

**LAPORAN AKHIR  
PENELITIAN FUNDAMENTAL - REGULER  
TAHUN ANGGARAN 2025**

Aplikasi Karagenan sebagai Ko-agen Penyalut dalam Proses  
Enkapsulasi Minyak Kelapa Murni menggunakan Pengeringan  
Semprot



**UBAYA**

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2025**





### PROTEKSI ISI LAPORAN AKHIR PENELITIAN FUNDAMENTAL - REGULER

Dilarang menyalin, menyimpan, memperbanyak sebagian atau seluruh isi proposal ini dalam bentuk apapun kecuali oleh pengusul dan pengelola administrasi penelitian dan pengabdian kepada masyarakat

#### LAPORAN AKHIR

#### 1. JUDUL PENELITIAN

Aplikasi Karagenan sebagai Ko-agen Penyalut dalam Proses Enkapsulasi Minyak Kelapa Murni menggunakan Pengeringan Semprot

Bidang Fokus	Tema	Topik (jika ada)	Prioritas Riset
Pangan	Teknologi pascapanen dan rekayasa teknologi pengolahan pangan	Penguatan agroindustri berbahan baku sumber daya lokal	Hilirisasi dan industrialisasi

Rumpun Ilmu Level 1	Rumpun Ilmu Level 2	Rumpun Ilmu Level 3
ILMU TEKNIK	ILMU KETEKNIKAN INDUSTRI	Teknik Kimia

Skema Penelitian	Strata (Dasar/Terapan/Pengembangan)	Nilai SBK	Target Akhir TKT	Lama Kegiatan
Penelitian Fundamental - Reguler	Riset Dasar	150.000.000	3	2 Tahun

#### 2. IDENTITAS PENGUSUL

Nama, Peran	Jenis	Program Studi/Bagian	Bidang Tugas	ID Sinta
LANNY SAPEI 0425017801  Ketua Pengusul Universitas Surabaya	Dosen	Teknik Kimia	-Mendesain percobaan pengeringan semprot untuk pembuatan bubuk VCO dengan menggunakan karagenan sebagai ko-agen penyalut -Mengkoordinasi dan memonitor percobaan -Trouble shooting selama pelaksanaan eksperimen -Mengevaluasi dan menginterpretasi data percobaan -Membuat laporan dan publikasi	<a href="#">5981633</a>
RUDY AGUSTRIYANTO 0709087201  Anggota Universitas Surabaya	Dosen	Teknik Kimia	-Membantu pelaksanaan karakterisasi bubuk VCO dengan berbagai metode -Membantu analisis data -Membantu pembuatan laporan dan publikasi	<a href="#">257134</a>
PUGUH SETYOPRATOMO 0715046401  Anggota Universitas Surabaya	Dosen	Teknik Kimia	-Membantu mendesain eksperimen dan interpretasi data hasil percobaan -Membantu pembuatan laporan dan publikasi	<a href="#">6652798</a>

#### 3. MITRA KERJASAMA PENELITIAN (Jika Ada)

Pelaksanaan penelitian dapat melibatkan mitra kerjasama yaitu mitra kerjasama dalam melaksanakan penelitian, mitra sebagai calon pengguna hasil penelitian, atau mitra investor

Mitra	Nama Mitra	Dana
PT. Lautan Natural Krimerindo	Ir. Rochmad Indrawanto, S.TP, M.MT	Tahun 1 Rp 0

#### 4. LUARAN DAN TARGET CAPAIAN

##### Luaran Wajib

Tahun Luaran	Kategori Luaran	Jenis Luaran	Status target capaian	Keterangan
1	Artikel di Jurnal	Artikel di Jurnal Bereputasi Internasional	Accepted/Published	Applied Food Research Journal. <a href="https://www.sciencedirect.com/journal/applied-food-research">https://www.sciencedirect.com/journal/applied-food-research</a>
2	Artikel di Jurnal	Artikel di Jurnal Bereputasi Internasional	Accepted/Published	Applied Food Research Journal. <a href="https://www.sciencedirect.com/journal/applied-food-research">https://www.sciencedirect.com/journal/applied-food-research</a>

#### 5. ANGGARAN

Rencana Anggaran Biaya penelitian mengacu pada PMK dan buku Panduan Penelitian dan Pengabdian kepada Masyarakat yang berlaku.

**Total RAB 1 Tahun Rp 119.950.000,00**

**Tahun 1 Total Rp 119.950.000,00**

Kelompok	Komponen	Item	Satuan	Vol.	Biaya Satuan	Total
Analisis Data	Biaya analisis sampel	Analisa PSA	Unit	20	200.000	4.000.000
Analisis Data	Biaya analisis sampel	Analisa GPC	Unit	10	600.000	6.000.000
Analisis Data	Biaya analisis sampel	Analisa RVA	Unit	10	300.000	3.000.000
Analisis Data	Biaya analisis sampel	Analisa FTIR	Unit	11	250.000	2.750.000
Analisis Data	Biaya analisis sampel	Uji XRD	Unit	15	250.000	3.750.000
Analisis Data	Biaya analisis sampel	Uji Bioaktifitas	Unit	2	5.000.000	10.000.000
Analisis Data	Biaya analisis sampel	Uji TGA/ DSC	Unit	5	750.000	3.750.000
Analisis Data	Biaya analisis sampel	Uji SEM	Unit	20	450.000	9.000.000
Analisis Data	Biaya analisis sampel	Uji Gel Strength	Unit	11	100.000	1.100.000
Analisis Data	HR Pengolah Data	Pengolah data penelitian	P (penelitian)	1	1.540.000	1.540.000
Analisis Data	Transport Lokal	PP dalam kota Surabaya, 2 orang, 5x	OK (kali)	10	150.000	1.500.000
Analisis Data	Uang Harian	TPD dalam kota	OH	10	160.000	1.600.000
Bahan	ATK	DVD external drive	Paket	1	265.000	265.000
Bahan	ATK	Kertas HVS ukuran A4	Paket	1	75.000	75.000
Bahan	ATK	Ordner plastik	Paket	1	17.000	17.000
Bahan	ATK	Tinta printer	Paket	4	120.000	480.000
Bahan	Bahan Penelitian (Habis Pakai)	Beaker tall 250 ml	Unit	10	65.000	650.000
Bahan	Bahan Penelitian (Habis Pakai)	Cellulase 50 ml	Unit	1	4.000.000	4.000.000
Bahan	Bahan	Dikalium Fosfat Merck	Unit	1	850.000	850.000

Kelompok	Komponen	Item	Satuan	Vol.	Biaya Satuan	Total
	Penelitian (Habis Pakai)	250 gr				
Bahan	Bahan Penelitian (Habis Pakai)	Dietil Eter p.a	Unit	1	1.600.000	1.600.000
Bahan	Bahan Penelitian (Habis Pakai)	Dinitrosalysilic acid 25 gr	Unit	1	1.300.000	1.300.000
Bahan	Bahan Penelitian (Habis Pakai)	Disposable petri dish 1 paket (50 pak)	Unit	1	1.000.000	1.000.000
Bahan	Bahan Penelitian (Habis Pakai)	Ethanol p.a. 2,5 L	Unit	1	720.000	720.000
Bahan	Bahan Penelitian (Habis Pakai)	Heksana 1 L	Unit	1	580.000	580.000
Bahan	Bahan Penelitian (Habis Pakai)	Isopropil Alkohol Teknis 1 L	Unit	10	68.000	680.000
Bahan	Bahan Penelitian (Habis Pakai)	Karagenan 1 kg	Unit	1	145.000	145.000
Bahan	Bahan Penelitian (Habis Pakai)	KCl Merck 1 Kg	Unit	1	570.000	570.000
Bahan	Bahan Penelitian (Habis Pakai)	KOH p.a Merck 1 kg	Unit	1	500.000	500.000
Bahan	Bahan Penelitian (Habis Pakai)	Kamera eksternal logitech	Unit	1	300.000	300.000
Bahan	Bahan Penelitian (Habis Pakai)	Mikropipet	Unit	3	500.000	1.500.000
Bahan	Bahan Penelitian (Habis Pakai)	NaCl Merck 1 Kg	Unit	1	900.000	900.000
Bahan	Bahan Penelitian (Habis Pakai)	Pipette tips	Unit	2	75.000	150.000
Bahan	Bahan Penelitian (Habis Pakai)	Plate count agar	Unit	1	1.250.000	1.250.000
Bahan	Bahan Penelitian (Habis Pakai)	Silica gel food grade 1 kg	Unit	1	300.000	300.000
Bahan	Bahan Penelitian (Habis Pakai)	Standing pouch 500 g	Unit	30	1.500	45.000
Bahan	Bahan Penelitian (Habis Pakai)	Solar 200L	Unit	100	15.000	1.500.000
Bahan	Bahan Penelitian (Habis Pakai)	Tween 20 Merck 500 mL	Unit	1	670.000	670.000
Bahan	Bahan Penelitian (Habis Pakai)	vacuum sealer	Unit	1	500.000	500.000
Bahan	Bahan Penelitian (Habis Pakai)	VCO 500 mL	Unit	3	120.000	360.000

Kelompok	Komponen	Item	Satuan	Vol.	Biaya Satuan	Total
Pelaporan Hasil Penelitian dan Luaran Wajib	Biaya Publikasi artikel di Jurnal Bereputasi Internasional	Artikel di Applied Food Reseach Journal	Paket	1	11.950.000	11.950.000
Pengumpulan Data	Biaya konsumsi	Konsumsi Rapat koordinasi 4 orang, 8 kali	OH	32	48.000	1.536.000
Pelaporan Hasil Penelitian dan Luaran Wajib	Biaya konsumsi rapat	Rapat koordinasi, 8 orang, 4x	OH	32	48.000	1.536.000
Pengumpulan Data	HR Pembantu Lapangan	Pembantu lapangan 1	OH	65	80.000	5.200.000
Pengumpulan Data	HR Pembantu Lapangan	Pembantu lapangan 2	OH	30	80.000	2.400.000
Pengumpulan Data	HR Pembantu Peneliti	Pembantu peneliti 2	OJ	235	25.000	5.875.000
Pengumpulan Data	HR Pembantu Peneliti	Pembantu peneliti 1	OJ	250	25.000	6.250.000
Pengumpulan Data	Penginapan	Akomodasi di Bandung	OH	1	686.000	686.000
Pengumpulan Data	Penginapan	Penginapan 2 orang, 1 malam, 2x Undip	OH	2	810.000	1.620.000
Pengumpulan Data	Transport	Dalam kota Surabaya PP	OK (kali)	4	150.000	600.000
Pengumpulan Data	Transport	Dari/ke stasiun Semarang	OK (kali)	2	230.000	460.000
Pengumpulan Data	Transport	Dari/ ke stasiun Bandung	OK (kali)	1	400.000	400.000
Pengumpulan Data	Tiket	Kereta Bandung-Surabaya, 1 orang, 1 kali	OK (kali)	1	800.000	800.000
Pengumpulan Data	Transport	sewa mobil 1 hari, 2x	OK (kali)	2	1.200.000	2.400.000
Pengumpulan Data	Tiket	Tiket Kereta, Surabaya - Semarang PP, 2 orang, 2 kali	OK (kali)	4	500.000	2.000.000
Pengumpulan Data	Uang Harian	TPD ke PT. LNK Mojokerto, 4 orang, 2x	OH	8	410.000	3.280.000
Pengumpulan Data	Uang Harian	TPD Surabaya-Bandung, 1 orang	OH	2	410.000	820.000
Pengumpulan Data	Uang Harian	TPD dalam kota, 5 orang, 2x	OH	10	160.000	1.600.000
Pengumpulan Data	Uang Harian	TPD Undip Semarang, 2 orang, 2x	OH	4	410.000	1.640.000

#### \*. KEMAJUAN PENELITIAN

##### A. RINGKASAN

Karagenan merupakan salah satu produk hidrokoloid yang berasal dari rumput laut dengan ketersediaan karagenan yang melimpah di Indonesia. Selain itu, karagenan memiliki kandungan serat yang tinggi dan dapat digunakan sebagai penstabil emulsi, oleh karena itu karagenan banyak dimanfaatkan pada bidang pengolahan dan pemrosesan pangan. Salah satu pemanfaatan karagenan adalah sebagai wall material dalam enkapsulasi bubuk Virgin Coconut Oil (VCO) menggunakan spray dryer. Pada penelitian ini, emulsi dibuat dengan variasi kandungan karagenan 0%, 1%, dan 2%, serta variasi total solid 45% dan 50%. Emulsi dihomogenisasi menggunakan homogenizer dan sonikator kemudian dikeringkan menggunakan spray dryer tipe Buchi B-290. Penelitian ini bertujuan untuk mengetahui pengaruh dari kandungan karagenan yang digunakan, persentase total solid, serta kondisi

pengeringan yang optimum untuk mendapatkan produk bubuk VCO dengan karakteristik terbaik. Karakteristik produk yang diuji meliputi yield, moisture, bulk and tapped density, time of rehydration, serta efisiensi enkapsulasi. Formulasi bubuk VCO dengan karakteristik terbaik ada pada variasi kandungan karagenan sebesar 2% dan persentase total solid sebesar 50%, serta dengan laju alir umpan 8 ml/ menit dan suhu pengeringan 150°C, dengan hasil uji karakteristik yaitu yield produk 92,41%, moisture content 3,45%, bulk density 0,38 gram/ml, tapped density 0,455 gram/ml, time of rehydration 63 detik, ukuran partikel 1015 nm, dan efisiensi enkapsulasi 91,37%.

#### **B. KATA KUNCI**

bubuk VCO; karagenan; pengeringan semprot; temperatur; total solid

Pengisian poin C sampai dengan poin H mengikuti template berikut dan tidak dibatasi jumlah kata atau halaman namun disarankan seringkas mungkin. Dilarang menghapus/memodifikasi template ataupun menghapus penjelasan di setiap poin.

**C. HASIL PELAKSANAAN PENELITIAN:** Tuliskan secara ringkas hasil pelaksanaan penelitian yang telah dicapai sesuai tahun pelaksanaan penelitian. Penyajian meliputi data, hasil analisis, dan capaian luaran (wajib dan atau tambahan). Seluruh hasil atau capaian yang dilaporkan harus berkaitan dengan tahapan pelaksanaan penelitian sebagaimana direncanakan pada proposal. Penyajian data dapat berupa gambar, tabel, grafik, dan sejenisnya, serta analisis didukung dengan sumber pustaka primer yang relevan dan terkini.

Hasil pelaksanaan penelitian dipaparkan dalam beberapa bagian, yakni pembuatan emulsi minyak VCO yang memiliki berbagai kandungan nutraceutical [1] dalam air, proses spray drying (pengeringan semprot), dan hasil percobaan.

### **1. Pembuatan Emulsi**

Air sebanyak 250 gram dipanaskan hingga mencapai suhu 70 °C, sementara VCO sebanyak 80 gram dipanaskan hingga mencapai suhu 60 °C. Selanjutnya, air dicampurkan dengan campuran variasi maltodekstrin dan karagenan [2] sesuai dengan Tabel I, sebanyak 155 gram, kemudian campuran dihomogenisasi menggunakan *homogenizer* dengan kecepatan rotasi 15.000 rpm selama 5 menit. Setelah itu, K<sub>2</sub>HPO<sub>4</sub> atau penstabil fosfat sebanyak 6,25 gram ditambahkan ke dalam campuran dan dihomogenisasi kembali dengan kecepatan rotasi 15.000 rpm selama 3 menit. Kemudian, natrium kaseinat sebanyak 6,25 gram ditambahkan ke dalam campuran dan dihomogenisasi dengan kecepatan rotasi 15.000 rpm selama 5 menit. Selanjutnya, gliserol monostearat (GMS) sebanyak 2,5 gram ditambahkan ke dalam campuran [3] dan dihomogenisasi dengan kecepatan rotasi 15.000 rpm selama 3 menit. VCO yang telah dipanaskan kemudian ditambahkan ke dalam campuran dan dihomogenisasi dengan kecepatan rotasi 15.000 rpm selama 3 menit. Kompensasi tetes air ditambahkan jika terjadi kehilangan selama proses homogenisasi. Setelah itu, emulsi yang telah dibuat dimasukkan ke dalam alat sonikator dan diproses dengan sonikasi selama 5 menit menggunakan 100% amplitudo. Jika terjadi kehilangan air selama proses sonikasi, beberapa tetes air ditambahkan. Emulsi yang telah disonikasi kemudian dipersiapkan untuk diumpankan ke spray dryer.

**Tabel I** Komposisi *Wall Material* untuk variasi kandungan karagenan

Berat Basis Kering (gram)	Massa Total <i>Wall Material</i> (gram)	Komposisi Karagenan (%)	Berat Karagenan (gram)	Berat Maltodekstrin (gram)
250	155	0	0	155
		1	1,55	153,45
		2	3,1	151,9

## 2. Proses *Spray Drying*

Pada tahap awal, dilakukan pemasangan alat spray dryer, kemudian menuangkan air RO sebagai larutan blanko untuk kondisi awal dan sampel emulsi. Kompresor yang digunakan dinyalakan, diikuti dengan mengalirkan udara dari akumulator kompresor ke dalam spray dryer. Selanjutnya, pompa dinyalakan dan larutan blanko digunakan untuk pengkondisian awal. Parameter lainnya juga ditetapkan, seperti tekanan nozzle sebesar 1 bar, laju alir udara pengering 35 m<sup>3</sup>/jam, dan suhu udara pengering 150°C. Setelah kondisi awal sudah sesuai dengan yang diinginkan, larutan blanko diganti dengan emulsi yang telah dibuat. Spray dryer dinyalakan, dan laju alir umpan diatur sesuai dengan variasi 5 dan 8 ml/min. Proses pengeringan dilakukan hingga sampel emulsi habis, kemudian jalur spray dryer dibilas menggunakan larutan blanko selama 5 menit. Setelah proses selesai, serangkaian alat spray dryer dimatikan dan dibiarkan hingga mencapai suhu lingkungan. Peralatan yang telah dipakai dilepaskan dan dicuci. Produk yang dihasilkan pada bagian produk diambil, kemudian dihitung *yield* produk bubuk yang didapat. Langkah-langkah ini diulang untuk setiap variasi laju alir umpan, yaitu 5 dan 8 ml/min. Setelah semua variasi laju alir umpan dilakukan, laju alir terbaik ditentukan sebagai parameter proses tetap untuk pengujian variasi suhu udara pengering terbaik. Tahapan ini kemudian diulang dengan mengatur variasi suhu udara pengering pada 130°C, 150°C, dan 180°C. Setelah semua variasi suhu dilakukan, suhu udara pengering terbaik ditentukan sebagai parameter proses tetap. Saat laju alir umpan dan suhu udara pengering optimum telah didapatkan, tahapan berikutnya adalah memvariasikan kandungan karagenan dalam *wall material* yaitu 0%, 1%, dan 2%, serta kandungan *total solid* yaitu 45% dan 50%.

