negative charges. When Agar comes into contact with CO₂ molecules, hydrogen atoms in hydroxyl groups can form hydrogen bonds with oxygen atoms in CO₂ molecules [56,57]. Although individual hydrogen bonds are relatively weak, the cumulative effect of a large number of hydroxyl groups in Agar enhances the binding force between Agar and CO₂, thereby promoting the CO₂ adsorption process.

Van der Waals forces also constitute a key component of the interactions between Agar and CO₂ [55]. Van der Waals forces, including dispersion forces, induction forces, and orientation forces, are universal weak intermolecular interactions. Agar and CO₂ molecules attract each other through van der Waals forces, allowing CO₂ molecules to approach and be adsorbed on the Agar surface [58]. Thanks to Agar's high specific surface area and special network structure, the scope of van der Waals forces is expanded, enabling more CO₂ molecules to interact with molecules on the Agar surface and further increasing the CO₂ adsorption capacity [55].

Electrostatic interaction also plays a critical role in the interactions between Agar and CO₂ [59]. Sulfate groups (–OSO₃[–]) on Agar molecules carry negative charges, while CO₂ molecules, although electrically neutral overall, possess a certain dipole moment due to their asymmetric molecular structure, resulting in partial positive charges at one end and partial negative charges at the other [60]. The negative charges of sulfate groups on Agar molecules generate electrostatic attraction with the dipole moment of CO₂ molecules. This electrostatic interaction endows Agar with high adsorption selectivity for CO₂ molecules, enabling it to preferentially adsorb CO₂ while exhibiting low adsorption capacity for other non-polar or weakly polar gas molecules, thereby improving the CO₂ capture efficiency in mixed gases [59].

Agar forms specific adsorption with CO₂ molecules through hydrogen bonding, van der Waals forces, and electrostatic interactions. These interaction mechanisms highlight agar's unique advantages in the field of CO₂ capture, laying a theoretical foundation for the further development of high-efficiency CO₂ capture materials based on Agar.

4.4. Application as adsorbents in physical/chemical adsorption methods

4.4.1. Pressure swing adsorption (PSA) and temperature swing adsorption (TSA) modification

Pressure Swing Adsorption (PSA) and Temperature Swing Adsorption (TSA) are commonly used industrial gas separation and purification technologies, widely applied in CO₂ capture. However, traditional adsorbents such as silica gel and molecular sieves have limitations in terms of adsorption capacity, selectivity, and cyclic stability [61]. As a natural polysaccharide material with unique structure and properties, Agar provides a new approach to improve the performance of traditional adsorbents.

Compounding agar with traditional adsorbents like silica gel and molecular sieves is an effective method to prepare high-performance adsorbent materials. During compounding, Agar can combine with traditional adsorbents through physical or chemical interactions to form porous composite adsorbents with unique structures and properties. Agar exhibits good hydrophilicity due to a large number of polar groups such as hydroxyl groups (–OH) in its molecular structure, which can form hydrogen bonds with water molecules. When compounded with traditional adsorbents, its hydrophilicity can adjust the surface polarity of the adsorbent, making the surface more conducive to interactions with CO₂ molecules. Meanwhile, Agar's porous structure can provide additional adsorption sites for CO₂ molecules, optimizing CO₂ adsorption kinetics and thus improving adsorption rate and capacity.

In practical application scenarios of low-concentration CO₂ capture (10%–15%), researchers prepared agar-molecular sieve composite materials and conducted comparative experiments with single molecular sieves. The results showed that the adsorption capacity of the agar-molecular sieve composite increased by 12%–17% compared with

the single molecular sieve [16]. This is because the addition of agar not only increases the specific surface area of the adsorbent but also enhances the adsorption capacity for CO₂ molecules through its hydrophilicity and polar groups. In multiple adsorption-desorption cycle experiments, among the four preparation methods the sorbent pellets prepared with agar as binder and silicone mold as hydrophobic material showed exhibiting the highest total capture capacity of 7.70 g CO₂/g during 15 cyclic captures, indicating its efficient and stable cyclic CO₂ capture [62]. This is mainly attributed to agar's three-dimensional network structure, which can effectively inhibit the agglomeration and sintering of molecular sieve particles, maintain the structural stability of the adsorbent, and thus improve the cyclic performance.

4.4.2. Application as membrane materials in membrane separation methods

Membrane separation is an efficient and energy-saving CO₂ capture technology, and the performance of membrane materials is crucial for determining the membrane separation effect. As a natural polymer material with good film-forming properties and a unique molecular structure, agar can be blended with polymer materials such as polyamide and polysulfone, or loaded with inorganic fillers such as silica and carbon nanotubes to prepare organic-inorganic hybrid membranes, which has become an important research direction to improve membrane performance [63]. Quantitatively, blending natural polysaccharides (e.g., chitosan with agar) has been shown to increase the short-term tensile strength of the resulting film from 7.86H/mm² to over 33H/mm² after 28 days of storage, demonstrating a significant mechanical enhancement [63]. In the case of inorganic filler loading, the addition of 0.3 wt% nano-silica to a konjac glucomannan/carrageenan blend film reduced the oxygen transmission rate (OTR) to 0.016 g·m^{–2}·d^{–1} and the carbon dioxide transmission rate (CDTR) to 0.153 g·m^{–2}·d^{–1}, while increasing the tensile strength to 69.11 MPa [64]. These quantitative values illustrate the potential of blending and filler incorporation to improve membrane barrier and mechanical properties.

When agar is blended with polymer materials such as polyamide and polysulfone, agar molecules can be uniformly dispersed in the polymer matrix to form an interpenetrating network structure. This interpenetrating polymer network (IPN) is stabilized by multiple intermolecular interactions, primarily hydrogen bonding between the abundant hydroxyl groups (–OH) of agar and the polar functional groups (e.g., amide –CONH– in polyamide or ether –O– in polysulfone) of the synthetic polymer [63]. Evidence for such hydrogen bond formation can be found in FTIR spectra, where the broad O–H stretching band shifts from approximately 3330 cm^{–1} to lower wavenumbers (e.g., 3348 cm^{–1}) upon blending, indicating strong intermolecular hydrogen bonding [64,65]. Additionally, the compatibility between agar and polyamide/polysulfone can be further enhanced by the presence of sulfate groups (–OSO₃[–]) on agar, which may participate in electrostatic or dipole-dipole interactions with the polymer matrix [63]. Polar groups such as hydroxyl groups in agar molecules can form hydrogen bonds or other interactions with polymer molecules, enhancing compatibility between the two and making the structure of the hybrid membrane more stable [63]. Agar's molecular sieving effect enables selective filtration of gas molecules. The pore size and shape on its molecular chains have a certain regularity, allowing it to screen gas molecules based on their size and shape, only permitting gas molecules of specific sizes to pass through. Polar groups in Agar molecules have a strong affinity for CO₂ molecules, enabling specific interactions with CO₂ molecules and further improving the selective adsorption and transport capacity for CO₂ [66].

When loading inorganic fillers such as silica and carbon/metal nanoparticles, these inorganic fillers can be uniformly dispersed in the agar-based membrane material to form an organic-inorganic composite structure [65]. Mechanistically, the enhanced performance arises from: (i) the formation of hydrogen bonds between the surface hydroxyl groups of the inorganic filler (e.g., silanol –Si–OH on nano-silica) and the hydroxyl/carboxyl groups of agar, which promotes uniform dispersion

and prevents particle agglomeration [64,65]; (ii) the disruption of regular polymer chain packing by well-dispersed nanoparticles, creating additional free volume and facilitating gas diffusion [64]; and (iii) the intrinsic barrier properties of the filler, which can selectively hinder the permeation of larger gas molecules while allowing smaller molecules like CO₂ to pass [64]. Quantitatively, the incorporation of 0.3 wt% nano-silica into a polysaccharide blend film reduced the water vapor permeability (WVTR) from 806.4 g·m⁻²·d⁻¹ to 644.4 g·m⁻²·d⁻¹, and decreased the OTR by approximately 59% compared to the unfilled film [64]. Similarly, the tensile strength increased from 50.63 MPa to 69.11 MPa, demonstrating a clear reinforcement effect [64]. Silica has high chemical stability and mechanical strength, which can enhance the stability and mechanical properties of the hybrid membrane [64]. Carbon/metal nanoparticles possess excellent electrical conductivity and mechanical properties, which can improve the mass transfer performance and mechanical properties of the hybrid membrane [65]. By optimizing the type, content, and dispersion method of inorganic fillers, the pore size distribution and surface properties of the hybrid membrane can be effectively regulated. Studies have shown that the pore size distribution of agar-based hybrid membranes prepared through rational design can be controlled between 0.3 and 0.5 nm. This pore size distribution is conducive to the selective passage of CO₂ molecules while effectively blocking other gas molecules such as N₂, thereby improving the CO₂/N₂ separation factor [67–69].

Practical test results indicate that the agar-based membrane incorporating Na₂CO₃ (300% agar) and glycerol (30% agar) showed considerable CO₂ absorption capacity amounting to 92% of the theoretical maximum with simultaneous absorption of water vapor [66]. This demonstrates the significant advantages of agar-based hybrid membranes in CO₂ capture, which can greatly improve the selectivity for CO₂ while ensuring a certain CO₂ permeability, providing a more promising membrane material option for the practical application of membrane separation in CO₂ capture.