**Tabel II** Rancangan Percobaan

Sampel	Karagenan (%)	Laju Alir Umpan (ml/min)	Suhu Udara Pengering (°C)	Aspiration Rate (%)	Tekanan Nozzle (bar)	Total Solid (%)
D515050	2	5	150	100	1	50
D815050	2	8	150	100	1	50
D813050	2	8	130	100	1	50
D818050	2	8	180	100	1	50
N815050	0	8	150	100	1	50
N815045	0	8	150	100	1	45
S815050	1	8	150	100	1	50
S815045	1	8	150	100	1	45
D815045	2	8	150	100	1	45

### 3. Hasil Percobaan

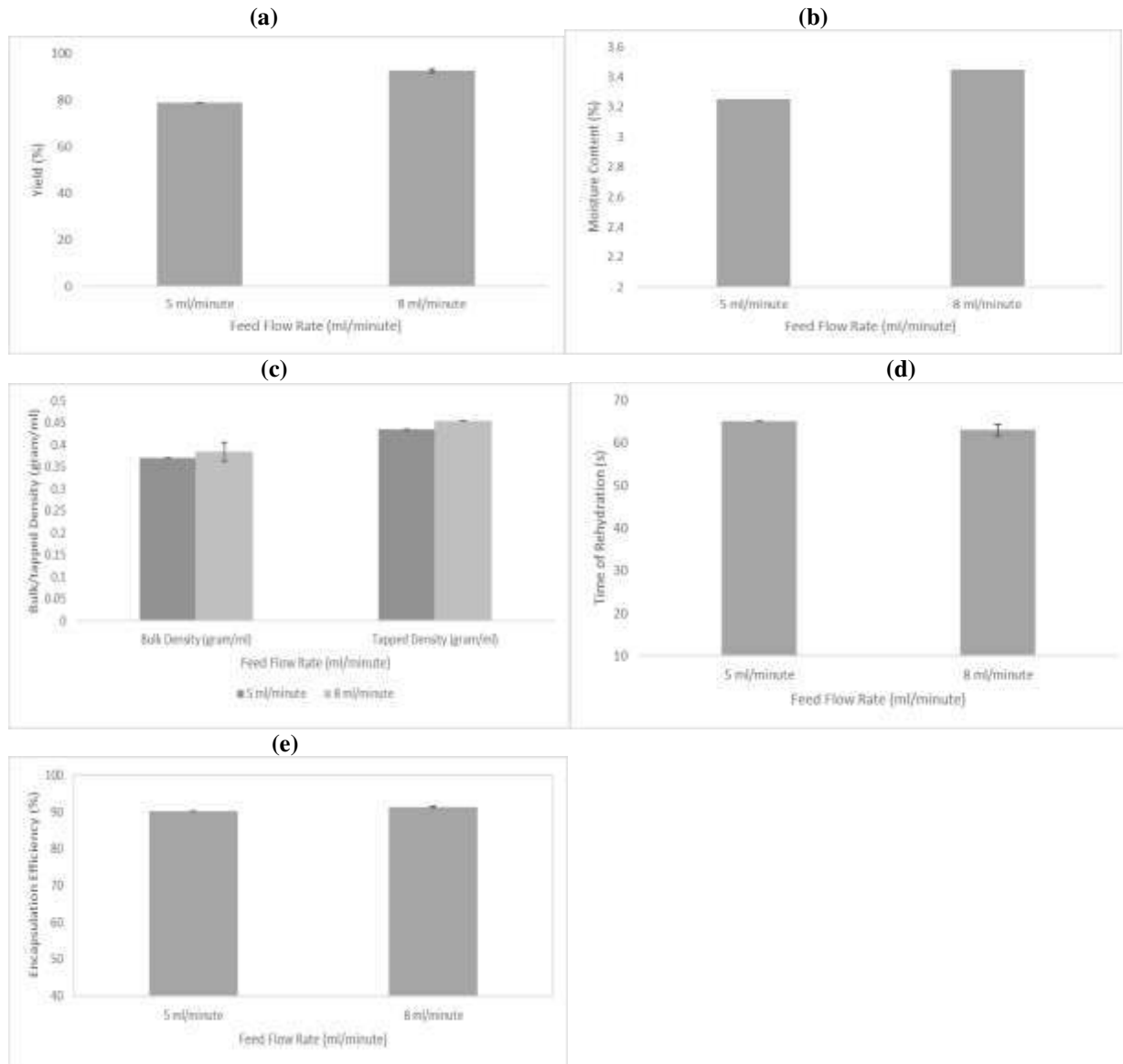
Penelitian ini mengkaji pengaruh penambahan karagenan dan kondisi spray drying terhadap karakteristik bubuk VCO yang dihasilkan. Emulsi O/W dibuat dan dikeringkan menggunakan spray dryer Buchi B-290. Tahap pertama menentukan laju alir umpan optimal (5 atau 8 ml/menit) pada emulsi dengan 2% karagenan, dengan parameter tetap seperti aspirator 100%, tekanan nozzle 1 bar, Total Solid 50%, dan suhu udara 150°C, di mana kondisi terbaik ditentukan berdasarkan yield. Tahap kedua menguji suhu udara pengering (130, 150, dan 180°C) pada laju alir terbaik. Setelah itu, dilakukan variasi kandungan karagenan (0, 1, dan 2%) pada Total Solid 45 dan 50% untuk menentukan kondisi emulsi terbaik. Karakterisasi bubuk VCO mencakup yield, moisture content, bulk & tapped density, time of rehydration, morfologi partikel, particle size, dan efisiensi enkapsulasi. Hasil uji karakterisasi semua variasi pada **Tabel III**.

**Tabel III** Karakteristik Bubuk VCO dengan Karagenan-Maltodekstrin.

Sampel	Yield (%)	Moisture Content (%)	Bulk Density (gram/ml)	Tapped Density (gram/ml)	Time of Rehydration (s)	Z (nm)	Efisiensi Enkapsulasi (%)
D515050	78,92	3,25	0,37	0,435	65	-	90,16
D815050	92,41 ± 0,806	3,45 ± 0,071	0,38 ± 0,021	0,455 ± 0,000	63 ± 1,414	1015	91,37 ± 0,117
D813050	87,62	3,56	0,40	0,465	64	545,3	90,53
D818050	90,88	3,05	0,34	0,435	65	2712	89,61
N815050	85,11 ± 4,115	3,50 ± 0,424	0,42 ± 0,025	0,468 ± 0,010	62 ± 1,414	831,1	89,89 ± 0,151
N815045	84,42 ± 1,365	3,75 ± 0,071	0,39 ± 0,011	0,462 ± 0,009	62,5 ± 0,707	1769	77,22 ± 0,163
S815050	89,05 ± 0,240	3,70 ± 0,141	0,41 ± 0,012	0,465 ± 0,033	64 ± 2,828	1210	91,16 ± 0,132
S815045	85,27 ± 1,308	3,45 ± 0,071	0,37 ± 0,02	0,455 ± 0,00	63 ± 0,00	1250	82,13 ± 0,711
D815045	85,85 ± 0,735	3,6 ± 0,141	0,33 ± 0,016	0,448 ± 0,018	61 ± 4,243	616	83,09 ± 0,156

#### 3.1 Pengaruh Laju Alir Umpan terhadap Karakteristik Bubuk VCO

Dalam penelitian ini, terdapat variasi laju alir umpan 5 ml/menit dan 8 ml/menit. Persentase *yield* produk bubuk akan menjadi parameter untuk menentukan laju alir umpan terbaik yang akan digunakan sebagai laju alir umpan pada pengujian variabel berikutnya. Terdapat juga beberapa parameter hasil seperti *bulk* dan *tapped density*, *time of rehydration*, dan persentase efisiensi enkapsulasi.



**Gambar I** Pengaruh laju alir umpan terhadap karakteristik produk bubuk VCO: (a) *yield*, (b) *moisture content*, (c) *bulk & tapped density*, (d) *time of rehydration*, (e) persentase efisiensi enkapsulasi. Parameter lain, seperti: aspirator 100%, tekanan nozzle 1 bar, *Total Solid* 50%, dan suhu udara pengering sebesar 150 °C dibuat konstan.

Penelitian ini menunjukkan bahwa bubuk VCO yang di-spray drying dengan laju alir umpan 8 ml/menit menghasilkan yield tertinggi (92,98%) dan kandungan moisture 3,4% (**Gambar I**). Laju alir umpan mempengaruhi perpindahan massa, ukuran droplet, dan waktu tinggal bahan dalam pengering. Peningkatan laju alir umpan menyebabkan waktu tinggal lebih singkat dan ukuran partikel lebih besar, serupa dengan temuan Kramm et al. (2023) [4] yang menunjukkan bahwa tekanan udara dan ukuran droplet berbanding terbalik. Hubungan matematis ukuran droplet dan tekanan cairan pada sprayer ditunjukkan oleh Sun et. al (2017) [5] sebagai berikut:

$$\frac{D_1}{D_2} = \left(\frac{P_2}{P_1}\right)^{-0,3}$$

Dari persamaan di atas diketahui bahwa nilai dari tekanan udara (P) berbanding terbalik dengan diameter droplet (D) yang dihasilkan,  $D_1$  dan  $D_2$  menunjukkan nilai diameter droplet pada tekanan  $P_1$  dan  $P_2$

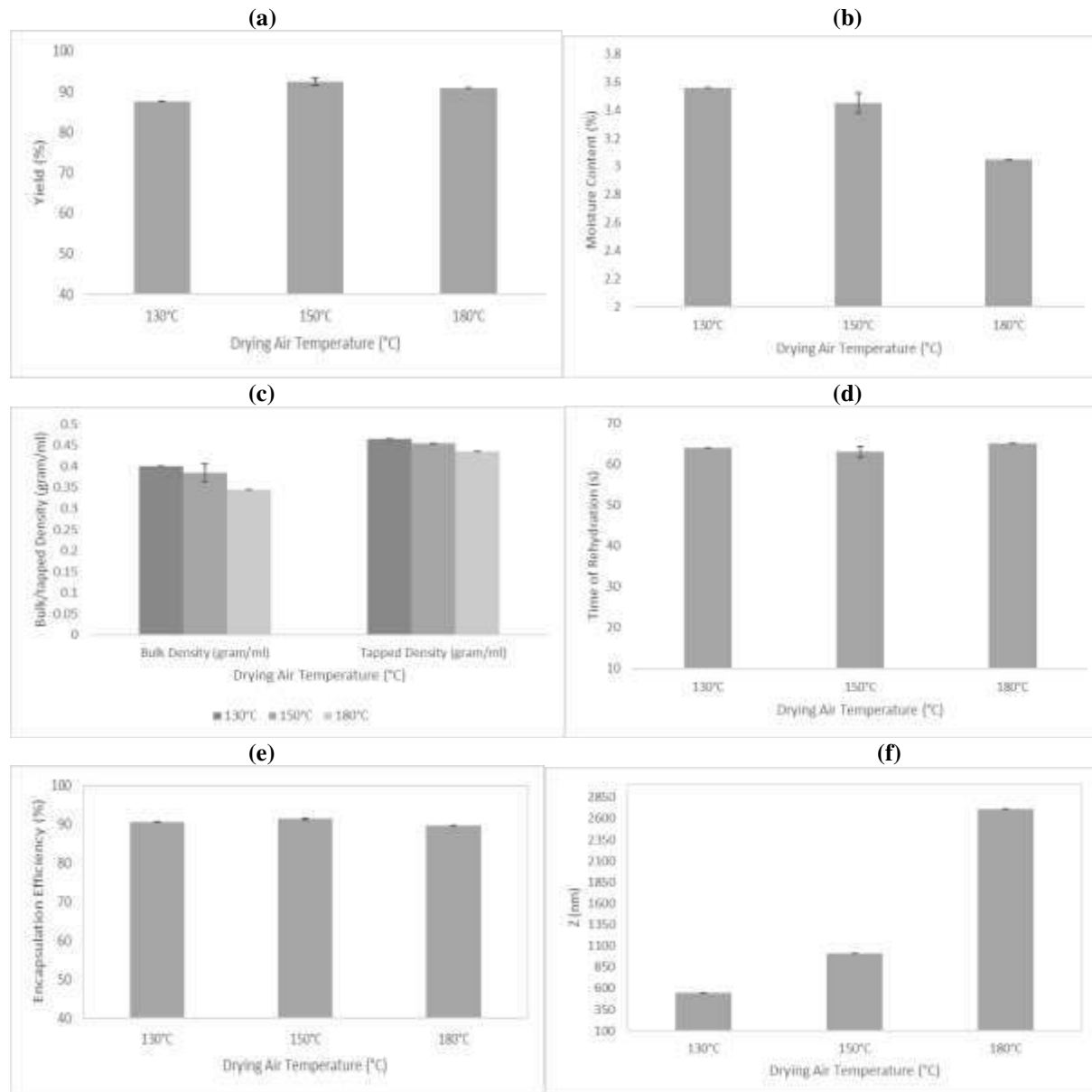
Pemilihan laju alir umpan yang optimal penting untuk mencegah masalah pengeringan tidak sempurna atau pembentukan crust. Hasil menunjukkan bahwa laju alir 8 ml/menit memiliki kandungan air lebih tinggi dibandingkan 5 ml/menit, karena droplet lebih besar dan waktu pengeringan lebih singkat. Ukuran rata-rata partikel adalah 1015

nm, serupa dengan penelitian Hee et al. (2017) [6]. Meskipun kandungan air lebih tinggi pada 8 ml/menit, yield dan efisiensi enkapsulasi lebih baik dibandingkan 5 ml/menit, menjadikan laju alir 8 ml/menit pilihan terbaik.

Pengujian *time of rehydration* menunjukkan bahwa bubuk VCO mudah larut dalam air, dengan sedikit perbedaan antara variasi laju alir. Pengujian efisiensi enkapsulasi menunjukkan bahwa laju alir 8 ml/menit menghasilkan efisiensi enkapsulasi lebih tinggi dibandingkan 5 ml/menit, karena *residence time* yang lebih pendek mengurangi kerusakan wall material.

### 3.2 Pengaruh Suhu Udara Pengering

Pada penelitian ini, pengaruh suhu udara pengering ditentukan dengan menguji tiga variasi, yaitu pada suhu 130°C, 150°C, dan 180°C. Dengan menggunakan laju alir umpan terbaik yang didapati pada pengujian sebelumnya dan parameter proses lain yang sama dengan sebelumnya. Suhu udara pengering terbaik dapat ditentukan dari nilai *yield* yang dihasilkan, selain itu terdapat juga parameter hasil lain, seperti: *moisture*, *bulk & tapped density*, dan *time of rehydration* yang dapat digunakan sebagai pembanding pada setiap variasi.

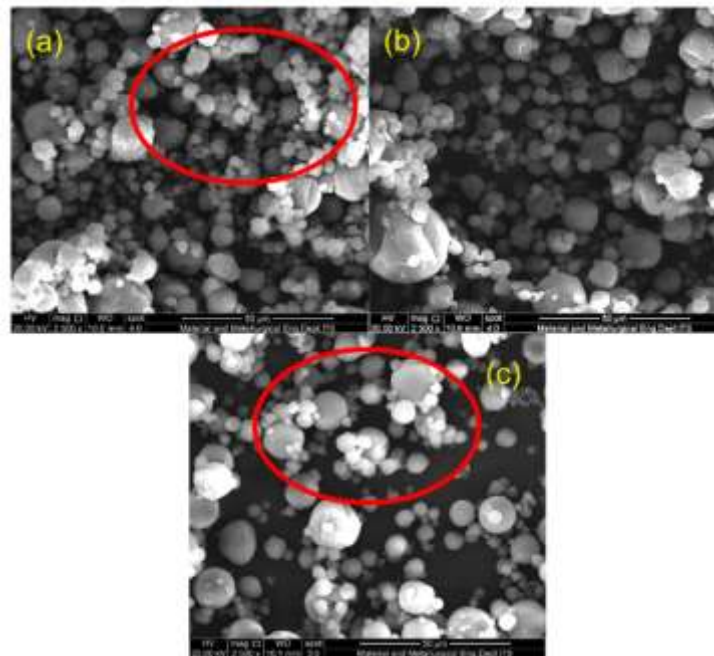


**Gambar II** Pengaruh suhu udara pengering terhadap karakteristik produk bubuk VCO: (a) *yield*, (b) *moisture content*, (c) *bulk & tapped density*, (d) *time of rehydration*, (e) persentase efisiensi enkapsulasi, (f) *particle size*. Parameter lain, seperti: aspirator 100%, tekanan nozzle 1 bar, *Total Solid* 50%, dan laju alir umpan sebesar 8 ml/menit dibuat konstan.

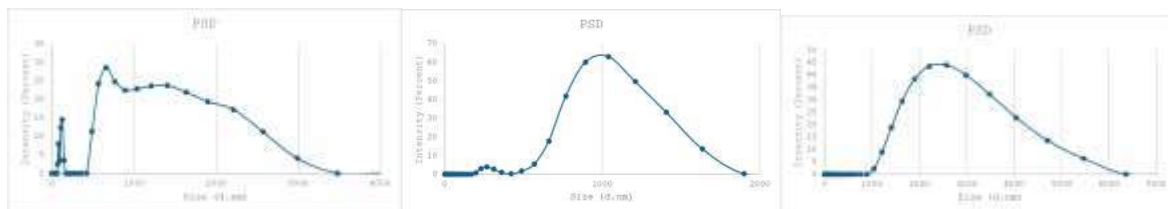
Suhu udara pengering dalam proses spray drying memiliki pengaruh terhadap karakteristik bubuk VCO, terutama dalam hal *yield*, kadar air, dan morfologi partikel. Pada suhu rendah, seperti 130°C, laju penguapan air dari emulsi lebih lambat sehingga kadar air dalam bubuk cenderung tinggi. Hal ini menyebabkan produk lebih higroskopis, mudah menggumpal, dan berpotensi mengalami aglomerasi, yang pada akhirnya menurunkan *yield* produk. Selain itu, ukuran partikel yang terbentuk lebih besar akibat tingginya kadar air yang masih tertahan dalam bubuk.

Pada suhu 150°C, hasil yang diperoleh menunjukkan *yield* produk yang lebih tinggi dibandingkan suhu lainnya. Suhu ini memberikan keseimbangan optimal antara laju pengeringan dan kestabilan emulsi, sehingga menghasilkan partikel yang lebih seragam dan memiliki kadar air yang lebih rendah. Partikel bubuk yang dihasilkan pada suhu ini cenderung berbentuk lebih bulat dengan permukaan yang halus, yang berkontribusi pada kestabilan penyimpanan serta meningkatkan efisiensi enkapsulasi VCO.

Namun, pada suhu yang lebih tinggi, seperti 180°C, terjadi penurunan *yield* akibat viskositas emulsi yang lebih rendah serta peningkatan laju pengeringan yang terlalu cepat. Kondisi ini menyebabkan koalesen antar droplet sebelum sepenuhnya mengering, sehingga terbentuk partikel yang lebih besar dan tidak seragam. Selain itu, suhu tinggi juga dapat mempengaruhi struktur komponen emulsi, seperti karagenan dan maltodekstrin, yang dapat mengalami degradasi termal. Oleh karena itu, pemilihan suhu pengeringan yang optimal sangat penting untuk mendapatkan bubuk VCO dengan kualitas terbaik.



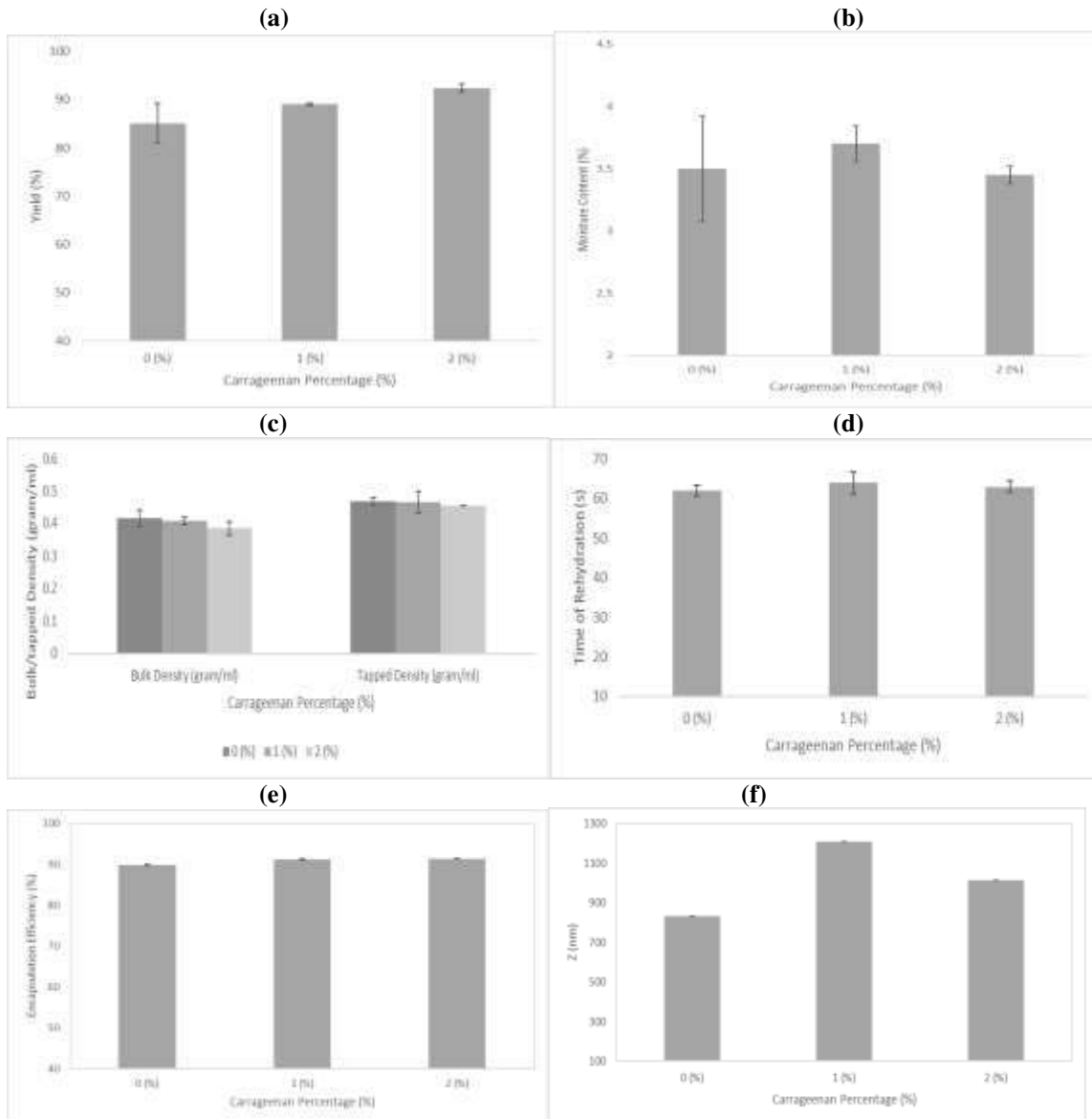
**Gambar III** Pengaruh suhu udara pengering terhadap SEM: (a) 130°C, (b) 150°C, dan (c) 180°C.



**Gambar IV** Pengaruh suhu udara pengering terhadap PSD: (a) 130°C, (b) 150°C, dan (c) 180°C.

### 3.3 Pengaruh Kandungan Karagenan terhadap Karakteristik Bubuk VCO

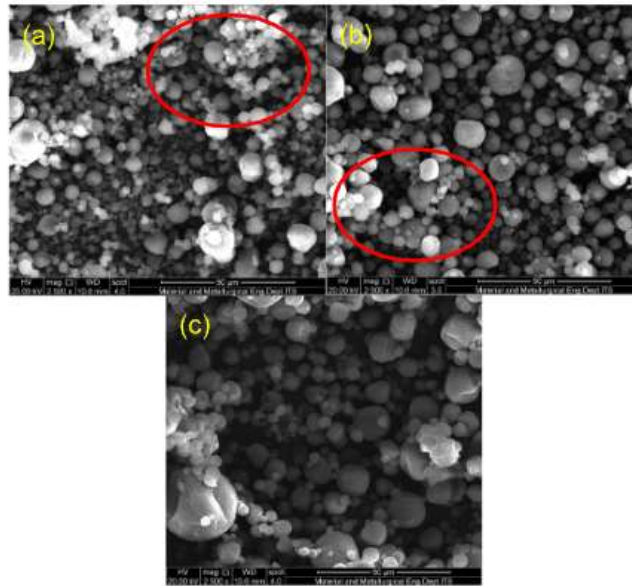
Dalam penelitian ini, digunakan variasi persen karagenan yaitu 0%, 1%, dan 2% kandungan karagenan dalam pembuatan emulsi yang akan dikeringkan menjadi produk bubuk VCO. Pengeringan produk bubuk dengan variasi karagenan dilakukan dengan laju alir umpan dan suhu udara pengering yang terbaik, yaitu laju alir umpan sebesar 8 ml/menit dan suhu udara pengering sebesar 150°C.



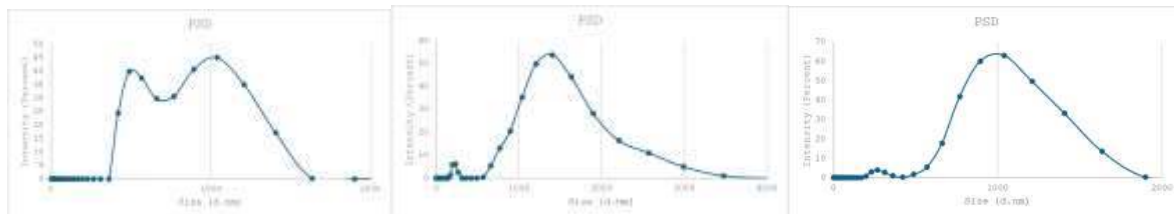
**Gambar V** Pengaruh karagenan terhadap karakteristik produk bubuk VCO: (a) *yield*, (b) *moisture content*, (c) *bulk & tapped density*, (d) *time of rehydration*, (e) persentase efisiensi enkapsulasi, (f) *particle size*. Parameter lain, seperti: aspirator 100%, tekanan nozzle 1 bar, *Total Solid* 50%, suhu udara pengering 150°C dan laju alir umpan sebesar 8 ml/menit dibuat konstan.

Penelitian ini menunjukkan bahwa peningkatan kandungan karagenan pada emulsi bubuk VCO dapat meningkatkan yield produk, seperti yang terlihat pada **Gambar III**. Kandungan karagenan yang lebih tinggi meningkatkan viskositas emulsi, yang dapat menstabilkan droplet minyak dan mengurangi koagulasi. Viskositas yang lebih tinggi juga mengurangi laju atomisasi, menghasilkan droplet lebih kecil, dan meningkatkan efisiensi perpindahan massa dan panas selama pengeringan. Ukuran droplet untuk variasi karagenan 0%, 1%, dan 2% masing-masing adalah 831,1, 1210, dan 1015 nm, sebanding dengan penelitian Nurhadi et al. (2022) [7] dimana ukuran *droplet* bubuk VCO rata-rata dari penelitian tersebut adalah 1500 nm. Karagenan 2% menghasilkan yield tertinggi, sementara aglomerasi terjadi pada bubuk dengan karagenan 0% dan 1% (**Gambar IV**), menunjukkan karagenan berfungsi sebagai penstabil emulsi yang baik.

Pengujian *bulk density*, *tapped density*, dan *time of rehydration* tidak menunjukkan perbedaan yang cukup besar antara variasi karagenan. Selain itu, efisiensi enkapsulasi meningkat seiring bertambahnya kandungan karagenan, yang membantu menstabilkan emulsi, mendistribusikan droplet secara merata, dan mempercepat pembentukan crust. Hasil ini sejalan dengan penelitian Gulzar et al. (2022) [8], yang menunjukkan bahwa karagenan meningkatkan efisiensi enkapsulasi dan yield produk.



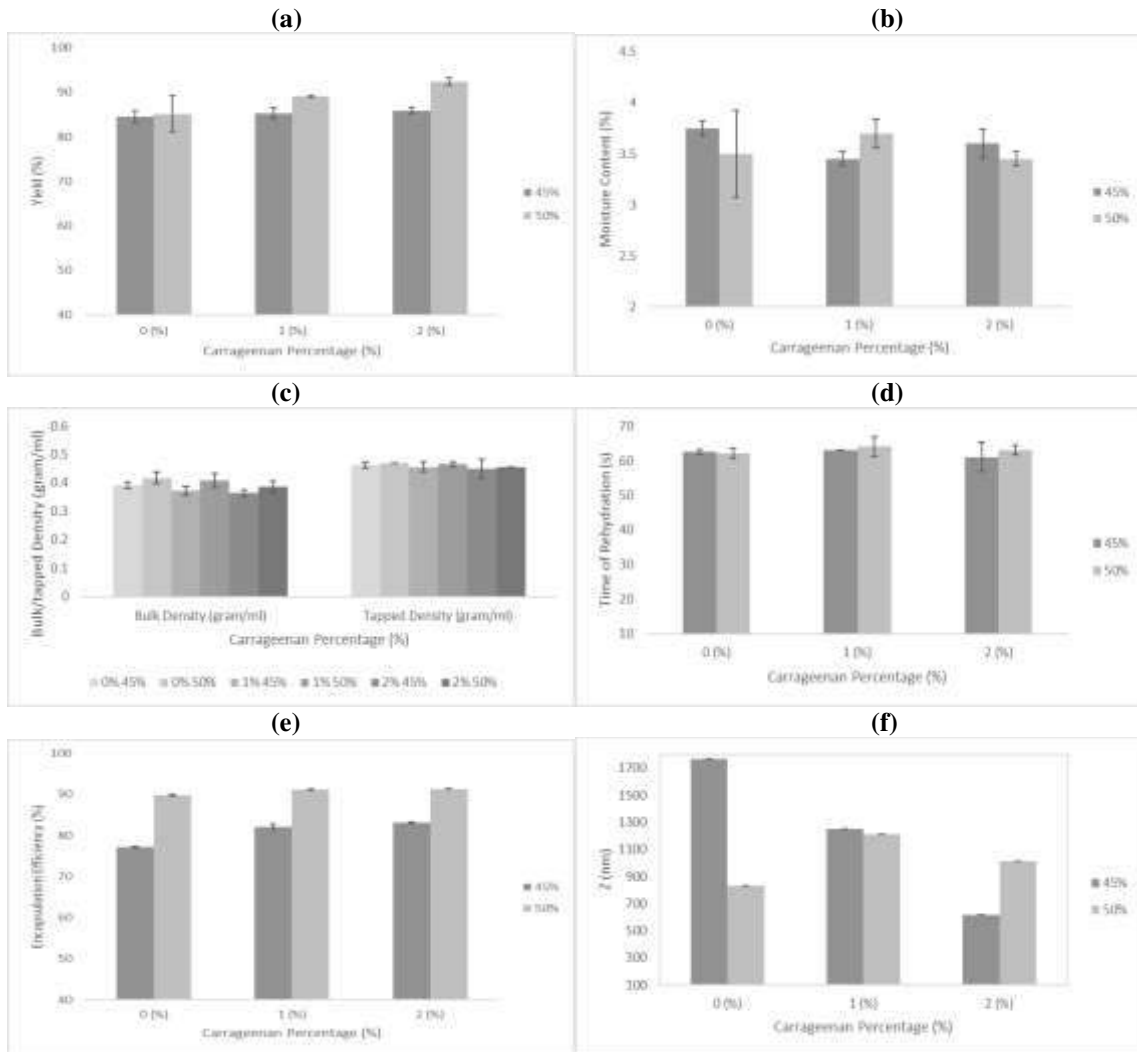
**Gambar VI** Pengaruh kandungan karagenan terhadap SEM: (a) 0% karagenan, (b) 1% karagenan, (c) 2% karagenan.



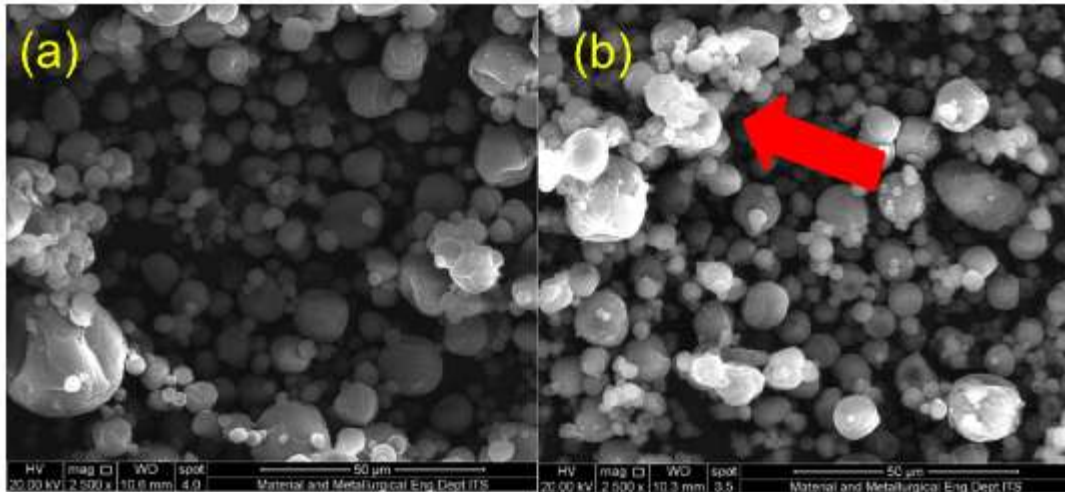
**Gambar VII** Pengaruh suhu udara pengering terhadap PSD: (a) 0% karagenan, (b) 1% karagenan, (c) 2% karagenan.

### 3.4 Pengaruh Kandungan *Total Solid* terhadap Karakteristik Bubuk VCO

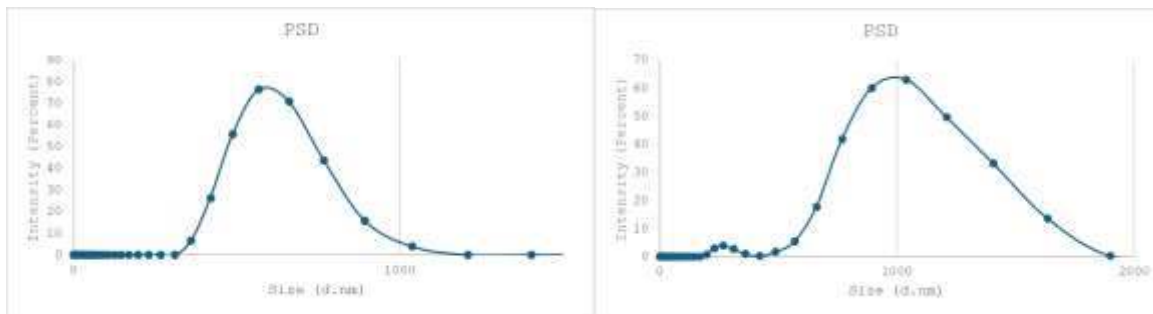
Kandungan total solid merupakan salah satu parameter yang dapat mempengaruhi karakteristik dari bubuk VCO. Pada penelitian ini, dilakukan variasi persentase *Total Solid* (%TS) 50% dan 45% untuk masing-masing persentase karagenan pada *wall material*. Kondisi operasi pengeringan menggunakan *spray drying* sama seperti sebelumnya dengan menggunakan laju alir umpan dan suhu udara pengering optimum, yaitu 8 ml/menit dan 150°C.



**Gambar VIII** Pengaruh persentase total solid terhadap karakteristik produk bubuk VCO: (a) yield, (b) moisture content, (c) bulk & tapped density, (d) time of rehydration, (e) persentase efisiensi enkapsulasi, (f) particle size. Parameter lain, seperti: aspirator 100%, tekanan nozzle 1 bar, suhu udara pengering 150°C dan laju alir umpan sebesar 8 ml/menit dibuat konstan.



**Gambar IX** Pengaruh %TS terhadap SEM pada kandungan karagenan 2%.



**Gambar X** Pengaruh %TS terhadap PSD pada kandungan karagenan 2%

Kandungan total solid (%TS) dalam emulsi berpengaruh terhadap karakteristik bubuk VCO yang dihasilkan melalui proses spray drying. Dalam penelitian ini, dilakukan variasi %TS sebesar 45% dan 50%, dengan kondisi operasi konstan yaitu suhu udara pengering 150°C dan laju alir umpan 8 ml/menit. Pada kandungan 45% total solid, jumlah bahan kering dalam emulsi lebih rendah, sehingga yield produk cenderung lebih sedikit. Selain itu, laju penguapan air lebih cepat, menghasilkan bubuk dengan ukuran lebih kecil dan ringan. Partikel yang terbentuk cenderung teraglomerasi, yang dapat mempengaruhi kestabilan produk akhir.