4.5. Research challenges

4.5.1. Large-scale production and cost control

The supply of seaweed raw materials is limited by seasons and regions, which also brings challenges to the large-scale production of agar. Seaweed grown in different seasons has differences in agar content and quality (Table 1). Seaweed varieties and growth environments in different regions also lead to differences in the quality and performance of agar. This makes it difficult to ensure stable raw material supply and consistent quality during large-scale agar production. The extraction process of agar is relatively complex. Extracting agar from red macroalgae usually involves multiple steps such as cleaning, soaking, alkali treatment, acid neutralization, filtration, and drying [20]. During alkali treatment, precise control of alkali concentration and treatment time is required to remove impurities from red algae and extract high-quality agar, which places high requirements on process operations. In the drying stage, different drying methods and conditions can significantly affect the quality and performance of agar. For example, traditional hot air drying may cause partial structural damage to agar, affecting its performance, while freeze-drying can better preserve agar's structure and performance but is costly [56,70].

Currently, the material cost of agar is relatively high, about 9 USD/kg, while traditional adsorbents such as monoethanolamine only cost about 5 USD/kg [71]. The high cost puts agar-based capture materials at a disadvantage in market competition, limiting their large-scale promotion and application. To reduce costs, it is necessary to develop more efficient extraction processes to improve the extraction rate and quality of agar, while finding stable raw material supply channels to reduce the impact of seasonal and regional factors.

4.5.2. Adaptability to complex flue gas environments

In actual industrial emission sources such as coal-fired power plants

and cement plants, the flue gas composition is complex. In addition to CO₂, it also contains acidic gases such as SO₂ and NO_x, as well as a large amount of water vapor [72]. These components can significantly affect the performance of Agar-based capture materials.

Acidic gases such as SO₂ and NO_x tend to compete for adsorption sites with sulfate groups in Agar molecules. Sulfate groups in Agar molecules are originally important active sites for interacting with CO₂, but when acidic gases such as SO₂ and NO_x are present in the flue gas, they will preferentially bind to sulfate groups, occupying adsorption sites, thereby reducing the CO₂ adsorption capacity of agar [73,74]. More critically, under humid flue gas conditions, these acidic gases dissolve in water vapor to form corrosive inorganic acids (e.g., H₂SO₃, H₂SO₄, HNO₃). The resulting acidic environment initiates multiple structural degradation mechanisms in agar: (i) acid-catalyzed hydrolysis of the glycosidic linkages (especially the β-1,4 linkages between D-galactose and 3,6-anhydro-L-galactopyranose) in the agarose backbone, leading to chain scission and a reduction in molecular weight [75]; (ii) desulfation of the sulfate ester groups at the C6 position of L-galactose units, which eliminates the primary CO₂-binding sites and simultaneously disrupts the polymer's charge distribution [76]; (iii) for NO_x species, nitration or oxidative side reactions may occur, inducing crosslinking or further chain degradation [77]. These degradation processes progressively weaken the mechanical integrity and long-term stability of agar-based membranes, manifesting as decreased CO₂ capture efficiency, increased material brittleness, and accelerated performance loss over time.

The swelling property of agar in high-humidity environments may also affect membrane structure stability. Agar has a certain degree of hydrophilicity. In high-humidity environments, agar molecules will absorb water and swell [78]. The swelling behavior of agar-based materials is highly dependent on their purity and modification state. For native agar, the gel typically exhibits limited water retention capacity (swelling ratio < 440%); in contrast, a hydrophobic modification strategy, such as esterification with glutaric anhydride, introduces a hydrophilic carboxyl group and a loose porous structure, providing more binding sites for water adsorption, and significantly enhances the swelling ratio to 1700% [78]. For agar-based membrane materials, swelling may lead to increased pore size and changed pore structure, thereby affecting the selectivity and separation performance of the membrane [79]. To improve the adaptability of agar-based capture materials in complex flue gas environments, it is necessary to modify the materials to enhance their anti-interference ability, or develop pre-treatment technologies to remove harmful components in the flue gas and reduce their impact on the capture materials.

4.5.3. Regeneration performance optimization

Currently, the regeneration of agar-based capture materials mainly adopts high-temperature desorption, where adsorbed CO₂ is desorbed from the material surface by increasing the temperature [55,80,81]. However, during high-temperature desorption, the chemical structure of agar is prone to degradation. Glycosidic bonds in agar molecules may break at high temperatures, leading to molecular chain degradation, thereby damaging the structure and performance of the material. Studies have shown that when the desorption temperature exceeds 120 °C, the chemical structure of agar begins to degrade significantly [82,83]. After multiple high-temperature desorption cycles, the adsorption capacity of the material will decrease sharply, reducing the service life and economy of the material [62].

To solve this problem, it is necessary to develop low-temperature regeneration processes such as microwave-assisted desorption. Microwaves have unique thermal and non-thermal effects, which can quickly and uniformly heat the material to promote CO₂ desorption. During microwave-assisted desorption, the thermal effect of microwaves can increase the temperature of the material, enabling CO₂ molecules to obtain sufficient energy to desorb from the adsorption sites [84]. The non-thermal effect can change the electron cloud distribution on the

material surface, weaken the interactions between CO₂ and the material, and further promote the desorption process [85,86].

Beyond microwave-assisted strategies, solar-driven photothermal desorption represents another promising green, low-energy regeneration alternative that is highly compatible with agar-based materials. Guo et al. [87] demonstrated that biomass-derived porous carbons with enhanced ultramicroporosity can achieve efficient CO₂ adsorption and low-energy regeneration under simulated solar irradiation (1 sun), reaching 71 °C within 6 min and a regeneration efficiency of 75% without external heating. This approach avoids high-temperature degradation and reduces reliance on external energy inputs, making it complementary to microwave-assisted desorption for protecting thermally sensitive biopolymers like agar. Notably, Guo et al. [87] emphasized that precisely engineered ultramicropores (< 0.7 nm) are critical for enhancing CO₂ uptake and facilitating mild desorption. This conclusion strongly supports the core direction of constructing hierarchical and multiscale pore structures within agar matrices: optimizing microporosity and ultramicroporosity can simultaneously improve CO₂ diffusion, adsorption capacity, and low-temperature regenerability. By combining agar's biocompatible skeleton with controlled porosity inspired by biomass carbon design, solar-assisted desorption can be effectively implemented without breaking glycosidic bonds, enabling durable, low-energy CO₂ capture cycles.

Currently, low-temperature regeneration processes, such as microwave-assisted desorption, are still in the laboratory stage. Further research is needed to explore the influence of factors such as microwave parameters and material properties on desorption efficiency, optimize process conditions, improve regeneration efficiency and cyclic stability of the material, and provide a more reliable regeneration method for the practical application of agar-based capture materials.

5. Sustainable utilization of agar in carbon capture and sequestration

Currently, the direct use of agar for capturing and sequestering CO₂ from ambient air or industrial flue gas remains economically unfeasible. This economic barrier is primarily attributed to the relatively high production cost of agar and the currently low global carbon pricing,

which fails to offset the expenses associated with agar-based CO₂ capture systems. Compared to current commercial adsorbents (e.g., mono-ethanol-amine) with CO₂ capture cost of 55.8 \$/tonne, the cost of agar-based CO₂ capture is estimated to be 90–110 USD/t CO₂ [88–91]. Recent progress in carbon-pricing optimization frameworks further highlights this challenge. Dai et al. [92] demonstrated that a systematic pricing-integrated optimization model is essential to balance economic returns and environmental benefits for carbon capture utilization and storage (CCUS) systems, particularly in overcoming cost-profit mismatches under low carbon prices. Their work provides a critical methodological precedent for quantifying economic barriers and designing viable market-ready pathways, which is highly relevant to advancing agar-based CO₂ capture from lab scale to industrial application. Agar possesses diverse biological functions, excellent biocompatibility, and a wide range of industrial applications, making it a promising biomass resource for sustainable development. To address the economic challenges and maximize the value of agar, a comprehensive and sustainable utilization strategy that integrates high-value product development, CO₂ capture, bioenergy recovery, and ecological carbon sequestration is proposed (Fig. 3).

Specifically, the strategy involves the fractionated utilization of agar to balance economic benefits and environmental goals. A significant portion of agar can be allocated to the food and biomedical industries, which typically offer high market value and stable demand. For instance, food-grade agar, widely used as a gelling agent, thickener, and stabilizer in dairy products, jellies, and meat products, has a market price ranging from 100 to 1000 €/kg, while high-purity biomedical-grade agar (purity ≥95%)—employed in cell culture media, drug delivery systems, and 3D cell scaffolds—commands a premium price of over 10,000 €/kg [93,94]. The remaining portion of agar, which may not meet the high purity requirements for food or biomedical applications, can be processed into high-performance CO₂ capture materials.

To further enhance the sustainability and circularity of the strategy, waste agar generated from various industrial processes should be collected and recycled for bioenergy production. Such waste includes discarded agar from biomedical experiments, chemical synthesis, spent agar culture media, and deactivated agar-based CO₂ capture materials.

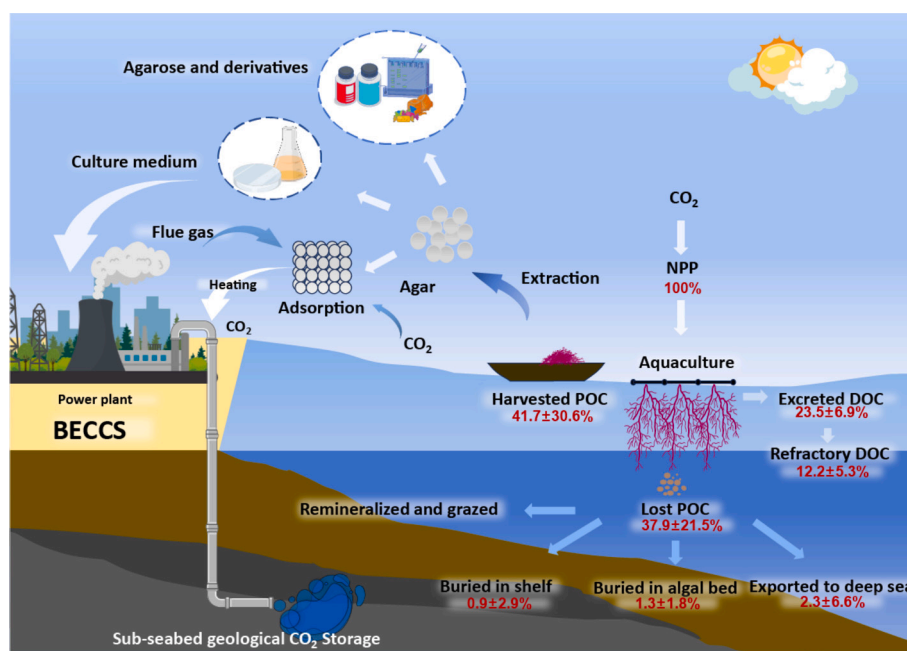


Fig. 3. Agar production and integrated application in carbon capture, utilization and storage. The numbers represent the corresponding proportions compared to NPP [44]. BECCGS: bioenergy combined with carbon capture and geological storage; NPP: net primary production; POC: particulate organic carbon; DOC: dissolved organic carbon.

As a natural carbohydrate-rich biomass, agar can be efficiently converted into biomethane through anaerobic digestion, a biological process mediated by facultative anaerobes and obligate methanogens that break down organic matter in the absence of oxygen [95]. This process yields biogas composed of 50%–80% methane, 20%–50% CO₂, and trace amounts of other gases, which can be purified to obtain high-purity biomethane for power generation [96,97]. Notably, the CO₂ emitted from biomethane-powered plants can be captured, compressed, transported, and permanently stored in geological reservoirs—such as saline aquifers, depleted oil and gas reservoirs, and deep coal seams—thereby integrating bioenergy production with carbon capture and offshore storage (BECCS) to achieve near-zero carbon emissions [93].

In addition to the artificial CO₂ storage pathway mentioned above, the ecological carbon sequestration potential of agar-derived from wild and cultivated red macroalgae biomass should not be overlooked. During the growth and natural decay of red macroalgae (the primary source of agar), significant amounts of particulate organic carbon (POC) and dissolved organic carbon (DOC) are released into the aquatic environment, contributing substantially to long-term CO₂ sequestration [17]. A key advantage of agar in this context is its inherent resistance to microbial degradation, which is attributed to its unique chemical structure and the protective effect of its polysaccharide matrix. This resistance enables agar to be transformed into more refractory organic compounds, reducing its decomposition rate and extending the carbon sequestration period. Furthermore, the transport of POC from coastal waters to the deep ocean via ocean currents and sedimentation processes further minimizes carbon remineralization by isolating organic carbon from the atmosphere and surface water, thereby enhancing the overall efficiency of carbon sequestration [44].

In summary, the integrated utilization strategy of agar derived from red macroalgae achieves a synergistic balance between economic development and environmental protection. On one hand, it generates high-value products for the food and biomedical industries, creating substantial economic benefits to offset the costs of CO₂ capture and sequestration. On the other hand, it realizes multi-pathway CO₂ mitigation through agar-based capture materials, bioenergy recovery with carbon storage, and ecological sequestration via macroalgal carbon export. This strategy not only maximizes the utilization value of agar but also provides essential ecological services, including mitigating global climate change and alleviating coastal eutrophication, thereby offering a promising solution for sustainable development in the context of carbon neutrality (Fig. 3).

6. Conclusions and future study

6.1. Conclusions

The rationale of this review is that agar—a polysaccharide from red macroalgae—holds significant but underexplored potential for carbon capture and sequestration, due to its wide interspecific variability in content and properties, its natural resistance to microbial degradation in marine environments, and its versatile physicochemical characteristics for green technology development. As mentioned in Introduction section, we established a sequential set of five objectives, with the following outcomes:

- (1) This article systematically synthesizes the distribution patterns of agar in red macroalgae and critically examines the factors regulating its content—from species-specific variations to extraction methodologies. Quantitatively, agar content exhibits a wide interspecific variation, ranging from as low as 3.5% of dry weight in *Gelidium corneum* to as high as 62.3% in *Gracilaria cliftonii*, with agarose accounting for 58–97% of the extracted agar. Gel strength, a key quality indicator for CO₂ capture applications, varies from 12 g·cm⁻² (*Gracilaria mammillaris*) to 1392 g·cm⁻² (*Gracilaria crassissima*). These quantitative benchmarks provide a

rational basis for species selection according to specific industrial or environmental objectives.

- (2) It further analyzes global agar production trends over the past three decades and evaluates its future potential. Global *Gracilaria* aquaculture has expanded dramatically, reaching over 8000 × 10³ t fresh weight by 2020, dominated by China, while *Gelidium* aquaculture remains comparatively limited (peak near 5 × 10³ t). Based on global suitable seaweed cultivation areas (approximately 48 million km²), theoretical annual agar production could reach 61.25 × 10⁹ t, corresponding to 27.56 × 10⁹ t of sequestered carbon—highlighting the substantial but largely untapped carbon sequestration capacity of agar.
- (3) Diverging from conventional studies that emphasize agar's biomedical and food industry applications, this work integrates its ecological significance into the research framework. Specifically, agar's role in oceanic carbon sequestration is elucidated, highlighting its function as a recalcitrant carbon reservoir due to its resistance to microbial degradation. The structural complexity of agar (alternating G-LA and G-L6S units, sulfate and methyl modifications) necessitates specialized CAZyme suites; its residence time of 1–3 years in surface waters confirms that bacterial degradation cannot keep pace with agar synthesis, making it a promising marine carbon sink.
- (4) Additionally, agar-based green technologies for carbon capture and sequestration are comprehensively reviewed. Notably, an agar-Na₂CO₃ composite membrane achieves CO₂ absorption reaching 92% of the theoretical maximum, while agar-based hybrid membranes with rationally designed pore sizes (0.3–0.5 nm) exhibit enhanced CO₂/N₂ selectivity. However, current challenges—including raw material supply variability (seasonal and regional fluctuations in agar content and gel strength), high production cost (~9 USD/kg vs. ~5 USD/kg for monoethanolamine), and degradation of agar structure during high-temperature regeneration (>120 °C)—must be addressed.
- (5) Finally, a sustainable agar utilization framework is proposed, distinguishing extraction strategies based on purity grades: high-purity agar for food and biomedical applications (purity ≥95%, price >10,000 €/kg), and low-purity agar for the production of CO₂ capture materials, with the captured CO₂ subsequently sequestered in geological reservoirs. This model establishes a circular “biorefinery–ecosequestration” system that bridges agar's biotechnological potential with global carbon neutrality objectives—a conceptual advance addressing both ecological imperatives and planetary sustainability.

In summary, this review sequentially transforms the fundamental understanding of agar's species-specific properties, production dynamics, and ecological persistence into actionable engineering strategies and a sustainable utilization framework, thereby providing a rational pathway for deploying agar as a functional biopolymer in carbon capture and sequestration.

6.2. Research needs in future

Based on identified research gap, the research needs in future are as follows:

- (1) Resilience to environmental changes. Establishing large-scale seaweed planting bases is the foundation of industrial production. *Gracilaria* and *Gelidium* are vulnerable to thermal stress, limiting their growth in hot seasons and areas. Increasing marine heatwave can also lead to their death [98]. Therefore, breeding including genetic engineering tools (CRISPR–Cas9) must be developed to enhance resilience of *Gracilaria* and *Gelidium* to thermal stress and ensure stable production. In addition, research is necessary to investigate how environmental conditions,

including temperature, light intensity, and nutrient availability, influence agar's content and composition.