Sebaliknya, pada kandungan 50% total solid, jumlah bahan kering lebih banyak sehingga pembentukan bubuk lebih efisien dengan yield yang lebih tinggi. Bubuk yang dihasilkan lebih padat, memiliki ukuran partikel yang lebih besar, serta kadar air yang lebih rendah dibandingkan dengan kandungan total solid 45%. Namun, peningkatan %TS juga menyebabkan peningkatan viskositas emulsi, yang dapat mempengaruhi efisiensi atomisasi pada spray dryer. Viskositas yang terlalu tinggi dapat menghambat aliran emulsi melalui nozzle, sehingga perlu diperhatikan batas optimal dalam formulasi.

Selain itu, kandungan total solid juga mempengaruhi efisiensi enkapsulasi minyak dalam bubuk VCO. Pada %TS yang lebih rendah, jumlah air yang diuapkan lebih banyak sehingga pembentukan crust lebih lambat, meningkatkan kemungkinan minyak naik ke permukaan sebelum proses enkapsulasi selesai. Akibatnya, terjadi oil losses yang lebih tinggi dan efisiensi enkapsulasi lebih rendah. Sebaliknya, pada %TS yang lebih tinggi, pembentukan crust lebih cepat dan minyak lebih terlindungi dalam matriks enkapsulasi, sehingga efisiensi enkapsulasi meningkat. Oleh karena itu, kandungan total solid yang optimal sangat penting untuk memperoleh bubuk VCO dengan yield tinggi, kadar air rendah, serta efisiensi enkapsulasi yang baik.

## KESIMPULAN

Pengaruh penambahan karagenan terhadap karakteristik produk bubuk VCO terbaik diperoleh pada variasi karagenan 2%, yang memiliki nilai yield dan efisiensi enkapsulasi (%EE) paling tinggi. Peningkatan *Total Solid* (%TS) sebanding dengan peningkatan yield dan efisiensi enkapsulasi (%EE), karena jumlah beban air yang diuapkan menjadi lebih sedikit, yang tidak memperlambat laju pembentukan *crust*. Hal ini membantu mengurangi terjadinya oil losses pada proses pengeringan. Yield tertinggi diperoleh pada kondisi operasi spray dryer dengan suhu udara pengering 150 °C dan laju alir umpan 8 ml/menit. Pada kondisi ini, penguapan air berjalan dengan baik dan menghasilkan pembentukan *crust* yang tidak terlalu cepat, sehingga memberikan hasil yang optimal.

**D. STATUS LUARAN:** Tuliskan jenis, identitas dan status ketercapaian setiap luaran wajib dan luaran tambahan (jika ada) yang dijanjikan. Jenis luaran dapat berupa publikasi, perolehan kekayaan intelektual, atau luaran lainnya yang telah dijanjikan pada proposal. Uraian status luaran harus didukung dengan bukti kemajuan ketercapaian luaran sesuai dengan luaran yang dijanjikan. Lengkapi isian jenis luaran yang dijanjikan serta unggah bukti dokumen ketercapaian luaran melalui BIMA.

Manuscript review journal dengan judul "Sustainable Innovations in Carrageenan Extraction and Applications: A Comprehensive Review of Green Technologies, Industrial Utilization, and Future Perspectives" telah di-submit pada *Food Research* (Q3).

Luaran tambahan berupa manuscript artikel hasil penelitian dengan judul tentative "Incorporation of Carrageenan during VCO Encapsulation using Spray Drying", *in preparation*.

Luaran tambahan berupa prototype produk bubuk VCO dengan ko-agen penyalut karagenan dengan TKT 3.

**E. PERAN MITRA:** Tuliskan realisasi kerjasama dan kontribusi Mitra baik *in-kind* maupun *in-cash* serta unggah bukti dokumen pendukung sesuai dengan kondisi yang sebenarnya. Bukti dokumen realisasi kerjasama dengan Mitra dapat unggah melalui BIMA.

**Catatan:**

*Bagian ini wajib diisi untuk penelitian terapan, untuk penelitian dasar (Fundamental, Pascasarjana, PKDN, Dosen Pemula) boleh mengisi bagian ini (tidak wajib) jika melibatkan mitra dalam pelaksanaan penelitiannya*

Peneliti berdiskusi dengan mitra (PT. LNK) khususnya dalam formulasi emulsi O/W. Mitra juga melakukan penelitian rheologi dari formulasi emulsi yang diaplikasikan di industri. Pengembangan produk emulsi cair sedang direncanakan untuk diproyeksikan di plant 3 di PT. LNK. Arah pengembangan emulsi pangan cair dengan kestabilan tinggi, bebas kontaminasi mikroba, dan masa simpan yang tinggi memerlukan riset pengembangan

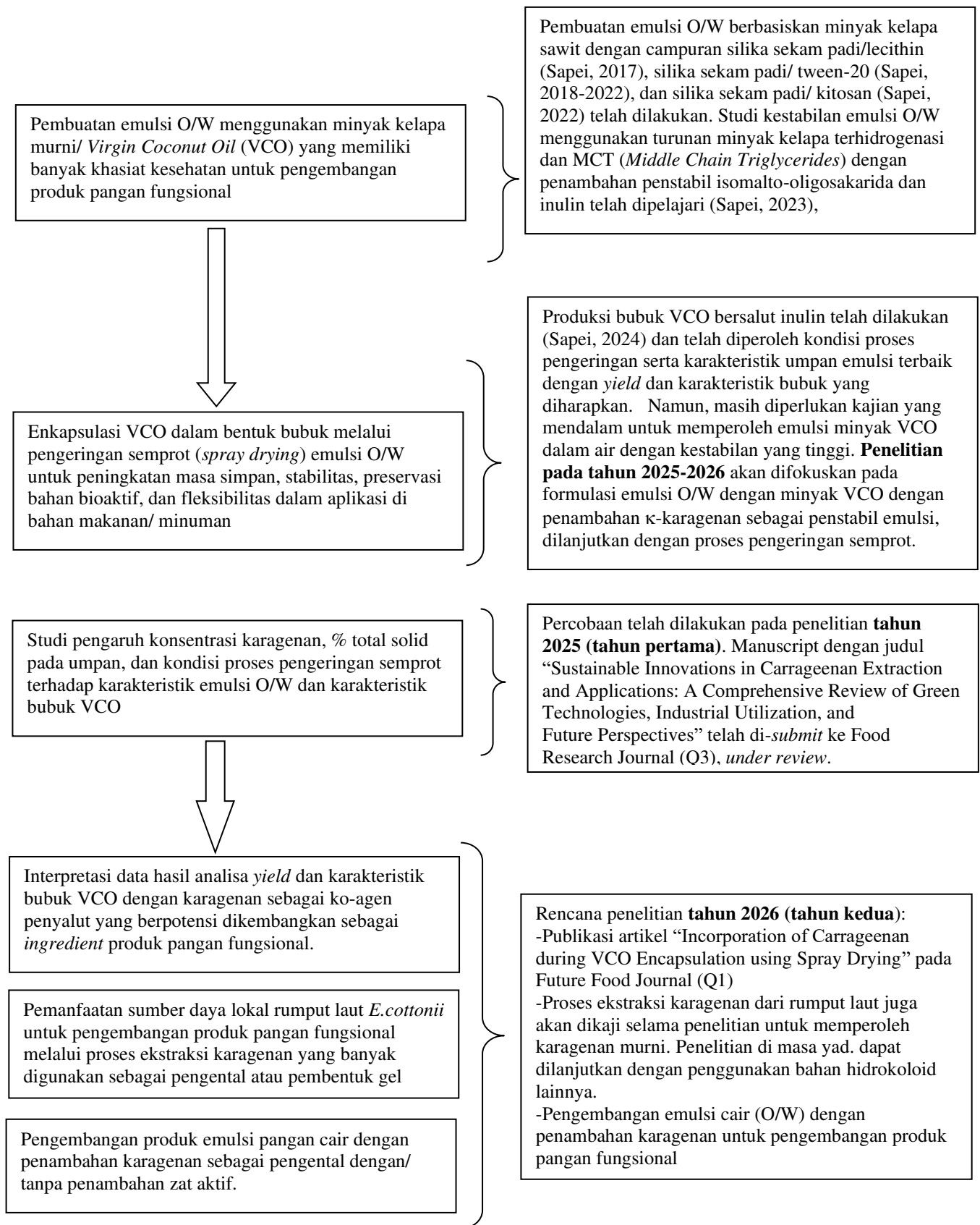
yang cukup komprehensif, termasuk di dalamnya formulasi, teknik sterilisasi, perhitungan mikroba, pengembangan packaging untuk produk cair, dan penentuan umur simpan produk.

**F. KENDALA PELAKSANAAN PENELITIAN:** Tuliskan kesulitan atau hambatan yang dihadapi selama melakukan penelitian dan mencapai luaran yang dijanjikan, termasuk penjelasan jika pelaksanaan penelitian dan luaran penelitian tidak sesuai dengan yang direncanakan atau dijanjikan.

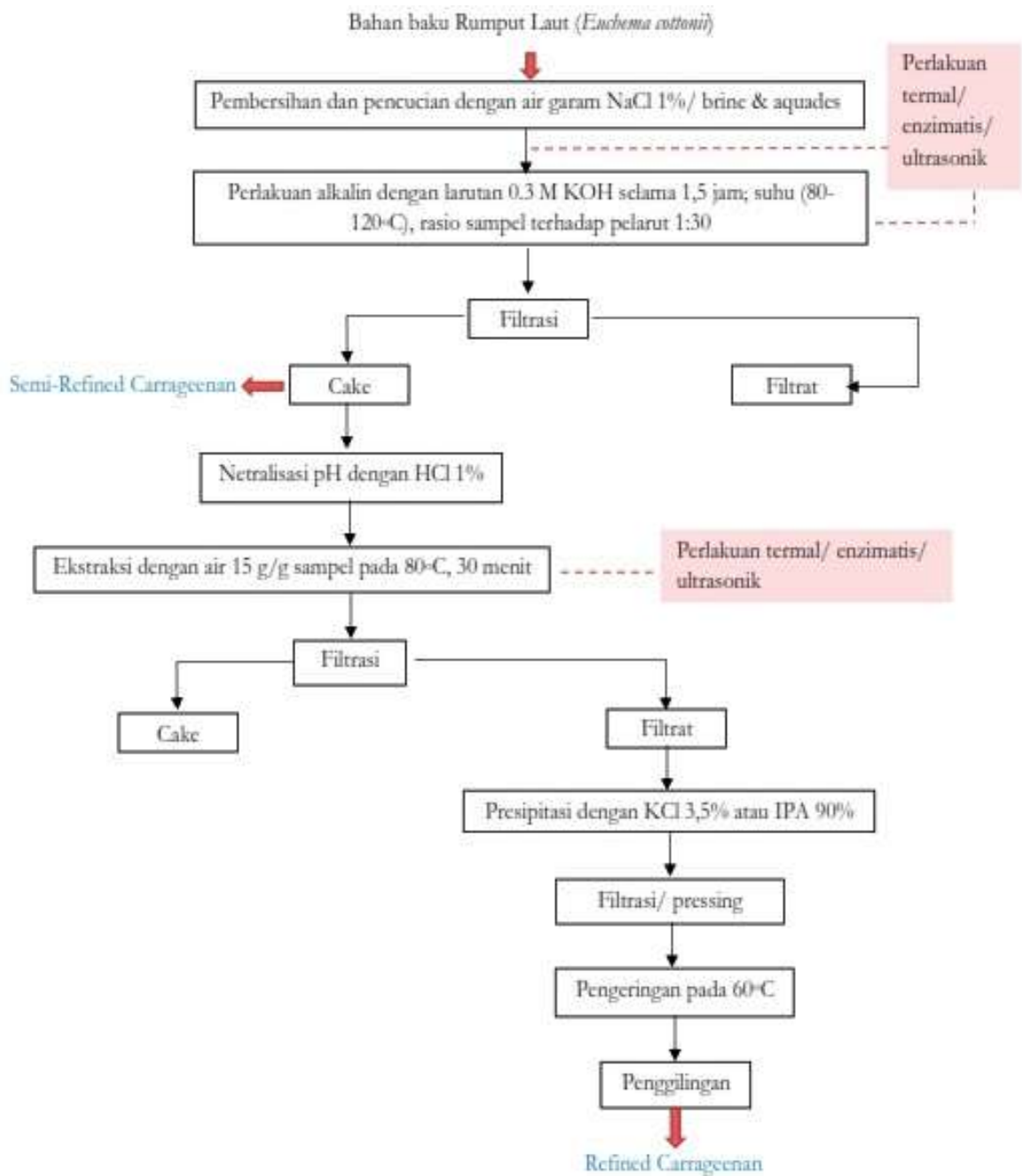
Masih diperlukan waktu untuk percobaan ulangan. Di samping itu, diperlukan pengolahan data dan menyajikannya dalam bentuk grafik atau tabel yang cukup komprehensif untuk penulisan hasil penelitian di jurnal internasional bereputasi. Interpretasi data dan diskusi yang cukup mendalam masih terus dilakukan melalui penelusuran jurnal-jurnal terkini.

**G. RENCANA TAHAPAN SELANJUTNYA:** Tuliskan dan uraikan rencana penelitian selanjutnya berdasarkan indikator luaran yang telah dicapai, rencana realisasi luaran wajib yang dijanjikan dan tambahan (jika ada) di tahun berikutnya serta *roadmap* penelitian keseluruhan. Pada bagian ini diperbolehkan untuk melengkapi penjelasan dari setiap tahapan dalam metoda yang akan direncanakan termasuk jadwal berkaitan dengan strategi untuk mencapai luaran seperti yang telah dijanjikan dalam proposal. Jika diperlukan, penjelasan dapat juga dilengkapi dengan gambar, tabel, diagram, serta pustaka yang relevan. Jika laporan kemajuan merupakan laporan pelaksanaan tahun terakhir, pada bagian ini dapat dituliskan rencana penyelesaian target yang belum tercapai.

1. Pada tahun pertama (2025), publikasi berupa telaah review karagenan yang mendasari arah roadmap penelitian pangan fungsional dengan penerapan rumput laut *E.cottonii* dan karagenan.
2. Penulisan artikel publikasi tahun ke-2 (2026) akan difokuskan pada hasil penelitian terkait pengeringan semprot VCO dengan menggunakan karagenan sebagai ko-agen penyalut. Dengan demikian masih diperlukan langkah-langkah sbb.:
  - melakukan pengujian-pengujian lanjutan
  - interpretasi data dan validasi data
  - penelusuran jurnal-jurnal terkini untuk pembahasan hasil penelitian
3. Penelitian terkait ekstraksi karagenan dari bahan baku rumput laut *E.cottonii* masih perlu ditelaah.
4. Pengembangan produk emulsi cair (O/W) dengan penambahan karagenan perlu dikaji mengingat penggunaan karagenan sebagai ko-agen penyalut dalam produk bubuk yang sangat terbatas (tidak dapat melebihi 2%).



**Gambar 1. Diagram Alir Penelitian untuk Pendanaan Hibah Fundamental 2025-2026**



Gambar 2. Diagram Alir Proses Ekstraksi Karagenan dari Rumput Laut *E.cottonii*

**H. DAFTAR PUSTAKA:** Penyusunan Daftar Pustaka berdasarkan sistem nomor sesuai dengan urutan pengutipan. Hanya pustaka yang disitasi pada laporan kemajuan yang dicantumkan dalam Daftar Pustaka.