- (2) Optimizing extraction Processes. Developing green extraction and purification processes such as enzymatic extraction and membrane separation can reduce production costs and environmental pollution, with the goal of reducing the cost of agar to below 100 yuan/kg, enhancing market competitiveness.
- (3) Molecular design and functional modification. This is a key direction to enhance the CO₂ capture performance of agar-based materials. Two effective chemical modification methods will be focused on: sulfation and amination. Sulfation uses reagents such as concentrated sulfuric acid to react with hydroxyl groups in agar molecules, introducing sulfate groups that form strong electrostatic interactions with CO₂, thereby improving adsorption capacity. Amination introduces amino groups into agar molecules, which react with CO₂ to form stable carbamates, significantly enhancing adsorption selectivity and stability. In addition, dispersing TiO₂, GO and other nanoparticles in the agar matrix to construct multi-scale pore structures is also a promising direction, which can optimize gas diffusion paths and increase adsorption sites.
- (4) Coupling with emerging technologies. Combining agar-based materials with electrochemical reduction, photocatalysis and other emerging technologies to develop multifunctional integrated materials is an important development trend. In electrochemical reduction, agar acts as an electrode carrier to cooperate with metal catalysts, promoting CO₂ reduction into CO, methanol and other useful chemicals. In photocatalysis, agar-based composite materials loaded with TiO₂, ZnO and other semiconductor materials can convert CO₂ into valuable products under light irradiation, realizing the integrated process of CO₂ capture and conversion.
- (5) Conducting life cycle assessment: Cooperating with power and chemical enterprises to carry out 10,000-ton scale demonstration projects, applying agar-based capture materials to flue gas and industrial waste gas treatment systems, and comprehensively monitoring their capture efficiency, stability and other key indicators in actual operating environments. A comprehensive life cycle assessment (LCA) will be conducted with clearly defined system boundaries covering the entire value chain from "cradle to grave": including (i) raw material extraction and agar production (cultivation/harvesting of seaweed, agar extraction and purification), (ii) material preparation (fabrication of agar-based membranes or sorbents), (iii) transport and installation at the capture site, (iv) operation phase (CO₂ capture, regeneration, and any pretreatment of flue gas), and (v) end-of-life management (disposal, recycling, or biodegradation). The functional unit for the LCA will be defined as "capturing 1 tonne of CO₂ from real flue gas under the specific operating conditions of the demonstration project" (e.g., a given flue gas composition, temperature, and pressure). This functional unit enables fair comparison with alternative CO₂ capture technologies. On this basis, establishing a comprehensive technical and economic model to optimize process parameters and reduce costs, aiming to lower the CO₂ capture cost to below 50 US dollars/ton, laying a solid foundation for the industrialization of agar-based capture materials.

CRediT authorship contribution statement

Yuling Yang: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Siwei Tang:** Writing – review & editing, Visualization, Methodology, Investigation. **Wenhao Wu:** Methodology, Investigation. **Chengji Wang:** Writing – review & editing, Methodology. **Guang Gao:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the International Cooperation Seed Funding Project for China's Ocean Decade Actions (GHZZ3702840002024020000020), the Open Project of Key Laboratory of Marine Environmental Survey Technology and Application, Ministry of Natural Resources of P.R. China (MESTA–2024–A001), the Key Projects of Natural Science Research in Colleges and Universities of Anhui Province (2024AH051754), and the Disciplinary (Professional) Leader Training Project from Education Department of Anhui Province (DTR2024042). The authors also appreciate the support from Google Climate Action Research Awards.

Data availability

Data will be made available on request.

References

- [1] N. Rhein-Knudsen, M.T. Ale, F. Ajallouiean, L. Yu, A.S. Meyer, Rheological properties of agar and carrageenan from Ghanaian red seaweeds, *Food Hydrocoll.* 63 (2017) 50–58, <https://doi.org/10.1016/j.foodhyd.2016.08.023>.
- [2] R. Arminen, F. Galatas, Production, properties and uses of agar, in: *Production and Utilization of Products from Commercial Seaweeds*, FAO, 1987, pp. 1–57.
- [3] S. Padmesh, A. Singh, Agars: properties and applications, in: *Polysaccharides*, 2021, pp. 75–93, <https://doi.org/10.1002/9781119711414.ch5>.
- [4] W.-K. Lee, Y.-Y. Lim, A.T.-C. Leow, P. Namasivayam, J. Ong Abdullah, C.-L., Ho, Biosynthesis of agar in red seaweeds: a review, *Carbohydr. Polym.* 164 (2017) 23–30, <https://doi.org/10.1016/j.carbpol.2017.01.078>.
- [5] B.H. Beni, M. Falahati, M.M. Rostamabadi, S. Navid, H. Rostamabadi, Agar as a natural polymer: from culture media to cutting-edge biomedical applications, *Carbohydr. Polym.* 368 (2025) 124100, <https://doi.org/10.1016/j.carbpol.2025.124100>.
- [6] C. Wang, J. Long, X. Li, X. Zhou, L. Chen, C. Qiu, Z. Jin, Preparation of agar polysaccharides and biological activities and relationships of agar-derived oligosaccharides and monosaccharides: a review, *Int. J. Biol. Macromol.* 295 (2025) 139552, <https://doi.org/10.1016/j.ijbiomac.2025.139552>.
- [7] M. Shah, A. Hameed, M. Kashif, N. Majeed, J. Muhammad, N. Shah, T. Rehan, A. Khan, J. Uddin, A. Khan, H. Kashtoh, Advances in agar-based composites: a comprehensive review, *Carbohydr. Polym.* 346 (2024) 122619, <https://doi.org/10.1016/j.carbpol.2024.122619>.
- [8] C.R. Contessa, G.S. da Rosa, C.C. Moraes, J.F.M. de Burkert, Agar-agar and chitosan as precursors in the synthesis of functional film for foods: a review, *Macromol* 3 (2023) 275–289, <https://doi.org/10.3390/macromol3020017>.
- [9] S. Karunanithi, K. Rajappan, Biofunctionalized agarose-based biopolymer composites for advanced biomedical applications: a review, *Polym. Bull.* 82 (2025) 4835–4877, <https://doi.org/10.1007/s00289-025-05718-2>.
- [10] N. El Messaoudi, Y. Miyah, J. Georgin, D.S.P. Franco, B.T. Ergen, B.G.F. Mbanga, S. Knani, M. Messali, Application of agar-based adsorbents in the removal of dyes and heavy metals from wastewater: Current advances, challenges, and future perspectives, *React. Funct. Polym.* 217 (2025) 106501, <https://doi.org/10.1016/j.reactfunctpolym.2025.106501>.
- [11] A. Akbari, H. Sarvi, M. Maleki, S. Bahreini, R. Azimi, A. Radpour, Characteristics, emissions, capture, storage, and utilization of carbon dioxide: a comprehensive review of challenges and technologies for greenhouse gas mitigation, *Pet. Res.* 11 (2026) 116–138, <https://doi.org/10.1016/j.ptlrs.2025.07.001>.
- [12] D.N. Meehan, Risks and challenges in CO₂ capture, use, transportation, and storage, *Sustainability* 17 (2025), <https://doi.org/10.3390/su17177871>.
- [13] M.C. Canvin, A.R. Borrero-Santiago, T. Brook, M. Gupta, J. Knoop, G. Menage, P. J. Moore, N.E. O'Connor, A.M. Ricart, D.A. Smale, Can the Emerging European Seaweed Industry Contribute to Climate Change Mitigation by Enhancing Carbon Sequestration? *Rev. Aquac.* 17 (2025) e70004 <https://doi.org/10.1111/raq.70004>.
- [14] Y. Hu, H. Lu, H. Li, Single step fabrication of spherical CaO pellets via novel agar-assisted moulding technique for high-temperature CO₂ capture, *Chem. Eng. J.* 404 (2021) 127137, <https://doi.org/10.1016/j.cej.2020.127137>.
- [15] H. Li, M. Qu, Y. Hu, Preparation of spherical Li₄SiO₄ pellets by novel agar method for high-temperature CO₂ capture, *Chem. Eng. J.* 380 (2020) 122538, <https://doi.org/10.1016/j.cej.2019.122538>.
- [16] W. Chen, Y. Tang, J. Tang, H. Liu, J. Deng, Z. Sun, X. Ma, Preparation of corn-cob-templated carbide slag sorbent pellets by agar method for CO₂ capture: One-step