- [1] Selvaraj, K. V., Bharathi, A., Sivakumar, V., Karthikeyan, A., & Maheswarappa, H. (2020). Virgin coconut oil: A nutraceutical and therapeutic food. *International Journal of Chemical Studies*, 8(3), 662–663. <https://doi.org/10.22271/chemi.2020.v8.i3h.9282>
- [2] Wang, Y., Ghosh, S., & Nickerson, M. T. (2022). Microencapsulation of Flaxseed Oil by Lentil Protein Isolate- $\kappa$ -Carrageenan and- $\iota$ -Carrageenan Based Wall Materials through Spray and Freeze Drying. *Molecules*, 27(10). <https://doi.org/10.3390/molecules27103195>
- [3] Wu, S., Wang, G., Lu, Z., Li, Y., Zhou, X., Chen, L., Cao, J., & Zhang, L. (2016). Effects of glycerol monostearate and Tween 80 on the physical properties and stability of recombined low-fat dairy cream. *Dairy Science and Technology*, 96(3), 377–390. <https://doi.org/10.1007/s13594-015-0274-x>
- [4] Kramm, K., Roucher, A., Descarrega, J. B., Ambühl, M., Kammerhofer, J., Meunier, V., & Heinrich, S. (2024). Influence of material characteristics on plant-based milk alternative properties. *Journal of Food Engineering*, 373, 112019. <https://doi.org/10.1002/cite.202200152>
- [5] Sun, T., Huang, X., Chen, Y., & Zhang, H. (2020). Experimental investigation of water spraying in an indirect evaporative cooler from nozzle type and spray strategy perspectives. *Energy and Buildings*, 214, 109871. 10.1615/AtomizSpr.2017019727
- [6] Hee, Y. Y., Tan, C. P., Rahman, R. A., Noranizan, M., Smith, R. L. and Chong, G. H. 2017. Production of virgin coconut oil microcapsules from oil-in-water emulsion with supercritical carbon dioxide spray drying. *Journal of Supercritical Fluids* 130: 118-124.
- [7] Nurhadi, B., Selly, S., Nurhasanah, S., Saputra, R. A., & Arifin, H. R. (2022). The virgin coconut oil (VCO) emulsion powder characteristics: Effect of pickering emulsion with microcrystalline cellulose (MCC) and different drying techniques. *Italian Journal of Food Science*, 34(1), 67–85. <https://doi.org/10.15586/ijfs.v34i1.2111>
- [8] Gulzar, S., Balange, A. K., Nagarajarao, R. C., Zhao, Q., & Benjakul, S. (2022). Microcapsules of Shrimp Oil Using Kidney Bean Protein Isolate and  $\kappa$ -Carrageenan as Wall Materials with the Aid of Ultrasonication or High-Pressure Microfluidization: Characteristics and Oxidative Stability. *Foods*, 11(10). <https://doi.org/10.3390/foods11101431>

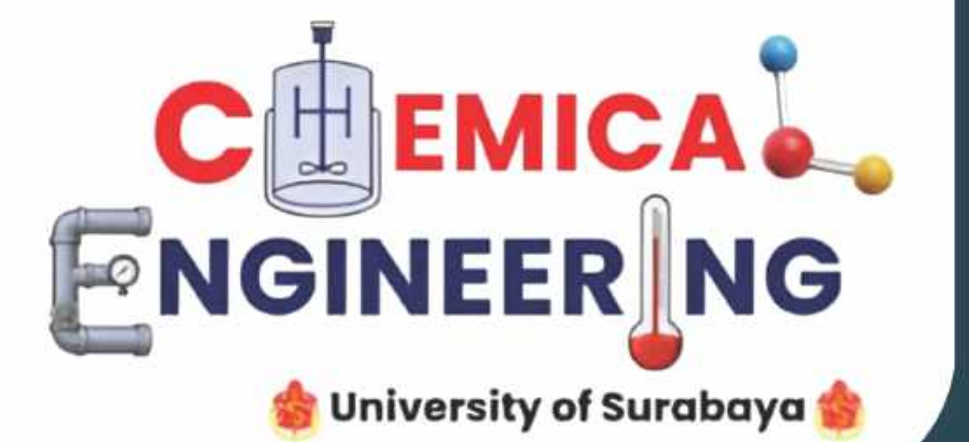


**DIKTISAINTEK  
BERDAMPAK**

# Aplikasi Karagenan sebagai Ko-agen Penyalut dalam Proses Enkapsulasi Minyak Kelapa Murni menggunakan Pengeringan Semprot



**UBAYA**



University of Surabaya

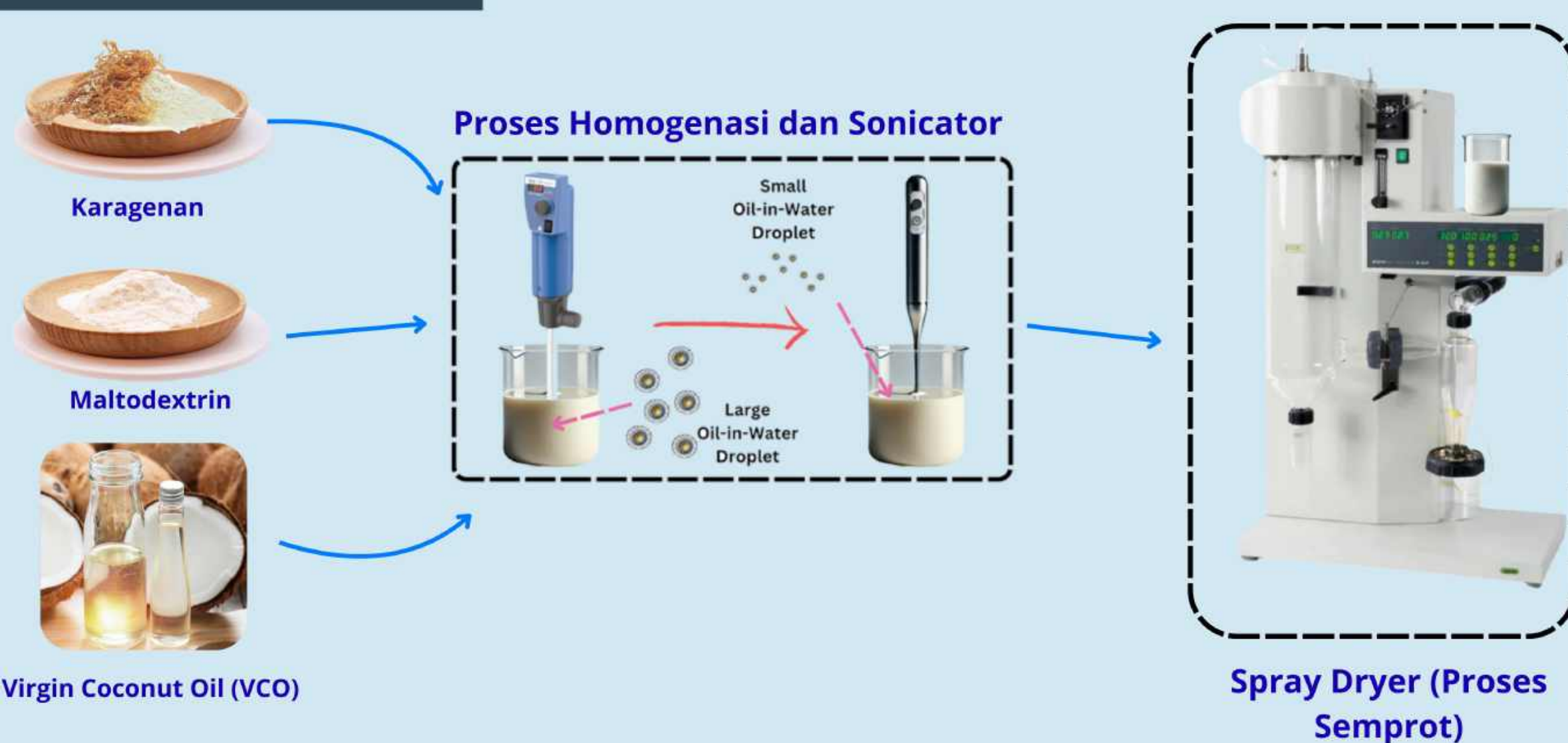
Dr.rer.nat. Lanny Sapei, S.T., M.Sc. (NIDN : 0425017801), Email : lanny.sapei@staff.ubaya.ac.id  
Prof. Ir. Rudy Agustriyanto, S.T., M.Sc., Ph.D., IPM. (NIDN : 0709087201)  
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## Abstrak

Penelitian ini bertujuan untuk menginvestigasi pengaruh variasi konsentrasi karagenan sebagai wall material dan persentase total padatan (total solid) terhadap karakteristik bubuk minyak kelapa murni (Virgin Coconut Oil, VCO) hasil enkapsulasi menggunakan spray drying. Karagenan, sebagai hidrokoloid yang melimpah dan kaya serat, dimanfaatkan karena kemampuannya sebagai penstabil emulsi. Emulsi VCO dibuat dengan variasi konsentrasi karagenan (0%, 1%, dan 2%) dan persentase total padatan (45% dan 50%). Emulsi dihomogenisasi menggunakan homogenizer dan sonikator, kemudian dikeringkan dengan spray dryer tipe Buchi B-290. Karakteristik produk bubuk yang diuji meliputi yield produk, kadar air (moisture content), kerapatan curah (bulk dan tapped density), waktu rehidrasi (time of rehydration), ukuran partikel, dan efisiensi enkapsulasi. Hasil penelitian menunjukkan bahwa formulasi optimum dicapai pada konsentrasi karagenan 2% dan total padatan 50%, dengan kondisi pengeringan laju alir umpan 8 ml/menit dan suhu pengeringan 150°C. Karakteristik terbaik dari bubuk VCO yang dihasilkan adalah yield produk 92,41%, kadar air 3,45%, bulk density 0,38 gram/ml, tapped density 0,455 gram/ml, waktu rehidrasi 63 detik, ukuran partikel 1015 nm, dan efisiensi enkapsulasi 91,37%. Pemanfaatan karagenan terbukti efektif sebagai wall material dalam proses enkapsulasi VCO.

(Kata Kunci : *emulsifikasi; enkapsulasi VCO; karagenan; pengeringan semprot; yield*)

## Metodologi



## Hasil Luaran

### Luaran Wajib

Paper submission to Applied Food Research Journal (Q3) entitled "Sustainable Extraction and Applications: A Comprehensive Review of Green Technologies, Industrial Utilization, and Future Perspectives"

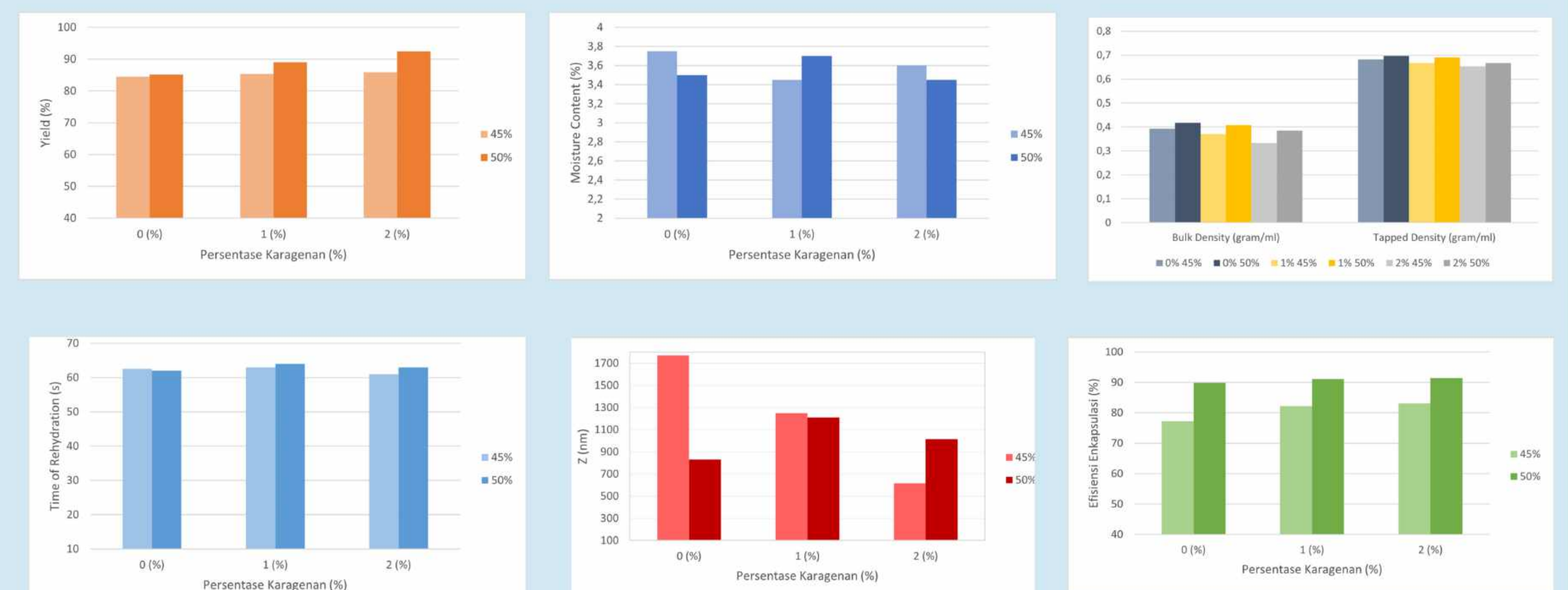
### Luaran Tambahan

Prototype produk bubuk VCO bersalut karagenan (TKT : 3)

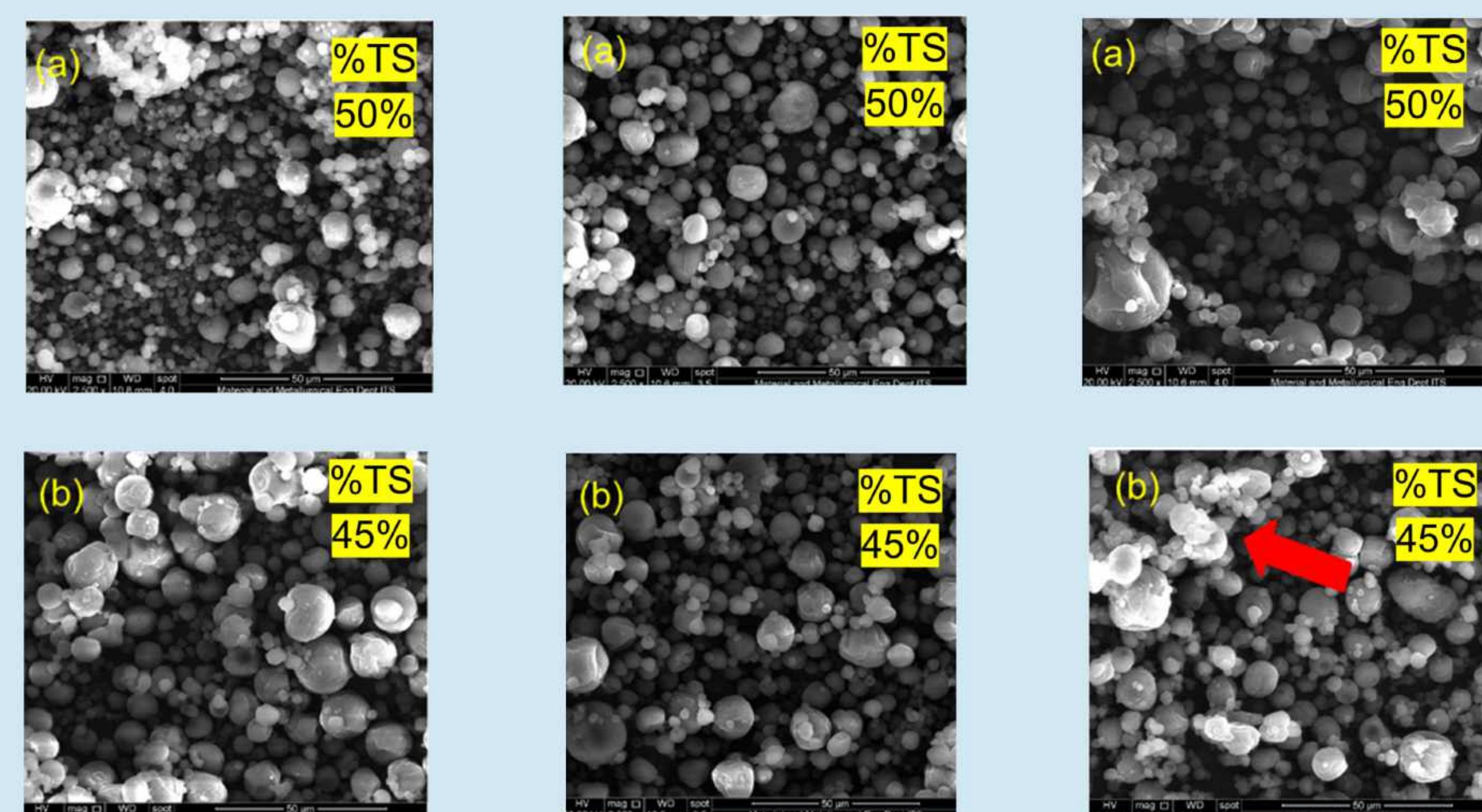


## Hasil Analisis

### KARAKTERISTIK BUBUK VCO DENGAN VARIASI KANDUNGAN KARAGENAN



### HASIL SEM (SCANNING ELECTRON MICROSCOPE) UNTUK VARIASI %TOTAL SOLID



## Karakterisasi dan Hasil Penelitian

### Variasi Percobaan

Sampel	Karagenan (%)	Laju Alir Umpan (ml/min)	Suhu Udara Pengering (°C)	Aspiration Rate (%)	Tekanan Nozzle (bar)	Total Solid (%)
D515050	2	5	150	100	1	50
D815050	2	8	150	100	1	50
D813050	2	8	130	100	1	50
D818050	2	8	180	100	1	50
N815050	0	8	150	100	1	50
N815045	0	8	150	100	1	45
S815050	1	8	150	100	1	50
S815045	1	8	150	100	1	45
D815045	2	8	150	100	1	45

### Hasil Percobaan

Sampel	Yield (%)	Moisture Content (%)	Bulk Density (gram/ml)	Tapped Density (gram/ml)	Time of Rehydration (s)	Z (nm)	Efisiensi Enkapsulasi (%)
D515050	78,92	3,25	0,37	0,435	65	-	90,16
D815050	92,41±0,806	3,45±0,071	0,38±0,021	0,455±0,000	63±1,414	1015	91,37±0,117
D813050	87,62	3,56	0,40	0,465	64	545,3	90,53
D818050	90,88	3,05	0,34	0,435	65	2712	89,61
N815050	85,11±4,115	3,50±0,424	0,42±0,025	0,468±0,010	62±1,414	831,1	89,89±0,151
N815045	84,42±1,365	3,75±0,071	0,39±0,011	0,462±0,009	62,5±0,707	1769	77,22±0,163
S815050	89,05±0,240	3,70±0,141	0,41±0,012	0,465±0,033	64±2,828	1210	91,16±0,132
S815045	85,27±1,308	3,45±0,071	0,37±0,02	0,455±0,00	63±0,00	1250	82,13±0,711
D815045	85,85±0,735	3,6±0,141	0,33±0,016	0,448±0,018	61±4,243	616	83,09±0,156

## Kesimpulan

- Yield tertinggi diperoleh pada kondisi operasi spray dryer dengan suhu udara pengering 150 °C dan laju alir umpan 8 ml/menit
- Pengaruh penambahan karagenan terhadap karakteristik produk bubuk vco terbaik diperoleh pada variasi karagenan 2% yang memiliki nilai yield dan efisiensi enkapsulasi (%ee) paling tinggi.
- Total umpan dengan %TS 50 menghasilkan bubuk VCO dengan yield dan efisiensi enkapsulasi lebih tinggi dibandingkan dengan %TS 45

## Daftar Pustaka

- Abdullah, Zalizawati & Taip, Farah & Mustapa Kamal, Siti & Rahman, Ribhan. (2020). The effect of drying temperature and sodium caseinate concentration on the functional and physical properties of spray-dried coconut milk. Journal of Food Science and Technology. 58. 1-9. 10.1007/s13197-020-04820-9.
- Carneiro, H. C. F., Tonon, R. V., Grosso, C. R. F., & Hubinger, M. D. (2013). Encapsulation efficiency and oxidative stability of flaxseed oil microencapsulated by spray drying using different combinations of wall materials. Journal of Food Engineering, 115(4), 443-451. <https://doi.org/10.1016/j.jfoodeng.2012.03.033>

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2 **Sustainable Innovations in Carrageenan Extraction and Applications: A Comprehensive Review of**  
3 **Green Technologies, Industrial Utilization, and Future Perspectives**

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20  
21 **Abstract**

22 Carrageenan, a polysaccharide derived from red seaweed, plays a crucial role in the food, pharmaceutical,  
23 and bioplastics industries due to its unique functional properties. This review paper aims to provide a  
24 comprehensive overview of current extraction techniques, with a focus on the transition from  
25 conventional to sustainable, environmentally friendly methods. It explores innovative approaches, such  
26 as ultrasound-assisted extraction, microwave-assisted extraction, supercritical carbon dioxide extraction,  
27 and deep eutectic solvents, alongside biorefinery strategies that enable the co-extraction of valuable  
28 bioactive compounds. The integration of artificial intelligence and machine learning for process  
29 optimization is also examined, highlighting their potential to enhance yield, quality, and environmental  
30 sustainability. Key findings reveal that hybrid extraction methods and biorefinery approaches significantly  
31 improve efficiency while reducing waste and environmental impact. The review underscores the  
32 importance of sustainable seaweed cultivation, particularly of species rich in carrageenan, such as  
33 *Euचेuma cottonii* and *Euचेuma denticulatum*, to support industrial scalability. Conclusively, the paper  
34 advocates continued development of green technologies, regulatory improvements, and AI-driven

35 process control to ensure safe, efficient, and sustainable carrageenan production, thereby advancing its  
36 functional applications in the food and biomedical sectors.