- synthesis and cyclic performance, Sep. Purif. Technol. 353 (2025) 128550, <https://doi.org/10.1016/j.seppur.2024.128550>.
- [17] M. Jiang, J.M. Hall-Spencer, L. Gao, Z. Ma, G. Gao, Nitrogen availability regulates the effects of a simulated marine heatwave on carbon sequestration and phycosphere bacteria of a marine crop, Limnol. Oceanogr. 69 (2024) 339–354, <https://doi.org/10.1002/lno.12487>.
 - [18] J. Chen, C. Song, Y. Ke, M. Wang, J. Qiu, L. Nie, G. Li, G. Gao, Nitrate modulates high CO₂ effects on carbon partitioning in *Gracilariopsis lemaneiformis*: trade-offs between particulate and dissolved organic carbon sequestration, Environ. Res. 286 (2025) 122897, <https://doi.org/10.1016/j.envres.2025.122897>.
 - [19] V. Cebrían-Lloret, A. Martínez-Abad, A. López-Rubio, M. Martínez-Sanz, Exploring alternative red seaweed species for the production of agar-based hydrogels for food applications, Food Hydrocoll. 146 (2024) 109177, <https://doi.org/10.1016/j.foodhyd.2023.109177>.
 - [20] Y. Pandya, M. Bakshi, A. Sharma, Agar-agar extraction, structural properties and applications: a review 11 (2022) 1151–1157.
 - [21] J. Rebello, M. Ohno, A.T. Critchley, M. Sawamura, Growth rates and agar quality of *Gracilaria gracilis* (Stackhouse) Steentoft from Namibia, Southern Africa, Bot. Mar. 39 (1996) 273–280, <https://doi.org/10.1515/botm.1996.39.1-6.273>.
 - [22] R. Ahmad, M. Surif, N. Ramli, N. Yahya, A.M. Nor, L. Bekbayeva, A preliminary study on the agar content and agar gel strength of *gracilaria manilaensis* using different agar extraction processes, World Appl. Sci. J. 15 (2011) 184–188.
 - [23] M.C. Rodríguez, M.C. Matulewicz, M.D. Nosedá, D.R.B. Ducatti, P.I. Leonardi, Agar from *Gracilaria gracilis* (Gracilariaceae, Rhodophyta) of the Patagonic coast of Argentina – Content, structure and physical properties, Bioresour. Technol. 100 (2009) 1435–1441, <https://doi.org/10.1016/j.biortech.2008.08.025>.
 - [24] K. Calvin, D. Dasgupta, G. Krinner, A. Mukherji, P.W. Thorne, C. Trisos, J. Romero, P. Aldunce, K. Barrett, G. Blanco, W.W.L. Cheung, S. Connors, F. Denton, A. Diongue-Niang, D. Dodman, M. Garschagen, O. Geden, B. Hayward, C. Jones, F. Jotzo, T. Krug, R. Lasco, Y.-Y. Lee, V. Masson-Delmotte, M. Meinshausen, K. Mintenbeck, A. Mokssit, F.E.L. Otto, M. Pathak, A. Pirani, E. Poloczanska, H.-O. Pörtner, A. Revi, D.C. Roberts, J. Roy, A.C. Ruane, J. Skea, P.R. Shukla, R. Slade, A. Slangen, Y. Sokona, A.A. Sörensson, M. Tignor, D. Van Vuuren, Y.-M. Wei, H. Winkler, P. Zhai, Z. Zommers, J.-C. Hourcade, F. X. Johnson, S. Pachauri, N.P. Simpson, C. Singh, A. Thomas, E. Totin, P. Arias, M. Bustamante, I. Elgizouli, G. Flato, M. Howden, C. Méndez-Vallejo, J.J. Pereira, R. Pichs-Madruga, S.K. Rose, Y. Saheb, R. Sánchez Rodríguez, D. Ürgé-Vorsatz, C. Xiao, N. Yassaa, A. Alegría, K. Armour, B. Bednar-Friedl, K. Blok, G. Cissé, F. Dentener, S. Eriksen, E. Fischer, G. Garner, C. Guivarch, M. Haasnoot, G. Hansen, M. Hauser, E. Hawkins, T. Hermans, R. Kopp, M. Leprince-Ringuet, J. Lewis, D. Ley, C. Ludden, L. Niamir, Z. Nicholls, S. Some, S. Szopa, B. Trewin, K.-I. Van Der Wijst, G. Winter, M. Witting, A. Birt, M. Ha, J. Romero, J. Kim, E. F. Haites, Y. Jung, R. Stavins, A. Birt, M. Ha, D.J.A. Orendain, L. Ignon, S. Park, Y. Park, A. Reisinger, D. Cammaramo, A. Fischlin, J.S. Fuglestedt, G. Hansen, C. Ludden, V. Masson-Delmotte, J.B.R. Matthews, K. Mintenbeck, A. Pirani, E. Poloczanska, N. Leprince-Ringuet, C. Péan, IPCC, Climate change 2023: synthesis report. contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change, in: Core Writing Team, H. Lee, J. Romero (Eds.), First Intergovernmental Panel on Climate Change (IPCC), 2023, IPCC, Geneva, Switzerland, 2023, <https://doi.org/10.59327/IPCC/AR6-9789291691647>.
 - [25] Y. Ji, K. Gao, Effects of climate change factors on marine macroalgae: A review, Adv. Mar. Biol. 88 (2021) 91–136, <https://doi.org/10.1016/bs.amb.2020.11.001>.
 - [26] G. Gao, X. Zhao, M. Jiang, L. Gao, Impacts of Marine Heatwaves on Algal Structure and Carbon Sequestration in Conjunction with Ocean Warming and Acidification, Front. Mar. Sci. 8 (2021), <https://doi.org/10.3389/fmars.2021.758651>.
 - [27] M. Dai, Y. Zhao, F. Chai, M. Chen, N. Chen, Y. Chen, D. Cheng, J. Gan, D. Guan, Y. Hong, J. Huang, Y. Lee, K. Leung, P.E. Lim, S. Lin, X. Lin, X. Liu, Z. Liu, Y.-W. Luo, Z. Zhang, Persistent eutrophication and hypoxia in the coastal ocean, Cambridge Prisms: Coastal, Futures 1 (2023) 1–71, <https://doi.org/10.1017/cft.2023.7>.
 - [28] Y. Yang, Y. Xiong, T. Wang, J. Zhang, L. Feng, G. Gao, Seaweed and shellfish mariculture as nature-based solutions: mitigating nutrient pollution from coastal fish mariculture and sewage, Mar. Pollut. Bull. 222 (2026) 118793, <https://doi.org/10.1016/j.marpolbul.2025.118793>.
 - [29] Y. Feng, Y. Xiong, J.M. Hall-Spencer, K. Liu, J. Beardall, K. Gao, J. Ge, J. Xu, G. Gao, Shift in algal blooms from micro- to macroalgae around China with increasing eutrophication and climate change, Glob. Chang. Biol. 30 (2024) e17018, <https://doi.org/10.1111/gcb.17018>.
 - [30] C. Liu, D. Zou, Z. Liu, C. Ye, Ocean warming alters the responses to eutrophication in a commercially farmed seaweed, *Gracilariopsis lemaneiformis*, Hydrobiologia 847 (2020) 1–15, <https://doi.org/10.1007/s10750-019-04148-2>.
 - [31] A.Q. Aroyehun, K. Palaniveloo, F. Ghazali, M. Rizman-Idid, S.A. Razak, Effects of seasonal variability on the physicochemical, biochemical, and nutritional composition of Western Peninsular Malaysia *Gracilaria manilaensis*, Molecules 24 (2019), <https://doi.org/10.3390/molecules24183298>.
 - [32] A. Boulus, E. Spaneir, M. Friedlander, Effect of outdoor conditions on growth rate and chemical composition of *Gelidium crinale* in culture, J. Appl. Phycol. 19 (2007) 471–478, <https://doi.org/10.1007/s10811-007-9158-7>.
 - [33] T. Li, J. Wu, H. Du, P. Pei, C. Yang, J. Huang, X. Liu, H. Liang, W. Chen, D. Zhang, S. Lin, Environmental nitrogen and phosphorus nutrient variability triggers intracellular resource reallocation in *Gracilariopsis lemaneiformis* (Rhodophyta), Algal Res. 66 (2022) 102778, <https://doi.org/10.1016/j.algal.2022.102778>.
 - [34] L. Liu, D. Zou, H. Jiang, B. Chen, X. Zeng, Effects of increased CO₂ and temperature on the growth and photosynthesis in the marine macroalga *Gracilaria lemaneiformis* from the coastal waters of south China, J. Appl. Phycol. 30 (2018) 1271–1280, <https://doi.org/10.1007/s10811-017-1316-y>.
 - [35] Y. Wang, Y. Feng, H. Wang, M. Zhong, W. Chen, H. Du, Physiological and proteomic analyses of two *Gracilaria lemaneiformis* strains in response to high-temperature stress, J. Appl. Phycol. 28 (2016) 1847–1858, <https://doi.org/10.1007/s10811-015-0723-1>.
 - [36] J. Yu, Y.-F. Yang, Physiological and biochemical response of seaweed *Gracilaria lemaneiformis* to concentration changes of N and P, J. Exp. Mar. Biol. Ecol. 367 (2008) 142–148, <https://doi.org/10.1016/j.jembe.2008.09.009>.
 - [37] W.-J. Chi, Y.-K. Chang, S.-K. Hong, Agar degradation by microorganisms and agar-degrading enzymes, Appl. Microbiol. Biotechnol. 94 (2012) 917–930, <https://doi.org/10.1007/s00253-012-4023-2>.
 - [38] N. Kolhatkar, D.S. Sambrani, Isolation and identification of agar degrading bacteria from marine environment, IOSR Journal of Pharmacy and Biological Sciences 13 (2018) 1–7, <https://doi.org/10.9790/3008-1303030107>.
 - [39] M. Bligh, N. Nguyen, H. Buck-Wiese, S. Vidal-Melgosa, J.-H. Hehemann, Structures and functions of algal glycans shape their capacity to sequester carbon in the ocean, Curr. Opin. Chem. Biol. 71 (2022) 102204, <https://doi.org/10.1016/j.cbpa.2022.102204>.
 - [40] L. Reisky, H.C. Büchsenstschütz, J. Engel, T. Song, T. Schweder, J.-H. Hehemann, U.T. Bornscheuer, Oxidative demethylation of algal carbohydrates by cytochrome P450 monooxygenases, Nat. Chem. Biol. 14 (2018) 342–344, <https://doi.org/10.1038/s41589-018-0005-8>.
 - [41] D.J. Repeta, L.I. Aluwihare, Radiocarbon analysis of neutral sugars in high-molecular-weight dissolved organic carbon: Implications for organic carbon cycling, Limnol. Oceanogr. (2006), <https://doi.org/10.4319/lo.2006.51.2.1045>.
 - [42] Z. Chan, The pilot fermentation strategies for agar-oligosaccharides production by the deep sea bacterium *Flammeovirga pacifica* WPAGA1 and the characterizations of related enzymes. PhD Thesis, Huaqiao University, 2018.
 - [43] Fisheries and Fishery Administration Bureau, National Aquatic Technology Extension Center, China Society of Fisheries, China Fishery Statistical Yearbook 2025, China Agriculture Press, Beijing, 2025.
 - [44] G. Gao, J. Beardall, P. Jin, L. Gao, S. Xie, K. Gao, A review of existing and potential blue carbon contributions to climate change mitigation in the Anthropocene, J. Appl. Ecol. 59 (2022) 1686–1699, <https://doi.org/10.1111/1365-2664.14173>.
 - [45] I. Vinoth Kanna, S. Roseline, K. Balamurugan, S. Jeeva, I. Santhiyagu, The Effects of Greenhouse Gas Emissions on Global Warming, 2024, pp. 143–154, <https://doi.org/10.1016/B978-0-323-93940-9.00216-4>.
 - [46] O.A. Odunlami, D.A. Vershima, T.E. Oladimeji, S. Nkongho, S.K. Ogunlade, B. S. Fakinle, Advanced techniques for the capturing and separation of CO₂ – a review, Results Eng. 15 (2022) 100512, <https://doi.org/10.1016/j.rineng.2022.100512>.
 - [47] S.P. Filippov, The economics of carbon dioxide capture and storage technologies (review), Therm. Eng. 69 (2022) 738–750, <https://doi.org/10.1134/S0040601522100020>.
 - [48] O.H.P. Gunawardene, C.A. Gunathilake, K. Vikrant, S.M. Amaraweera, Carbon dioxide capture through physical and chemical adsorption using porous carbon materials: a review, Atmosphere 13 (2022), <https://doi.org/10.3390/atmos13030397>.
 - [49] F. Jiang, X.-W. Xu, F.-Q. Chen, H.-F. Weng, J. Chen, Y. Ru, Q. Xiao, A.-F. Xiao, Extraction, modification and biomedical application of agarose hydrogels: a review, Mar. Drugs 21 (2023), <https://doi.org/10.3390/md21050299>.
 - [50] X. Chen, X. Fu, L. Huang, J. Xu, X. Gao, Agar oligosaccharides: a review of preparation, structures, bioactivities and application, Carbohydr. Polym. 265 (2021) 118076, <https://doi.org/10.1016/j.carbpol.2021.118076>.
 - [51] M.-F. Lai, C. Lii, Rheological and thermal characteristics of gel structures from various agar fractions, Int. J. Biol. Macromol. 21 (1997) 123–130, [https://doi.org/10.1016/S0141-8130\(97\)00051-2](https://doi.org/10.1016/S0141-8130(97)00051-2).
 - [52] R. Armisen, F. Gaiatas, Agar, in: G.O. Phillips, P.A. Williams (Eds.), Handbook of Hydrocolloids (Second Edition), Woodhead Publishing, 2009, pp. 82–107, <https://doi.org/10.1533/9781845695873.82>.
 - [53] S. Arnott, A. Fulmer, W.E. Scott, I.C.M. Dea, R. Moorhouse, D.A. Rees, The agarose double helix and its function in agarose gel structure, J. Mol. Biol. 90 (1974) 269–284, [https://doi.org/10.1016/0022-2836\(74\)90372-6](https://doi.org/10.1016/0022-2836(74)90372-6).
 - [54] S. Sharma, M. Bhende, An overview: non-toxic and eco-friendly polysaccharides—its classification, properties, and diverse applications, Polym. Bull. 81 (2024) 12383–12429, <https://doi.org/10.1007/s00289-024-05307-9>.
 - [55] J. Xu, H. Cui, J. Shi, N. Yan, Y. Liu, D. Li, Agar-derived nitrogen-doped porous carbon for CO₂ adsorption, ChemistrySelect 3 (2018) 10977–10982, <https://doi.org/10.1002/slct.201802031>.
 - [56] Z.K. Brown, P.J. Fryer, I.T. Norton, R.H. Bridson, Drying of agar gels using supercritical carbon dioxide, J. Supercrit. Fluids 54 (2010) 89–95, <https://doi.org/10.1016/j.supflu.2010.03.008>.
 - [57] R. Leones, F. Sentanin, L.C. Rodrigues, I.M. Marrucho, J.M.S.S. Esperanca, A. Pawlicka, M.M. Silva, Investigation of polymer electrolyte based on agar and ionic liquids, Express Polym Lett 6 (2012) 1007–1016, <https://doi.org/10.3144/expresspolymlett.2012.106>.
 - [58] P.G.G. Lascuain, S. Goidanich, F.B. Vangosa, M. Anzani, A. Rabbolini, A. Sansonetti, L. Toniolo, Agar foam: properties and cleaning effectiveness on gypsum surfaces, Coatings 13 (2023), <https://doi.org/10.3390/coatings13030615>.
 - [59] Y. Gu, G. Wang, X. Chen, X. Xu, Y. Liu, J. Yang, D. Zhang, Unlocking the potential of CO₂ capture: a synergistic hybridization strategy for polymeric hydrogels with