37 **Keywords:** carrageenan, extraction, green technologies, nutraceuticals, seaweeds

38

## 39 **1. Introduction**

### 40 *1.1. Overview of Carrageenan Extraction and Its Significance*

41 Carrageenan, a sulfated polysaccharide derived from red seaweed, is widely utilized in the food,  
42 pharmaceutical, and biomedical industries due to its excellent gelling, thickening, and stabilizing  
43 properties (Prado-Fernández et al., 2003). As the demand for plant-based and sustainable food additives  
44 rises, carrageenan has gained prominence as an alternative to synthetic stabilizers and animal-derived  
45 gelatin (Dong et al., 2021).

46 The primary sources of carrageenan are *Kappaphycus alvarezii* or *Euचेuma cottonii* and *Euचेuma*  
47 *denticulatum*, cultivated extensively in tropical regions such as Indonesia, the Philippines, and Malaysia  
48 (FAO, 2021). Indonesia is one of the largest global producers of seaweed, contributing significantly to the  
49 international hydrocolloid market (Sutrisno et al., 2024). Despite this, much of the seaweed harvested in  
50 Indonesia is exported in raw form without significant value addition, leading to missed economic  
51 opportunities (Sedayu et al., 2019).

52 However, carrageenan extraction processes remain energy-intensive and environmentally taxing,  
53 necessitating sustainable alternatives (Zainal-Abidin et al., 2017). The inefficiencies in conventional  
54 extraction methods, including high chemical usage and wastewater generation, highlight the need for  
55 greener approaches to improve industrial sustainability (Delattre et al., 2016). Figure 1 presents an  
56 overview of carrageenan extraction from red seaweed, comparing conventional methods with emerging  
57 green technologies. While traditional processes are energy-intensive and produce chemical waste,  
58 sustainable techniques such as ultrasound-assisted, microwave-assisted, and supercritical CO<sub>2</sub> extraction  
59 improve efficiency and reduce environmental impact. The resulting carrageenan finds broad applications  
60 in food, biomedical, and bioplastics industries.

61

### 62 *1.2. Importance of Carrageenan in the Global Market*

63 Carrageenan plays a crucial role in the global hydrocolloid industry due to its diverse applications. The  
64 food sector is the primary consumer of carrageenan, where it is used in dairy, meat products,  
65 confectionery, and beverages to enhance texture and stability (Antonopoulos et al., 2004). Its ability to  
66 form thermo-reversible gels makes it an essential ingredient in processed foods.

67 Beyond the food industry, carrageenan has demonstrated promising applications in pharmaceuticals  
68 and biomedicine. Studies have indicated that carrageenan possesses antiviral, anti-inflammatory, and  
69 immunomodulatory properties, which make it a potential candidate for drug delivery and biomedical  
70 applications (Hentati et al., 2020). Additionally, the rise of vegan-friendly alternatives has increased  
71 interest in carrageenan as a replacement for gelatin (Oliyaei et al., 2022).

72

73 *1.3. The Need for Green Extraction Techniques*

74 Conventional carrageenan extraction relies on alkaline treatment and alcohol precipitation, leading  
75 to high energy consumption and excessive waste production (Gereniu et al., 2018). As industries shift  
76 towards more sustainable practices, alternative green extraction techniques are gaining momentum.  
77 These include:

78 • Deep Eutectic Solvents (DES) Technology:

79 Uses eutectic mixtures of natural compounds as solvents. It is cheap and environmentally  
80 friendly (El Achkar et al., 2019).

81 • Ultrasound-Assisted Extraction (UAE):

82 Enhances cell wall disruption, increasing extraction efficiency (Youssof et al., 2017).

83 • Sub and Super Critical Fluid Extraction:

84 Uses compressed fluids under sub and supercritical conditions for the extraction of  
85 bioactive components, increasing yield (Gallego et al., 2019).

86 • Enzymatic Hydrolysis:

87 Reduces the need for harsh chemicals by employing specific enzymes to break down  
88 seaweed cell walls (Parab et al., 2017; Tan & Lee, 2014).

89 These green techniques not only improve carrageenan yield but also contribute to sustainability by  
90 reducing energy consumption and minimizing environmental impact. Figure 2 illustrates the transition  
91 from conventional extraction, which is energy-intensive and generates chemical waste, to green  
92 extraction techniques such as ultrasound, microwave-assisted processes, supercritical CO<sub>2</sub>, and deep  
93 eutectic solvents that offer higher efficiency and sustainability.

94

95 *1.4. Research Gaps and the Need for Further Study*

96 Despite technological advancements in carrageenan processing, several knowledge gaps remain,  
97 including:

98 1. Optimisation of Green Extraction Techniques:

99 Further research is needed to refine process parameters and enhance efficiency (Delattre  
100 et al., 2016).

101 2. Bioactive Potential and Functionalization:

102 More studies are required to explore carrageenan's bioactive properties, such as  
103 antioxidant and antimicrobial effects (Hentati et al., 2020).

104 3. Industrial Scalability:

105 Many of the advanced extraction techniques remain in laboratory settings and need  
106 further exploration for commercialization (FAO, 2021).

107 4. Regulatory and Safety Considerations:

108 While carrageenan is widely used, its safety in food applications continues to be a topic  
109 of debate, necessitating further research (Rhein-Knudsen & Meyer, 2021).

110 By addressing these gaps, future research can significantly improve the industrial applicability of  
111 carrageenan, particularly in sustainable extraction and functional food development. Figure 3 highlights  
112 the main research gaps in carrageenan extraction, including limited scale-up studies, insufficient  
113 integration with biorefinery approaches, lack of sustainability metrics, emphasizing the need for further  
114 investigation.

115

116 **2. Seaweed as a Sustainable Resource**

117 Seaweed cultivation has emerged as a vital industry that contributes to sustainable food production,  
118 marine conservation, and economic development. As an environmentally friendly aquaculture practice,  
119 seaweed farming requires minimal inputs while offering significant benefits in carbon sequestration,  
120 biodiversity enhancement, and water quality improvement (Mendes, Cotas, Pacheco, et al., 2024). Among  
121 the various species, *Eucheuma cottonii* and *Eucheuma denticulatum* are particularly significant due to  
122 their high carrageenan content, which is widely utilized in food, pharmaceuticals, and bioplastics (Waseem  
123 et al., 2023).

124

125 *2.1 Global Seaweed Production and Indonesia's Role*

126 The global production of seaweed has expanded rapidly in recent decades, reaching over 35 million  
127 metric tons per year, with Asia being the dominant producer (A et al., 2024; Bapuly & Sharma, 2023;  
128 Pereira et al., 2024; van Oort et al., 2023; Webb et al., 2023). China, Indonesia, and the Philippines  
129 collectively account for the majority of seaweed farming, particularly for hydrocolloid extraction (Yong et  
130 al., 2024). Indonesia, with its vast coastline and favorable tropical waters, has become one of the largest  
131 producers of red seaweed, primarily exporting raw dried biomass for further processing abroad (Ceaser  
132 et al., 2025).

133 Despite its leading role in seaweed production, Indonesia faces challenges in maximizing its economic  
134 potential. Most of the seaweed harvested is exported in unprocessed form, missing out on the added  
135 value of carrageenan extraction and refinement (Salazar et al., 2024). By investing in local processing  
136 infrastructure and technology, Indonesia could significantly enhance its position in the global hydrocolloid  
137 industry.

138

139 *2.2 Economic and Environmental Benefits of Seaweed Cultivation*

140 Seaweed farming is a major economic driver for coastal communities, providing income and  
141 employment for small-scale farmers, particularly in developing countries. The low investment and  
142 operational costs make it an accessible livelihood for many (Lomartire et al., 2022). Additionally, the  
143 expanding demand for plant-based and sustainable food ingredients has made seaweed an increasingly  
144 valuable commodity in international markets (Baghel et al., 2021).

145 Beyond economic contributions, seaweed farming provides extensive environmental benefits.  
146 Seaweed absorbs large amounts of carbon dioxide from seawater, mitigating ocean acidification and  
147 contributing to carbon sequestration (Nakhate & van der Meer, 2021). Furthermore, seaweed acts as a

148 biofilter, removing excess nutrients such as nitrogen and phosphorus, thus improving coastal water  
149 quality and preventing eutrophication (Blikra et al., 2021).

150 Unlike traditional agriculture, seaweed farming requires no freshwater, pesticides, or fertilizers,  
151 making it one of the most sustainable forms of biomass production (Ali et al., 2024). Additionally, well-  
152 managed seaweed farms provide habitats for marine organisms, enhancing local biodiversity and  
153 supporting fisheries (Puspita et al., 2020).

154

### 155 *2.3 Seaweed's Role in the Hydrocolloid Industry*

156 Seaweed-derived hydrocolloids, such as carrageenan, agar, and alginate, play a crucial role in various  
157 industries. Carrageenan extracted from red seaweed is widely used as a gelling, stabilizing, and thickening  
158 agent in food and pharmaceuticals (Rawiwan et al., 2022). It is a key ingredient in dairy products, plant-  
159 based alternatives, and processed meats due to its ability to improve texture and stability (C. Liu et al.,  
160 2024).

161 In recent years, carrageenan has gained attention in biomedical applications due to its antiviral, anti-  
162 inflammatory, and immunomodulatory properties. Studies suggest its potential in drug delivery systems,  
163 tissue engineering, and wound healing (Rhein-Knudsen & Meyer, 2021). Additionally, as consumer  
164 preference shifts towards natural and plant-based products, the demand for carrageenan is expected to  
165 grow significantly (Santana et al., 2024).

166

### 167 *2.4 Sustainability Challenges and Future Outlook*

168 Despite its numerous benefits, seaweed farming and carrageenan production face sustainability  
169 challenges. Unregulated expansion of seaweed farms can lead to habitat degradation and disrupt local  
170 ecosystems (Bisht et al., 2022). Overharvesting and poorly managed farming practices can also deplete  
171 marine biodiversity, affecting surrounding fisheries (Nakhate & van der Meer, 2021).

172 Additionally, conventional carrageenan extraction methods are resource-intensive, requiring high  
173 energy input and producing chemical waste. Addressing these challenges requires the adoption of eco-  
174 friendly extraction technologies, such as enzymatic hydrolysis and ultrasound-assisted methods, which  
175 reduce chemical waste and energy consumption (Ceaser et al., 2025).

176 Government policies and international collaborations are essential for promoting sustainable  
177 seaweed farming. Investments in research and development, improved farming techniques, and  
178 responsible resource management will be crucial in ensuring the long-term sustainability of the industry.

179

## 180 **3. Carrageenan: Structure, Properties, and Functions**

181 Carrageenan is a naturally occurring sulfated polysaccharide extracted primarily from red seaweed  
182 species such as *Kappaphycus alvarezii*, *Eucheuma denticulatum*, and *Gigartina*. This polysaccharide plays  
183 a vital role in the food, pharmaceutical, and biomedical industries due to its unique gelling, thickening,  
184 and stabilizing properties. Recent advancements have expanded its applications beyond food processing  
185 to include drug delivery, tissue engineering, and biopolymer-based materials (James et al., 2023). This  
186 section provides an in-depth analysis of the molecular structure, physicochemical properties, gelation  
187 mechanisms, and diverse industrial applications of carrageenan, along with an overview of sustainability  
188 concerns and potential solutions.

189

### 190 *3.1 Molecular Structure and Classification*

191 Carrageenan is a naturally occurring sulfated polysaccharide extracted from red seaweeds  
192 (*Rhodophyta*), particularly *Kappaphycus alvarezii*, *Eucheuma denticulatum*, and *Gigartina* species. It is  
193 composed of alternating units of 3-linked  $\beta$ -D-galactopyranose and 4-linked  $\alpha$ -D-galactopyranose, with  
194 variations in sulfate group content and anhydrogalactose determining its classification (Nunes et al.,  
195 2024). These molecular differences influence the physicochemical properties, solubility, and gelling ability  
196 of carrageenan, making it highly versatile in industrial applications.

197

198 • Structural Composition

199 The primary structure of carrageenan consists of a linear backbone of galactose and anhydrogalactose  
200 units, connected by alternating  $\alpha$ -1,3 and  $\beta$ -1,4 glycosidic linkages. The presence of sulfate ester groups (-  
201 OSO<sub>3</sub><sup>-</sup>) in different positions of the polymer chain affects its charge density and ability to interact with  
202 cations, which is essential for its gel-forming capabilities (Mohamed, 2024).

203

204 • Three main types of carrageenan:

205 Carrageenan is categorized into three major types based on the sulfate content and their gelation  
206 properties in the presence of different cations.

207 1. Kappa ( $\kappa$ ) carrageenan:

- 208 ○ Contains one sulfate group per disaccharide and forms strong, brittle gels with potassium ions.
- 209 ○ Gelation: Forms strong, brittle gels in the presence of potassium (K<sup>+</sup>) ions.
- 210 ○ Applications: Commonly used in dairy products, processed meat, and confectionery.
- 211 ○ Properties: Creates a firm, elastic gel with high transparency

212 Kappa-carrageenan has a high affinity for potassium ions, which promote aggregation of its  
213 helices, leading to thermoreversible gel formation (Pinto Tiago C.and Sabet, 2024). This type of  
214 carrageenan is widely utilized in food industries, particularly in cheese and dairy desserts, where  
215 it provides texture enhancement and stability.

216

217 2. Iota ( $\iota$ ) carrageenan:

- 218 ○ Structure: Contains two sulfate groups per disaccharide unit.
- 219 ○ Gelation: Forms soft, elastic gels in the presence of calcium (Ca<sup>2+</sup>) ions.
- 220 ○ Applications: Used in cosmetics, food thickeners, and biomedical applications.
- 221 ○ Properties: Produces a flexible and elastic gel with improved water-holding capacity.

222 Iota-carrageenan interacts effectively with calcium ions, leading to the formation of soft,  
223 cohesive gels. These properties make it an ideal ingredient in gel-based personal care products  
224 and hydrogel formulations (Mohamed, 2024). Additionally,  $\iota$ -carrageenan has shown potential  
225 antiviral and drug delivery applications due to its ability to form biocompatible hydrocolloid  
226 networks.

227

228 3. Lambda ( $\lambda$ ) carrageenan:

- 229 ○ Structure: Highly sulfated, with three sulfate groups per disaccharide unit
- 230 ○ Gelation: Does not form gels, functions mainly as a thickener
- 231 ○ Applications: Used in beverages, dressings, and pharmaceutical formulations
- 232 ○ Properties: Highly soluble in cold water and provides viscosity without gel formation

233 Lambda-carrageenan has a high negative charge density, making it highly soluble in water but  
234 incapable of forming a structured gel (Pinto Tiago C.and Sabet, 2024). It is frequently used in liquid food

235 applications where stabilization and viscosity enhancement are needed, such as in chocolate milk, sauces,  
236 and syrups.

237

#### 238 • Hybrid and Modified Carrageenan Structures

239 Recent research has explored modified carrageenan derivatives, including blended or hybrid  
240 carrageenans, which combine  $\kappa$ - and  $\iota$ -carrageenan properties for enhanced gelation (Mohamed, 2024).  
241 Some studies also indicate cross-linking with chitosan or other biopolymers to improve carrageenan's  
242 mechanical strength and stability for biomedical use.

243

### 244 3.2 Physicochemical Properties of Carrageenan

245 Carrageenan exhibits unique physicochemical properties that make it highly valuable in the food,  
246 pharmaceutical, and biomedical industries. These properties depend on molecular weight, sulfate  
247 content, ionic interactions, and processing conditions (Exarhopoulos et al., 2025). The three primary  
248 factors influencing carrageenan functionality are solubility, viscosity, and gel strength. Understanding  
249 these properties is crucial for optimizing its applications in hydrocolloid formulations, edible coatings,  
250 drug delivery systems, and biopolymer films.

251

#### 252 • Solubility

253 Carrageenan solubility is highly dependent on temperature, pH, and ionic environment.

- 254 ○  $\lambda$ -carrageenan is highly sulfated and is soluble in cold water, forming a viscous solution.
- 255 ○  $\kappa$ - and  $\iota$ -carrageenan require heating to dissolve in water, typically above 60°C–80°C, due to their  
256 higher molecular order and tendency to form helices (Cvetković et al., 2025).
- 257 ○ Solubility is pH-dependent, with carrageenan being stable in neutral and slightly acidic conditions  
258 (pH 6-9) but degrading in strongly acidic environments (pH <4) due to hydrolysis of the glycosidic  
259 bonds.
- 260 ○ The presence of cations ( $K^+$ ,  $Na^+$ ,  $Ca^{2+}$ ) influences solubility by promoting gelation or aggregation  
261 of molecular chains (Rezaei et al., 2025).

262

#### 263 • Viscosity

264 The viscosity of carrageenan solutions is influenced by sulfate content, concentration, and  
265 temperature.

- 266 ○ High sulfate content reduces viscosity by increasing the negative charge repulsion between  
267 polymer chains (Cvetković et al., 2025).
- 268 ○ Increasing temperature lowers viscosity, as heat disrupts hydrogen bonds and helical structures,  
269 reducing intermolecular interactions (Exarhopoulos et al., 2025).
- 270 ○ Carrageenan solutions exhibit shear-thinning behavior, meaning viscosity decreases under high  
271 shear stress, making it suitable for emulsions, suspensions, and thickening applications.

272 Viscosity increases with higher carrageenan concentration but plateaus at higher molecular weights due  
273 to chain entanglement effects.

274

275 • Gel Strength and Ionic Interactions

276 The gelation properties of carrageenan are highly dependent on ionic interactions and sulfate group  
277 positioning:

278 ○  $\kappa$ -Carrageenan forms rigid, brittle gels in the presence of potassium ( $K^+$ ) ions, stabilizing its double-  
279 helix conformation. This strong network makes it ideal for dairy gels, processed meat, and  
280 biopolymer films (Huang et al., 2025).