- tunable physicochemical properties, *Small* 20 (2024) e2402529, <https://doi.org/10.1002/sml.202402529>.
- [60] J.M. Weber, The interaction of negative charge with carbon dioxide – insight into solvation, speciation and reductive activation from cluster studies, *Int. Rev. Phys. Chem.* 33 (2014) 489–519, <https://doi.org/10.1080/0144235X.2014.969554>.
- [61] X. Wang, C. Song, Developing high-capacity solid “molecular basket” sorbents for selective CO₂ capture and separation, *Acc. Chem. Res.* 56 (2023) 3358–3368, <https://doi.org/10.1021/acs.accounts.3c00444>.
- [62] W. Chen, Y. Tang, H. Liu, J. Tang, J. Deng, Z. Sun, X. Ma, Preparation of nano-Al₂O₃ support CaO-based sorbent pellets by novel methods for high-temperature CO₂ capture, *J. Environ. Chem. Eng.* 12 (2024) 114157, <https://doi.org/10.1016/j.jece.2024.114157>.
- [63] A. Godziszewska, E. Lopashinova, A. Snegireva, M. Kurasova, T. Trifonova, Rh (III) and Ir(IV)-containing films based on chitosan and agar-agar: dynamics of changes in physical and chemical properties, *ChemChemTech* 67 (2024) 63–68, <https://doi.org/10.6060/ivkkt.20246711.7050>.
- [64] R. Zhang, X. Wang, J. Wang, M. Cheng, Synthesis and characterization of Konjac Glucomannan/Carrageenan/Nano-silica films for the preservation of postharvest white mushrooms, *Polymers* 11 (2018), <https://doi.org/10.3390/polym11010006>.
- [65] M. Sutharsan, K. Senthil Murugan, K. Narayanan, T.S. Natarajan, Chitosan/agar-agar/TiO₂ biopolymer nanocomposite film for solar photocatalysis, antibacterial activity, and food preservation applications, *Next Mater.* 9 (2025) 101225, <https://doi.org/10.1016/j.nxmte.2025.101225>.
- [66] H.J. Wang, Y.H. Jo, D.S. An, J.-W. Rhim, D.S. Lee, Properties of agar-based CO₂ absorption film containing Na₂CO₃ as active compound, *Food Packag. Shelf Life* 4 (2015) 36–42, <https://doi.org/10.1016/j.fpsl.2015.03.004>.
- [67] D.S. Lee, Carbon dioxide adsorbents for food packaging applications, *Trends Food Sci. Technol.* 57 (2016) 146–155, <https://doi.org/10.1016/j.tifs.2016.09.014>.
- [68] H.J. Wang, D.S. An, D.S. Lee, Development of multifunctional active film and its application in modified atmosphere packaging of shiitake mushrooms, *J. Food Prot.* 79 (2016) 1599–1608, <https://doi.org/10.4315/0362-028X.JFP-16-114>.
- [69] H.E. Irianto, D. Fransiska, G. Giatyati, Agar for biodegradable plastics packaging, in: *Biopolymers in Pharmaceutical and Food Applications* (2024) 177–202, <https://doi.org/10.1002/9783527848133.ch9>.
- [70] M. Guastaferrero, L. Baldino, E. Reverchon, S. Cardea, Production of porous agarose-based structures: freeze-drying vs. supercritical CO₂ drying, *Gels* 7 (2021), <https://doi.org/10.3390/gels7040198>.
- [71] R. Dhandapani, M.P. Elangovan, R. Subbarayalu, A.Y.Z. Khalifa, R. Paramasivam, Sankaranarayanan, S. Thangavelu, V. Selvakumar, Small, large-scale production and cost-benefit analysis and marketing of agar from *Gelidium*, in: N. Amarasena, D. Dharumadurai, D.R. Cundell (Eds.), *Industrial Microbiology Based Entrepreneurship: Making Money from Microbes*, Springer Nature Singapore, Singapore, 2022, pp. 127–145, https://doi.org/10.1007/978-981-19-6664-4_10.
- [72] Q. Thabit, A. Nassour, M. Nelles, Flue gas composition and treatment potential of a waste incineration plant, *Appl. Sci.* 12 (2022), <https://doi.org/10.3390/app12105236>.
- [73] L. Ma, J. Li, R. Ke, L. Fu, Catalytic performance, characterization, and mechanism study of Fe₂(SO₄)₃/TiO₂ Catalyst for selective catalytic reduction of NO_x by ammonia, *J. Phys. Chem. C* 115 (2011) 7603–7612, <https://doi.org/10.1021/jp200488p>.
- [74] G. Saracco, V. Specchia, Catalytic Filters for Flue Gas Cleaning, in: USA. <https://iris.polito.it/handle/11583/1396447?mode=complete>, 1998 (accessed March 15, 2026).
- [75] L. Yan, L. Li, Y. Zhou, C. Hu, C. Lu, X. Shen, Mechanistic kinetic comparison of terrestrial biomass-derived cellulose and marine algae-derived agarose acidic degradation to monosaccharides and 5-hydroxymethylfurfural, *Biomass Convers. Biorefinery* 13 (2023) 4305–4315, <https://doi.org/10.1007/s13399-022-02607-w>.
- [76] I.J. Miller, J.W. Blunt, Desulfation of algal galactans, *Carbohydr. Res.* 309 (1998) 39–43, [https://doi.org/10.1016/S0008-6215\(98\)00104-9](https://doi.org/10.1016/S0008-6215(98)00104-9).
- [77] J. Duan, D.L. Kasper, Oxidative depolymerization of polysaccharides by reactive oxygen/nitrogen species, *Glycobiology* 21 (2011) 401–409, <https://doi.org/10.1093/glycob/cwq171>.
- [78] L. Zhang, Q. Xiao, Z. Xiao, Y. Zhang, H. Weng, F. Chen, A. Xiao, Hydrophobic modified agar: Structural characterization and application in encapsulation and release of curcumin, *Carbohydr. Polym.* 308 (2023) 120644, <https://doi.org/10.1016/j.carbpol.2023.120644>.
- [79] R.M. Felfel, M.J. Gideon-Adeniyi, K.M. Zakir Hossain, G.A.F. Roberts, D.M. Grant, Structural, mechanical and swelling characteristics of 3D scaffolds from chitosan-agarose blends, *Carbohydr. Polym.* 204 (2019) 59–67, <https://doi.org/10.1016/j.carbpol.2018.10.002>.
- [80] E. Ciurcina, L. Taboada-Ruiz, E. Fuente, S. Paniagua, L.F. Calvo, F. Suárez-García, M.D. Somoano, B. Ruiz, Pyrolysis of agar-agar industry macroalgal waste for biofuel generation and high-performance adsorbents for pressurized gas storage, *J. Environ. Chem. Eng.* 13 (2025) 119121, <https://doi.org/10.1016/j.jece.2025.119121>.
- [81] W. Song, Y. Wen, G. Kang, D. Li, H. Hu, L. Jin, S. Lu, Z. Yan, P. Liu, Catalytic desorption performance of CO₂-rich amine solution over SO₂–4/TiO₂-HZSM-5, *J. Fuel Chem. Technol.* 53 (2025) 1342–1353, [https://doi.org/10.1016/S1872-5813\(25\)60559-7](https://doi.org/10.1016/S1872-5813(25)60559-7).
- [82] O. Iglesias, J.L. Bueno, Water agar-agar equilibrium: determination and correlation of sorption isotherms, *Int. J. Food Sci. Technol.* (1999), <https://doi.org/10.1046/j.1365-2621.1999.00251.x>.
- [83] Q.-Q. Ouyang, Z. Hu, S.-D. Li, W.-Y. Quan, L.-L. Wen, Z.-M. Yang, P.-W. Li, Thermal degradation of agar: mechanism and toxicity of products, *Food Chem.* 264 (2018) 277–283, <https://doi.org/10.1016/j.foodchem.2018.04.098>.
- [84] M. Erguvan, S. Amini, Experimental microwave assisted CO₂ desorption of a solid sorbent in a fluidized bed reactor, *Sep. Purif. Technol.* 343 (2024) 127062, <https://doi.org/10.1016/j.seppur.2024.127062>.
- [85] T.H. Lim, J.E. Foster, B.R. Ellis, S.J. Skerlos, Microwave-based CO₂ desorption for enhanced direct air capture: experimental validation and techno-economic perspectives, *Environ. Res. Lett.* 19 (2024) 034002, <https://doi.org/10.1088/1748-9326/ad239f>.
- [86] R. Rehemtuli, Z. Zhang, X. Yang, F. Yang, Y. Liu, J. Hou, Research on CO₂ desorption using microwave-assisted novel blended alkanolamine formulations, *Processes* 12 (2024), <https://doi.org/10.3390/pr12112547>.
- [87] P. Guo, R. Xue, Q. Zou, X. Ma, C. Su, Z. Zeng, L. Li, Enhanced ultramicro-pore of biomass-derived porous carbon for efficient and low-energy CO₂ capture: integration of adsorption and solar desorption, *Energy Environ. Mater.* 9 (2026) e70140, <https://doi.org/10.1002/eem.2.70140>.
- [88] A.N. Antzaras, T. Papalas, E. Heracleous, C. Kouris, Techno-economic and environmental assessment of CO₂ capture technologies in the cement industry, *J. Clean. Prod.* 428 (2023) 139330, <https://doi.org/10.1016/j.jclepro.2023.139330>.
- [89] P. In-na, F. Byrne, G.S. Caldwell, J.G.M. Lee, Techno-economic analysis of living biocomposites for carbon capture from breweries, *Algal Res.* 66 (2022) 102781, <https://doi.org/10.1016/j.algal.2022.102781>.
- [90] S.G. Pereira, A.A. Martins, T.M. Mata, R.N. Pereira, J.A. Teixeira, C.M.R. Rocha, Life cycle assessment and cost analysis of innovative agar extraction technologies from red seaweeds, *Bioresour. Technol.* 414 (2024) 131649, <https://doi.org/10.1016/j.biortech.2024.131649>.
- [91] L. Amponsah, E. Jones, J. Davies, S. Shokri, S. Parsons, C.J. Chuck, Life cycle assessment and techno-economic analysis of a macroalgal-derived biopolymer film coupled with carbon capture, *Sustain. Sci. Technol.* 3 (2026) 024001, <https://doi.org/10.1088/2977-3504/ae4806>.
- [92] Q. Dai, L. Zhang, K. Zhang, G. Chen, Z. Chen, X. Xue, Y. Wang, C. Di, F. Zhao, J. Bai, Carbon-pricing optimization framework for oilfield carbon dioxide-water alternation with economic and environmental gains, *Energy Convers. Manag.* 348 (2026) 120613, <https://doi.org/10.1016/j.enconman.2025.120613>.
- [93] X. Zhao, X. Wang, J. Zhang, L. Feng, G. Gao, Sustainable production of ulvan from green macroalgae and its potential in carbon sequestration: a critical review, *Int. J. Biol. Macromol.* 330 (2025) 147978, <https://doi.org/10.1016/j.ijbiomac.2025.147978>.
- [94] W.-K. Lee, Y.-Y. Lim, C.-L. Ho, *Gracilaria* as the major source of agar for food, health and biotechnology applications, in: A. Ranga Rao, G.A. Ravishanker (Eds.), *Sustainable Global Resources of Seaweeds Volume 2: Food, Pharmaceutical and Health Applications*, Springer International Publishing, Cham, 2022, pp. 145–161, https://doi.org/10.1007/978-3-030-92174-3_7.
- [95] M. Ma, S.P. Narayanan, A. Ga, R. Sa, The Biogas Production from mixture of Agar and Rumen Wastes, *Int. J. Adv. Res.* 3 (2015) 362–369.
- [96] G. Gao, J.G. Burgess, M. Wu, S. Wang, K. Gao, Using macroalgae as biofuel: current opportunities and challenges, *Bot. Mar.* 63 (2020) 355–370, <https://doi.org/10.1515/bot-2019-0065>.
- [97] I. Angelidaki, L. Treu, P. Tsapekos, G. Luo, S. Campanaro, H. Wenzel, P. G. Kougi, Biogas upgrading and utilization: current status and perspectives, *Biotechnol. Adv.* 36 (2018) 452–466, <https://doi.org/10.1016/j.biotechadv.2018.01.011>.
- [98] M. Jiang, L. Gao, R. Huang, X. Lin, G. Gao, Differential responses of bloom-forming *Ulva intestinalis* and economically important *Gracilaria lemaneiformis* to marine heatwaves under changing nitrate conditions, *Sci. Total Environ.* 840 (2022) 156591, <https://doi.org/10.1016/j.scitotenv.2022.156591>.
- [99] E. Murano, R. Toffanin, C. Pedersini, A. Carabot-Cuervo, G. Blunden, R. Rizzo, Structure and properties of agar from two unexploited agarophytes from Venezuela, *Hydrobiologia* 326 (1996) 497–500, <https://doi.org/10.1007/BF00047851>.
- [100] D.F. Kapraun, E. Ganzon-Forbes, K.T. Bird, G. Trono, C. Breden, Karyology and agar analysis of the agarophyte *Gelidiella acerosa* (Forsskål) Feldmannet Hamel from the Philippines, *J. Appl. Phycol.* 6 (1994) 545–550, <https://doi.org/10.1007/BF02182409>.
- [101] G.A. Santos, M.S. Doty, Agar from some Hawaiian red algae, *Aquat. Bot.* 16 (1983) 385–389, [https://doi.org/10.1016/0304-3770\(83\)90084-0](https://doi.org/10.1016/0304-3770(83)90084-0).
- [102] Y. Freile-Pelegrín, D.R. Robledo, G. García-Reina, Seasonal agar yield and quality in *Gelidium canariensis* (Grunow) Seoane-Camba (Gelidiales, Rhodophyta) from Gran Canaria, Spain, *J. Appl. Phycol.* 7 (1995) 141–144, <https://doi.org/10.1007/BF00693060>.
- [103] A. Lemus, K. Bird, D.F. Kapraun, F. Koehn, Agar yield, quality and standing crop biomass of *Gelidium serrulatum*, *Gelidium floridanum* and *Pterocladia capillacea* in Venezuela, *Food Hydrocoll.* 5 (1991) 469–479, [https://doi.org/10.1016/S0268-005X\(91\)80105-7](https://doi.org/10.1016/S0268-005X(91)80105-7).
- [104] B. Matsushiro, C.C. Urzúa, Agars from *Gelidium rex* (Gelidiales, Rhodophyta), *Hydrobiologia* 204 (1990) 545–549, <https://doi.org/10.1007/BF00040284>.
- [105] Y. Freile-Pelegrín, D. Robledo, E. Serviere-Zaragoza, *Gelidium robustum* agar: quality characteristics from exploited beds and seasonality from an unexploited bed at Southern Baja California, México, *Hydrobiologia* 398 (1999) 501–507, <https://doi.org/10.1023/A:1017029915910>.
- [106] N.E. Montañón, R.D. Villanueva, J.B. Romero, Chemical characteristics and gelling properties of agar from two Philippine *Gracilaria* spp. (Gracilariaceae),