281 ○  $\iota$ -Carrageenan forms soft, elastic gels in the presence of calcium ( $Ca^{2+}$ ) ions, making it useful for  
282 hydrogels, biofilms, and encapsulation systems (Rezaei et al., 2025).

283 ○  $\lambda$ -Carrageenan does not form gels but provides high viscosity, making it useful as a thickening and  
284 stabilizing agent in liquid formulations (Rosmawati et al., 2025).

285

286 • Thermoreversibility and Syneresis

287 ○ Carrageenan gels are thermoreversible, meaning they melt upon heating and re-gel upon cooling.

288 ○ Syneresis, or water expulsion from gels, can occur in  $\kappa$ -carrageenan systems due to excessive  
289 polymer aggregation in strong ionic environments (Sharifi et al., 2025).

290

291 *3.3 Gelation Mechanism of Carrageenan*

292 Carrageenan gelation is a thermoreversible process, meaning that gels form upon cooling and melt  
293 when reheated. This property makes carrageenan highly valuable in food structuring, drug delivery, and  
294 biomaterials (Chang et al., 2025). The gelation mechanism primarily involves three stages: a coil-to-helix  
295 transition, helix aggregation, and gel network formation. The presence of cations (such as  $K^+$  or  $Ca^{2+}$ )  
296 significantly influences the gel strength and structure by stabilizing intermolecular interactions (Z. Liu et  
297 al., 2025).

298 • Coil-to-Helix Transition

299 At high temperatures, carrageenan molecules exist in a random coil conformation, where the  
300 polysaccharide chains remain flexible and unstructured. This disordered state prevents gel formation as  
301 there is insufficient intermolecular association between carrageenan chains (Tariq et al., 2025a). When  
302 the solution is cooled, a transition from a random coil to an ordered helical structure occurs due to the  
303 formation of hydrogen bonds and electrostatic interactions.

304 • Helix Formation

305 As the temperature drops, the carrageenan molecules start forming double helices, which align and  
306 aggregate into structured networks (Luo et al., 2024). The rate of helix formation depends on:

307 ○ Temperature: The cooling rate influences the gel stiffness and water-holding capacity.

- 308 ○ Ionic Environment: Different cations enhance or inhibit helix stabilization (Chang et al., 2025).
- 309 ○ Sulfate Content: Higher sulfate content increases solubility but weakens gelation due to
- 310 electrostatic repulsion.

311 During this phase,  $\kappa$ -carrageenan helices stabilize in the presence of potassium ( $K^+$ ) ions, while  $\iota$ -  
312 carrageenan helices require calcium ( $Ca^{2+}$ ) ions for gel reinforcement (Rezaei et al., 2025).  $\lambda$ -carrageenan,  
313 being highly sulfated, does not undergo helix formation, which is why it functions as a thickener rather  
314 than a gelling agent (Feng et al., 2025).

#### 315 • Gel Network Formation

316 Once helices aggregate, they entangle to form a three-dimensional gel matrix. The gel strength and  
317 elasticity depend on ionic interactions and polymer concentration (Chen et al., 2025).

- 318 ○  $\kappa$ -Carrageenan gels are rigid and brittle, stabilized by  $K^+$  ions, which enhance intermolecular
- 319 aggregation and lead to strong but fracture-prone gels (Z. Liu et al., 2025).
- 320 ○  $\iota$ -Carrageenan forms softer, more elastic gels, as  $Ca^{2+}$  ions promote network flexibility, making it
- 321 ideal for hydrogels, biomedical applications, and food stabilizers (Chang et al., 2025).
- 322 ○  $\lambda$ -Carrageenan does not form gels but contributes to viscosity enhancement, making it useful in
- 323 emulsions, beverages, and pharmaceutical suspensions (Rezaei et al., 2025).

324

#### 325 • Factors Influencing Carrageenan Gelation

326 Several factors affect the gelation mechanism and properties:

##### 327 ■ Cation Type and Concentration

- 328 ○  $K^+$  ions promote strong, brittle  $\kappa$ -carrageenan gels.
- 329 ○  $Ca^{2+}$  ions induce soft, elastic  $\iota$ -carrageenan gels(Chen et al., 2025).
- 330 ○  $Na^+$  ions have minimal effect on gelation but increase carrageenan solubility.

##### 331 ■ pH Sensitivity

- 332 ○ Optimal gelation occurs in a neutral to slightly alkaline pH range (pH 6–9).
- 333 ○ Strongly acidic conditions (pH <4) cause hydrolysis of carrageenan chains, weakening gel
- 334 formation (Luo et al., 2024).

##### 335 ■ Polymer Concentration

- 336 ○ Higher carrageenan concentrations lead to stronger gels due to increased polymer-
- 337 polymer interactions.
- 338 ○ Too high a concentration can result in gel syneresis (water release), impacting gel stability
- 339 (Chang et al., 2025).

##### 340 ■ Temperature Effects

341                   ○ Rapid cooling favors strong gel formation, while gradual cooling results in more flexible,  
342                   thermoreversible gels.

343                   ○ Heating disrupts the gel, reverting the carrageenan back to a random coil state.

344

345     • Advanced Applications of Carrageenan Gelation

346         Due to its biocompatibility, gel-forming ability, and controlled release properties, carrageenan is  
347         widely used in:

348             ○ Food Industry: Thickening and stabilizing dairy products, desserts, and meat analogs.

349             ○ Pharmaceuticals: Controlled drug release and capsule formulations.

350             ○ Biomedicine: Hydrogel-based wound dressings, tissue engineering scaffolds, and bioprinting for 3D  
351             bioprinting (Chen et al., 2025).

352

353         *3.4 Functional Applications of Carrageenan*

354         Carrageenan is widely used across various industries due to its unique gelling, stabilizing, and  
355         emulsifying properties. Its biocompatibility, ability to interact with proteins and water, and structural  
356         adaptability make it an essential ingredient in food processing, pharmaceuticals, biomedicine, and beyond  
357         (Kumar et al., 2025). This section explores key functional applications of carrageenan in different fields.

358     • Food Industry

359         Carrageenan is a crucial hydrocolloid in the food industry, serving as a gelling agent, stabilizer,  
360         thickener, and emulsifier. Its ability to form gels, modify viscosity, and interact with proteins and water  
361         makes it a versatile additive in many food products (Awais et al., 2025).

362     Key Applications in Food Processing:

363         ▪ Dairy Products

364             ○ Used in yogurt, ice cream, and plant-based milk to enhance texture, mouthfeel, and  
365             stability.

366             ○ Prevents phase separation in chocolate milk and flavored dairy drinks.

367             ○ Improves whipping properties in aerated dairy desserts.

368         ▪ Meat Processing

369             ○ Improves water retention and texture in processed meats such as sausages, hams, and  
370             poultry products.

371             ○ Reduces cooking loss by binding water and fats, maintaining juiciness and firmness in  
372             meat products.

373             ○ Enhances sliceability and cohesion in restructured meat formulations (Awais et al., 2025).

- 374       ▪ Confectionery & Bakery Products
- 375             - Acts as a vegan-friendly gelatin substitute in gummy candies and soft chews.
- 376             ○ Provides stability and texture improvement in bakery fillings, preventing syneresis (water  
377               separation).
- 378             ○ Helps encapsulate flavors and active ingredients for controlled release in chewing gums  
379               and coatings.
- 380       ▪ Sauces, Dressings, and Beverages
- 381             ○ Prevents ingredient separation in salad dressings and fruit-based sauces.
- 382             ○ Improves mouthfeel and viscosity in liquid formulations like protein shakes and plant-  
383               based drinks.
- 384             ○ Enhances foam stability in beer and coffee-based beverages (Kumar et al., 2025).
- 385
- 386       • Pharmaceuticals and Biomedicine
- 387       Carrageenan has gained attention for its biomedical and pharmaceutical applications due to its  
388       biodegradability, biocompatibility, and unique molecular interactions (Bandaru & Kuchana, 2024). It is  
389       used in drug delivery systems, wound healing, and antiviral therapies.
- 390       ▪ Drug Delivery Systems
- 391             ○ Used in hydrogels and nanoparticles for controlled drug release.
- 392             ○ Enhances bioavailability of poorly soluble drugs by forming protective hydrogels.
- 393             ○ Employed in oral, topical, and injectable drug formulations, ensuring sustained release  
394               and improved therapeutic effects (Kumar et al., 2025).
- 395
- 396       ▪ Wound Healing and Tissue Engineering
- 397             ○ Forms biocompatible scaffolds for tissue regeneration and wound dressing materials.
- 398             ○ Helps create moist wound-healing environments, accelerating cell migration and tissue  
399               repair.
- 400             ○ Used in biopinks for 3D-printed tissue structures, supporting cell attachment and  
401               proliferation (Awais et al., 2025).
- 402
- 403       ▪ Antiviral and Antimicrobial Properties
- 404             ○ Demonstrates antiviral effects by blocking viral entry into host cells.

- 405           ○ Research shows efficacy against SARS-CoV-2, HPV, and influenza viruses (Bandaru &  
406           Kuchana, 2024).
- 407           ○ Used in nasal sprays and lozenges to prevent viral infections.
- 408           ○ Displays antibacterial and antifungal properties, making it helpful in preserving  
409           pharmaceutical formulations.

410

411   • Emerging Applications in Sustainable Packaging and Cosmetics

412       ▪ Biodegradable Packaging

- 413           ○ Used in edible films and biodegradable coatings for food preservation.
- 414           ○ Improves moisture retention and oxygen barrier properties, reducing food spoilage.
- 415           ○ A sustainable alternative to synthetic plastic packaging (Kumar et al., 2025).

416       ▪ Cosmetic and Personal Care Products

- 417           ○ Functions as a stabilizer and thickener in lotions, creams, and shampoos.
- 418           ○ Enhances hydration and skin-feel in moisturizers and serums.
- 419           ○ Helps in controlled fragrance release in personal care products (Awais et al., 2025).

420

421       *3.5 Environmental and Sustainability Considerations*

422       The production of carrageenan plays a significant role in coastal economies, particularly in Indonesia,  
423       the Philippines, and Tanzania, where seaweed farming provides employment and economic stability.  
424       However, conventional carrageenan extraction methods pose several environmental challenges, including  
425       high energy consumption, chemical waste production, and ecological impacts of overharvesting (Singh et  
426       al., 2024). The demand for sustainable seaweed farming and eco-friendly processing methods has led to  
427       green extraction technologies and improved regulatory frameworks to minimize negative environmental  
428       effects.

429

430   • Environmental Challenges in Carrageenan Production

431       ▪ High Energy Consumption

432           Traditional carrageenan extraction methods involve alkaline treatment, high-temperature  
433           processing, and mechanical separation, requiring significant energy input. The most energy-  
434           intensive steps include:

- 435           ○ Drying and milling of seaweed before extraction.
- 436           ○ Alkaline boiling (using NaOH or KOH) to break down the seaweed cell walls.

437           ○ Filtration and precipitation, which require large volumes of water and chemical reagents  
438           (Lubowa et al., 2024).

439           The heavy energy footprint of conventional methods contributes to carbon emissions and  
440           environmental degradation, making it necessary to explore energy-efficient alternatives such as  
441           microwave-assisted and ultrasound-assisted extraction.

442           ▪ Chemical Waste and Pollution

443           ○ Alkaline extraction produces wastewater containing chemical residues that can harm aquatic  
444           ecosystems.

445           ○ The acid and alkaline solutions used for extraction alter pH levels in local water bodies, leading  
446           to toxic environmental effects.

447           ○ Chemical bleaching and refining steps generate byproducts that require proper waste  
448           management to prevent contamination of marine environments (de Souza Mesquita, 2024).

449           Research into green solvents and biodegradable reagents aims to reduce chemical pollution  
450           while maintaining carrageenan yield and quality.

451           ▪ Overharvesting of Seaweed and Marine Biodiversity Impact

452           The rising demand for carrageenan has led to overharvesting of red seaweeds, affecting:

453           ○ Coastal biodiversity, as excessive seaweed harvesting disrupts marine habitats.

454           ○ Nutrient cycling in ocean waters, leading to imbalanced marine ecosystems.

455           ○ Sustainability of local seaweed farms, as uncontrolled harvesting depletes natural seaweed  
456           stocks faster than they can regenerate.

457           Sustainable seaweed farming practices, such as rotational harvesting and integrated multi-trophic  
458           aquaculture (IMTA), are being implemented to protect marine biodiversity and ensure long-term  
459           resource availability.

460           • Sustainable Solutions and Green Extraction Technologies

461           To mitigate environmental concerns, researchers are exploring eco-friendly alternatives that focus  
462           on low-energy processing, reduced chemical use, and sustainable farming (Erge & Dülger, 2024).

463           ▪ Green Extraction Technologies

464           Innovative extraction methods aim to reduce energy consumption and chemical waste while  
465           maintaining the purity and functionality of carrageenan.

466           ▪ Enzymatic Hydrolysis

467           ○ Uses biocatalysts (such as cellulases and alginate lyases) to extract carrageenan without  
468           harsh chemicals.

469           ○ Reduces water pollution and improves extraction efficiency compared to alkaline  
470           methods.

- 471       ▪ Microwave-Assisted Extraction (MAE)
  - 472           ○ Uses microwave radiation to heat seaweed at a controlled frequency, reducing
  - 473           processing time by up to 50%.
  - 474           ○ Requires less solvent and energy, leading to lower environmental impact.
- 475       ▪ Supercritical Fluid Extraction (SFE)
  - 476           ○ Utilizes supercritical CO<sub>2</sub> or water to extract carrageenan without organic solvents.
  - 477           ○ Produces high-purity carrageenan with minimal waste but remains costly for large-scale
  - 478           operations.
- 479       ▪ Deep Eutectic Solvent (DES) Extraction
  - 480           ○ Employs biodegradable eutectic solvents derived from natural compounds, eliminating
  - 481           the need for toxic reagents.
  - 482           ○ Enhances extraction selectivity and reduces chemical waste production (de Souza
  - 483           Mesquita, 2024).
- 484
- 485       • Sustainable Seaweed Farming Practices
  - 486           Sustainability efforts focus on promoting responsible seaweed cultivation methods to support
  - 487           long-term environmental health.
  - 488           ▪ Eco-Friendly Seaweed Farming Models
    - 489               ○ Integrated Multi-Trophic Aquaculture (IMTA): Combines seaweed farming with shellfish
    - 490               and fish aquaculture, reducing nutrient runoff and improving marine ecosystem balance.
    - 491               ○ Seaweed Regeneration Zones: Implemented in the Philippines and Indonesia to allow
    - 492               natural seaweed populations to recover.
  - 493           ▪ Waste Reduction and Byproduct Utilization
    - 494               ○ Carrageenan byproducts are being repurposed into biodegradable packaging materials and
    - 495               compostable bioplastics.
    - 496               ○ Seaweed biomass waste is being upcycled into animal feed and fertilizers, reducing landfill
    - 497               waste (Grant & May, 2024).

498

#### 499 **4. Extraction Methods for Carrageenan**

500 Carrageenan extraction is a crucial process that determines the yield, quality, and functional  
501 properties of the final product. Various methods have been developed over time, ranging from  
502 conventional alkaline extraction to modern green technologies aimed at improving efficiency and  
503 sustainability. This section explores traditional and innovative extraction techniques, their advantages and  
504 limitations, and emerging trends in carrageenan processing.

505

#### 506 *4.1 Conventional Extraction Methods*

507 Traditional methods for extracting carrageenan from red seaweed involve multiple steps, including  
508 pre-treatment, alkaline or water extraction, filtration, precipitation, and drying. The two most widely used  
509 conventional techniques are hot water extraction and alkaline extraction. Figure 4 summarizes the  
510 conventional carrageenan extraction methods, namely hot water and alkaline processes.

511

##### 512 • Hot Water Extraction

513 Hot water extraction is one of the simplest and most commonly used methods. It involves soaking dried  
514 seaweed in hot water (60–90°C) to solubilize carrageenan, followed by filtration to remove solid residues.  
515 The extract is then precipitated using alcohol or potassium chloride to separate carrageenan from  
516 impurities (Salazar et al., 2024).

517 Advantages:

- 518 ○ Simple and cost-effective
- 519 ○ Requires minimal chemical usage
- 520 ○ Suitable for large-scale processing

521 Disadvantages:

- 522 ○ High energy consumption due to prolonged heating
- 523 ○ Low selectivity, leading to co-extraction of unwanted compounds
- 524 ○ Inefficient removal of proteins and pigments, affecting purity

525

##### 526 • Alkaline Extraction

527 Alkaline extraction is an improved version of hot water extraction that uses alkaline solutions (typically  
528 potassium hydroxide or sodium hydroxide) to enhance carrageenan yield. This process helps break down  
529 the cell wall of seaweed, increasing the release of carrageenan (Luo et al., 2024).

530 Advantages:

- 531 ○ Higher carrageenan yield compared to hot water extraction
- 532 ○ Improves gel strength and viscosity
- 533 ○ Reduces extraction time

534 Disadvantages:

- 535 ○ High chemical usage leads to environmental concerns
- 536 ○ Requires neutralization steps, adding to processing costs
- 537 ○ Produces large volumes of wastewater with high pH levels

538

## 539 4.2 Green and Advanced Extraction Techniques

540 Given the environmental and efficiency limitations of conventional methods, researchers have  
541 developed green extraction techniques that aim to reduce chemical usage, energy consumption, and  
542 waste generation. These methods include enzymatic hydrolysis, ultrasound-assisted extraction (UAE),  
543 microwave-assisted extraction (MAE), supercritical fluid extraction (SFE), and deep eutectic solvent (DES)  
544 extraction. Figure 5 and Table 1 summarize the main green and advanced carrageenan extraction  
545 techniques.

546

### 547 • Enzymatic Hydrolysis

548 Enzymatic hydrolysis employs specific enzymes such as cellulases, agarases, and proteases to break  
549 down the seaweed cell wall, facilitating carrageenan release while minimizing damage to its structure  
550 (Bandaru & Kuchana, 2024).

551 Advantages:

- 552 ○ Reduces chemical and energy consumption
- 553 ○ Enhances carrageenan purity by selective hydrolysis of unwanted polysaccharides
- 554 ○ Mild reaction conditions preserve bioactivity

555 Disadvantages:

- 556 ○ Higher production cost due to enzyme usage
- 557 ○ Requires precise control of enzymatic activity

558

### 559 • Ultrasound-Assisted Extraction (UAE)

560 UAE uses high-frequency sound waves to disrupt the seaweed cell structure, enhancing the diffusion  
561 of carrageenan into the solvent. This technique significantly improves extraction efficiency and reduces  
562 processing time (Rezaei et al., 2025).