- Rhodophyta), J. Appl. Phycol. 11 (1999) 27–34, <https://doi.org/10.1023/A:1008084228609>.
- [107] Y. Freile-Pelegrin, E. Murano, Agars from three species of *Gracilaria* (Rhodophyta) from Yucatán Peninsula, Bioresour. Technol. 96 (2005) 295–302, <https://doi.org/10.1016/j.biortech.2004.04.010>.
- [108] E. Marinho-Soriano, Agar polysaccharides from *Gracilaria* species (Rhodophyta, Gracilariaceae), J. Biotechnol. 89 (2001) 81–84, [https://doi.org/10.1016/S0168-1656\(01\)00255-3](https://doi.org/10.1016/S0168-1656(01)00255-3).
- [109] E. Marinho-Soriano, E. Bourret, M.L. de Casabianca, L. Maury, Agar from the reproductive and vegetative stages of *Gracilaria bursa-pastoris*, Bioresour. Technol. 67 (1999) 1–5, [https://doi.org/10.1016/S0960-8524\(99\)00092-9](https://doi.org/10.1016/S0960-8524(99)00092-9).
- [110] E. Marinho-Soriano, E. Bourret, Effects of season on the yield and quality of agar from *Gracilaria* species (Gracilariaceae, Rhodophyta), Bioresour. Technol. 90 (2003) 329–333, [https://doi.org/10.1016/S0960-8524\(03\)00112-3](https://doi.org/10.1016/S0960-8524(03)00112-3).
- [111] E. Marinho-Soriano, T.S.F. Silva, W.S.C. Moreira, Seasonal variation in the biomass and agar yield from *Gracilaria cervicornis* and *Hydropuntia cornea* from Brazil, Bioresour. Technol. 77 (2001) 115–120, [https://doi.org/10.1016/S0960-8524\(00\)00158-9](https://doi.org/10.1016/S0960-8524(00)00158-9).
- [112] S.-M. Phang, S. Shaharuddin, H. Noraishah, A. Sasekumar, Studies on *Gracilaria changii* (Gracilariales, Rhodophyta) from Malaysian mangroves, Hydrobiologia 326 (1996) 347–352, <https://doi.org/10.1007/BF00047829>.
- [113] W.-K. Lee, P.-E. Lim, S.-M. Phang, P. Namasivayam, C.-L. Ho, Agar properties of *Gracilaria* species (Gracilariaceae, Rhodophyta) collected from different natural habitats in Malaysia, Reg. Stud. Mar. Sci. 7 (2016) 123–128, <https://doi.org/10.1016/j.rsma.2016.06.001>.
- [114] V. Kumar, R. Fotedar, Agar extraction process for *Gracilaria cliftonii* (Withell, Millar, & Kraft, 1994), Carbohydr. Polym. 78 (2009) 813–819, <https://doi.org/10.1016/j.carbpol.2009.07.001>.
- [115] R. Meena, K. Prasad, M. Ganesan, A.K. Siddhanta, Superior quality agar from *Gracilaria* species (Gracilariales, Rhodophyta) collected from the Gulf of Mannar, India, J. Appl. Phycol. 20 (2008) 397–402, <https://doi.org/10.1007/s10811-007-9272-6>.
- [116] G.K. Mehta, R. Meena, K. Prasad, M. Ganesan, A.K. Siddhanta, Preparation of galactans from *Gracilaria debilis* and *Gracilaria salicornia* (Gracilariales, Rhodophyta) of Indian waters, J. Appl. Phycol. 22 (2010) 623–627, <https://doi.org/10.1007/s10811-010-9502-1>.
- [117] E. Marinho-Soriano, E. Bourret, Polysaccharides from the red seaweed *Gracilaria dura* (Gracilariales, Rhodophyta), Bioresour. Technol. 96 (2005) 379–382, <https://doi.org/10.1016/j.biortech.2004.04.012>.
- [118] J. Praiboon, A. Chirapart, Y. Akakabe, O. Bhumbhamon, T. Kajiware, Physical and chemical characterization of agar polysaccharides extracted from the Thai and Japanese species of *Gracilaria*, ScienceAsia 32 (s1) (2006) 11–17, [https://doi.org/10.2306/scienceasia1513-1874.2006.32\(s1\).011](https://doi.org/10.2306/scienceasia1513-1874.2006.32(s1).011).
- [119] A.V. Skriptsova, Y.V. Nabivailo, Comparison of three gracilarioids: growth rate, agar content and quality, J. Appl. Phycol. 21 (2009) 443–450, <https://doi.org/10.1007/s10811-008-9389-2>.
- [120] G. Capillo, G. Genovese, A. Monteleone, M. Morabito, A. Manganaro, From culture to application. Agar from *Gracilaria gracilis* of Ganzirri lagoon (Sicily, Italy), J. Biol. Res. - Boll. Soc. Ital. Biol. Sper. 87 (2014) 9, <https://doi.org/10.4081/jbr.2014.s1>.
- [121] M.D. Oza, G.K. Mehta, S. Kumar, R. Meena, A.K. Siddhanta, Galactans from *Gracilaria millardetii* and *G. textorii* (Gracilariales, Rhodophyta) of Indian waters, Phycol. Res. 59 (2011) 244–249, <https://doi.org/10.1111/j.1440-1835.2011.00622.x>.
- [122] A. Buriyo, A. Kivaisi, Standing stock, agar yield and properties of *Gracilaria salicornia* harvested along the Tanzanian Coast, West. Indian Ocean J. Mar. Sci. 2 (2004) 171–178, <https://doi.org/10.4314/wiojms.v2i2.28433>.
- [123] S. Yarnpakdee, S. Benjakul, P. Kingwascharapong, Physico-chemical and gel properties of agar from *Gracilaria tenuistipitata* from the lake of Songkhla, Thailand, Food Hydrocoll. 51 (2015) 217–226, <https://doi.org/10.1016/j.foodhyd.2015.05.004>.
- [124] R.D. Villanueva, A.M.M. Sousa, M.P. Gonçalves, M. Nilsson, L. Hilliou, Production and properties of agar from the invasive marine alga, *Gracilaria vermiculophylla* (Gracilariales, Rhodophyta), J. Appl. Phycol. 22 (2010) 211–220, <https://doi.org/10.1007/s10811-009-9444-7>.
- [125] R.D. Villanueva, J.B. Romero, A.L.R. Ragasa, M.N.E. Montaña, Agar from the red seaweed, *Laurencia flexilis* (Ceramiales, Rhodophyta) from northern Philippines, Phycol. Res. 58 (2010) 151–156, <https://doi.org/10.1111/j.1440-1835.2010.00573.x>.