563 Advantages:

- 564 ○ Reduces extraction time by up to 50%
- 565 ○ Improves yield and selectivity
- 566 ○ Low energy consumption compared to traditional heating

567 Disadvantages:

- 568 ○ High initial equipment costs
- 569 ○ Requires optimization for different seaweed species

570

### 571 • Microwave-Assisted Extraction (MAE)

572 MAE applies microwave radiation to heat the solvent, enhancing the solubility and release of  
573 carrageenan from seaweed. This method accelerates the extraction process while preserving  
574 carrageenan's functional properties (Chen et al., 2025).

575 Advantages:

- 576 ○ Rapid heating reduces energy consumption
- 577 ○ Enhances carrageenan extraction yield
- 578 ○ Less degradation of heat-sensitive bioactive compounds

579 Disadvantages:

- 580 ○ Limited scalability for industrial production
- 581 ○ Potential alteration of carrageenan's molecular structure

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- Supercritical Fluid Extraction (SFE)

SFE uses supercritical carbon dioxide (CO<sub>2</sub>) or water under high pressure and temperature to extract carrageenan without using organic solvents. This method is known for its ability to produce high-purity carrageenan with minimal environmental impact (Feng et al., 2025).

Advantages:

- Solvent-free process eliminates chemical residues
- Produces high-quality, food-grade carrageenan
- Low environmental impact

Disadvantages:

- High equipment and operational costs
- Requires specialized expertise

- Deep Eutectic Solvent (DES) Extraction

DES extraction utilizes green solvents derived from natural compounds (e.g., choline chloride, urea) to dissolve carrageenan from seaweed. This emerging technology offers a biodegradable and eco-friendly alternative to conventional chemical solvents (de Souza Mesquita, 2024).

Advantages:

- Non-toxic and biodegradable solvents
- High selectivity and efficiency
- Low processing temperature preserves carrageenan bioactivity

Disadvantages:

- Limited industrial-scale application
- Requires further research for process optimization

- Instant Controlled Pressure Drop (DIC) Extraction

One of the most promising emerging technologies for carrageenan extraction is Instant Controlled Pressure Drop (DIC), a technique that applies a sudden pressure drop to disrupt the seaweed cell structure, facilitating the release of bioactive compounds, including carrageenan. This method significantly enhances extraction efficiency while maintaining the quality of the extracted product (Tariq et al., 2025a).

How DIC Extraction Works

DIC involves two main steps:

1. Saturation Phase: The seaweed is subjected to high-temperature steam under moderate pressure (3–10 bar) for a short duration (a few seconds to minutes).
2. Instant Pressure Drop: A rapid pressure release (vacuum stage) causes an abrupt expansion of intracellular water, leading to structural rupture of the cell walls, enhancing the release of carrageenan into the extraction medium.

This technique is particularly effective in reducing processing time, enhancing extraction yield, and improving the physicochemical properties of carrageenan (Luo et al., 2024).

## 624 Advantages of DIC Extraction

- 625 ○ Higher Yield – DIC can improve carrageenan yield by up to 30–40% compared to conventional  
626 extraction methods
- 627 ○ Enhanced Purity – Since DIC does not rely on excessive chemical use, it reduces contamination  
628 with unwanted seaweed components.
- 629 ○ Energy Efficiency – Unlike conventional alkaline extraction, which requires prolonged heating, DIC  
630 operates on short bursts of thermal energy, reducing energy consumption.
- 631 ○ Improved Gel Strength – Studies indicate that carrageenan extracted using DIC exhibits better  
632 gelling properties, particularly for  $\kappa$ -carrageenan, due to minimal molecular degradation.
- 633 ○ Eco-Friendly Process – DIC minimizes wastewater generation and chemical residues, making it a  
634 more sustainable extraction technique (Feng et al., 2025).

635

## 636 Challenges and Limitations

- 637 ○ High Initial Cost – DIC equipment is expensive and may not be economically viable for small-scale  
638 producers.
- 639 ○ Optimization Required – The effectiveness of DIC depends on precise control of steam pressure,  
640 exposure time, and pressure release rate
- 641 ○ Limited Industrial Application – While DIC has been widely applied in food and pharmaceutical  
642 industries for drying and extraction, its large-scale application in carrageenan extraction is still  
643 under development.

644

## 645 Future Perspectives

646 As sustainability becomes a key concern in the carrageenan industry, DIC extraction holds great  
647 promise as an alternative to energy-intensive traditional methods. Future research should focus on:

- 648 ○ Scaling up DIC technology for commercial seaweed processing.
- 649 ○ Combining DIC with other green techniques (e.g., enzymatic hydrolysis or supercritical CO<sub>2</sub>  
650 extraction) to further improve yield and product quality.
- 651 ○ Optimizing process parameters using AI and machine learning to predict the best conditions for  
652 carrageenan extraction (Sharifi et al., 2025).

653 The main green and advanced extraction techniques discussed in this section, together with their  
654 mechanisms, advantages, and disadvantages, are summarised in Table 1.

655

## 656 *4.3 Emerging Trends and Future Directions*

657 To further improve carrageenan extraction efficiency and sustainability, recent research has focused  
658 on hybrid extraction techniques, biorefinery approaches, and machine learning-based process  
659 optimization. Figure 6 highlights hybrid extraction, biorefinery approaches, and AI-based optimization as  
660 emerging directions in carrageenan research.

661

### 662 • Hybrid Extraction Techniques

663 Combining different extraction methods, such as UAE+MAE or enzymatic hydrolysis+UAE, has shown  
664 promise in improving carrageenan yield and quality while reducing environmental impact (Tariq et al.,  
665 2025a).

666 • Biorefinery Approaches

667 Biorefinery approaches integrate carrageenan extraction with the recovery of other valuable seaweed-  
668 derived compounds such as proteins, antioxidants, and pigments, enhancing overall resource utilization  
669 and economic feasibility (Z. Liu et al., 2025).

670

671 • Machine Learning and AI Optimization

672 The use of machine learning algorithms to optimize extraction parameters (e.g., temperature, time,  
673 pH, solvent concentration) is gaining attention. AI-driven models can predict optimal conditions,  
674 minimizing trial-and-error experiments and improving process efficiency (Sharifi et al., 2025).

675

676 **5. Factors Affecting Extraction Efficiency and Product Quality**

677 The efficiency of carrageenan extraction and the quality of the final product depend on various  
678 factors, including raw material properties, extraction process parameters, and environmental influences.  
679 Optimizing these factors is essential for maximizing yield, improving functionality, and ensuring  
680 consistency in industrial applications.

681

682 *5.1 Raw Material Factors*

683 • Seaweed Species and Composition

684 The species of red seaweed used directly impacts carrageenan yield and functionality. Commonly used  
685 species include:

- 686 ○ *Kappaphycus alvarezii* (*kappa-carrageenan*): High gel strength, interacts with potassium ions.
- 687 ○ *Eucheuma denticulatum* (*iota-carrageenan*): Produces soft, elastic gels interacting with calcium  
688 ions.
- 689 ○ *Gigartina* spp. (*lambda-carrageenan*): High sulfation, non-gelling, used as a thickener (Rupert et  
690 al., 2022).

691

692 • Seasonal and Environmental Variability

693 Environmental conditions such as temperature, nutrient levels, and salinity affect polysaccharide  
694 content, molecular weight, and sulfate groups in seaweed:

- 695 ○ Winter-harvested seaweed: Higher gel strength, but lower yield.
- 696 ○ Summer-harvested seaweed: Higher extraction yield, but weaker gel structure.
- 697 ○ Seaweed grown in polluted waters may contain heavy metals, reducing quality (Villanueva et al.,  
698 2011).

699

700 • Pre-Treatment Methods

701 Pre-treatment steps such as washing, drying, and alkaline soaking influence yield and purity:

- 702 ○ Alkaline pre-treatment (KOH, NaOH) enhances gel strength and removes impurities.
- 703 ○ Enzymatic pre-treatment (e.g., cellulase, pectinase) increases yield and selectivity, reducing  
704 contamination from unwanted polysaccharides (C. Wang et al., 2020).

705

706 *5.2 Extraction Process Parameters*

707

708 • Temperature and Time  
709 Extraction temperature and duration significantly affect carrageenan yield and molecular stability. As  
710 shown in Table 2, moderate extraction temperatures (60–80°C) provide the best compromise  
711 between extraction efficiency and gel properties, whereas excessively high temperatures lead to  
712 carrageenan degradation and reduced molecular weight.

713  
714 • pH and Alkaline Treatment  
715 pH plays a crucial role in extraction:  
716 ○ Ideal pH range (7–9): Maintains structural integrity.  
717 ○ pH >10: Leads to depolymerization, weakening gel strength.  
718 ○ pH <6: Causes hydrolysis, breaking down functional properties (Rupert et al., 2022).

719  
720 • Advanced Extraction Techniques  
721 To improve carrageenan yield, minimize chemical usage, and enhance quality, advanced extraction  
722 methods are being adopted. These techniques increase efficiency while reducing environmental impact.  
723 The main challenges and opportunities for implementing green extraction technologies in the  
724 carrageenan value chain are presented in Table 3.

725  
726  
727 *5.3 Post-Processing Factors*

728 • Drying and Storage  
729 To provide a more straightforward overview of process selection, the primary drying methods used  
730 in carrageenan processing, along with their respective benefits and limitations, are summarised in  
731 Table 4. Moisture content should be <12% to avoid degradation.

732  
733 • Milling and Particle Size  
734 ○ Fine particles (<50 µm): Improve solubility but increase oxidation risk.  
735 ○ Coarse particles (>200 µm): Provide higher stability but take longer to dissolve (Rupert et al.,  
736 2022).

737  
738 *5.4 Emerging Trends and Quality Control*

739 • AI-Based Process Optimization  
740 Machine learning (ML) and real-time monitoring are being used for:  
741 ○ Predicting optimal conditions (pH, temperature, extraction time).  
742 ○ Automated process adjustments to minimize variability (C. Wang et al., 2020).

743  
744 • Sustainable Biorefinery Approaches  
745 New strategies integrate carrageenan extraction with other valuable compounds (e.g., proteins,  
746 bioactives) to maximize resource utilization (Gross, 2024; Pari et al., 2025).

747  
748

## 749 **6. Functional and Bioactive Applications of Carrageenan**

750 Carrageenan, a sulfated polysaccharide derived from red seaweed, has gained significant attention  
751 for its multifunctional applications across various industries, including food, pharmaceuticals, biomedical  
752 sciences, and sustainable packaging. Beyond its traditional role as a thickening, gelling, and stabilizing  
753 agent, carrageenan also exhibits bioactive properties, including antiviral, antimicrobial, anti-  
754 inflammatory, and tissue regenerative capabilities. This section discusses the diverse functional and  
755 bioactive applications of carrageenan, supported by recent studies and advancements. Figure 7 illustrates  
756 the multifunctional roles of carrageenan, highlighting its applications in food systems (dairy, meat, plant-  
757 based products, confectionery, and beverages), its bioactive and pharmaceutical potential (antiviral,  
758 wound healing, and drug delivery), as well as its contribution to sustainable innovations such as  
759 biodegradable packaging and cosmetic formulations.

760

### 761 *6.1 Functional Applications in the Food Industry*

762 Carrageenan plays a crucial role in food formulations, offering desirable textural modifications and  
763 stability enhancements. It is widely incorporated in dairy, meat, bakery, and beverage products, as well  
764 as in novel food packaging materials.

765

#### 766 • Dairy and Plant-Based Alternatives

767 Carrageenan is extensively used in dairy products to prevent phase separation and enhance texture. In  
768 plant-based milk alternatives,  $\kappa$ -carrageenan stabilizes protein suspensions and prevents sedimentation  
769 (Liew & Chin, 2024). It also enhances the viscosity and mouthfeel of non-dairy yogurts (Thakur et al.,  
770 2024).

771 ○ Applications: Flavored milk, yogurt, plant-based dairy

772 ○ Function: Stabilizer, thickener

773 ○ Benefit: Improves texture and prevents syneresis

774

#### 775 • Meat and Alternative Protein Products

776 Carrageenan plays a crucial role in processed meats and alternative protein products, where it  
777 enhances water retention, texture, and structural integrity. Its ability to interact with proteins and form  
778 stable gels has made it a valuable ingredient in both traditional meat products and plant-based  
779 alternatives.

780 ○ Processed Meats

781 In the meat industry, carrageenan is used to improve juiciness, enhance slicing properties, and  
782 reduce cooking losses. It binds with myofibrillar proteins and water, creating a gel matrix that  
783 improves meat texture and maintains its structural integrity. This is particularly beneficial in  
784 processed meats such as sausages, ham, and deli products, where maintaining uniformity and  
785 moisture retention is essential (Carrasqueira et al., 2025).

786

787 Functional Benefits in Processed Meats:

788 - Water retention:  $\kappa$ -carrageenan increases the binding of water molecules within the meat  
789 matrix, reducing moisture loss during cooking.

790 - Improved texture and mouthfeel: enhances firmness and elasticity, particularly in  
791 restructured meat products.

- 792 - Reduced cooking loss: Forms a gel network that prevents excessive shrinkage of meat during  
793 heat processing.  
794 - Improved slicing quality: Helps maintain uniform structure, preventing crumbling in deli  
795 meats and cold cuts.  
796

797 Carrageenan is commonly used in low-fat meat formulations, where it compensates for the loss  
798 of fat by enhancing juiciness and improving the overall sensory (Liang et al., 2024). This has  
799 significant applications in the development of healthier meat products.  
800

801 Examples of Processed Meat Products Using Carrageenan:

- 802 - Sausages and hot dogs – Improves firmness, prevents fat separation  
803 - Deli meats (ham, turkey breast, bologna) – Enhances slicing properties, maintains texture  
804 - Meat patties and nuggets – Reduces oil absorption, retains moisture  
805

806 ○ Plant-Based Meat Alternatives

807 With the rising demand for plant-based protein products, carrageenan has gained prominence as  
808 a key structural and textural enhancer. In plant-based meat formulations, it mimics the fibrous  
809 structure of animal proteins, providing a meat-like mouthfeel and binding capacity (Thakur &  
810 Singh, 2024).  
811

812 Key Functions of Carrageenan in Plant-Based Meat:

- 813 - Gelling Agent: Forms a gel network that enhances the chewiness and firmness of plant-based  
814 proteins.  
815 - Water Binder: Improves moisture retention, preventing dry or rubbery textures in vegan  
816 meat products.  
817 - Emulsifier: Helps stabilize fat and protein emulsions, crucial for replicating the mouthfeel of  
818 conventional meat.  
819 - Thermal Stability: Ensures consistency during cooking, freezing, and reheating, maintaining  
820 the structural integrity of the product.  
821

822 Examples of Plant-Based Meat Products Using Carrageenan:

- 823 - Plant-based burgers and sausages – Improves bite texture, enhances juiciness  
824 - Vegan chicken strips and nuggets – Provides a fibrous, meaty feel  
825 - Meat analogues (beef, pork, and seafood alternatives) – Enhances mouthfeel and moisture  
826 retention  
827

828 Recent studies suggest that combining carrageenan with other hydrocolloids, such as  
829 methylcellulose and soy protein isolates, can further improve the texture of plant-based meat  
830 products and make them closer to traditional meat in sensory evaluation (Thakur & Singh, 2024).  
831

832 Additionally, carrageenan-based coatings are being explored for extending the shelf-life of  
833 alternative protein products by preventing oxidative deterioration and microbial contamination  
834 (El Asri et al., 2025).

835

836 ○ Future Trends and Innovations

837 The meat and alternative protein industries are actively researching novel carrageenan  
838 formulations to further optimize their functionality in low-fat meats, high-protein vegan  
839 alternatives, and clean-label formulations. Key trends include:

- 840 - Hybrid Meat Products: Using carrageenan in combination with plant proteins to reduce meat  
841 content while maintaining sensory quality.
- 842 - Bioengineered Carrageenan Blends: Creating modified carrageenan structures for better gel  
843 strength and protein interaction.
- 844 - Sustainable Processing: Exploring eco-friendly carrageenan extraction methods to support  
845 green food innovation.

846 With continued advancements in food science, carrageenan is expected to play an even more  
847 significant role in the next generation of high-performance, sustainable protein products.

848

849 ● Functional Confectionery and Bakery

850 Carrageenan is an important gelling agent in confectionery, particularly in vegan gummy candies as a  
851 gelatin alternative. It provides elasticity and texture while ensuring product stability (Liang et al., 2024).  
852 Additionally, its water-binding properties help prevent syneresis in bakery fillings, extending shelf life (El  
853 Asri et al., 2025).

- 854 ○ Applications: Gummy candies, pastry fillings
- 855 ○ Function: Gel-forming agent, moisture stabilizer
- 856 ○ Benefit: Maintains elasticity and prevents moisture migration

857

858 ● Beverages and Emulsified Sauces

859 In beverage applications,  $\lambda$ -carrageenan enhances viscosity and mouthfeel, particularly in protein  
860 shakes and flavored beverages (Y. Wang et al., 2025). It also improves emulsion stability in low-fat  
861 dressings and sauces, preventing phase separation.

- 862 ○ Applications: Protein drinks, salad dressings
- 863 ○ Function: Thickener, emulsifier
- 864 ○ Benefit: Improves texture and stability

865

866 *6.2 Bioactive and Pharmaceutical Applications*

867 Beyond its functional roles in food, carrageenan exhibits significant bioactive properties, making it a  
868 valuable compound in medical and pharmaceutical research.

869

870 ● Antiviral and Antimicrobial Properties

871 Recent studies have shown that carrageenan can inhibit viral replication by forming a protective barrier  
872 on cell surfaces. This has led to its incorporation in antiviral nasal sprays designed to prevent respiratory  
873 infections, including SARS-CoV-2 (Thakur et al., 2024).

- 874 ○ Applications: Antiviral nasal sprays, pharmaceutical coatings
- 875 ○ Function: Viral attachment inhibitor
- 876 ○ Benefit: Reduces viral transmission and infection risks

877

- 878 • Anti-Inflammatory and Wound Healing  
879 Carrageenan-derived hydrogels have been developed for wound care applications, leveraging  
880 their biocompatibility and moisture-retaining properties. These hydrogels accelerate wound healing  
881 and tissue regeneration while reducing inflammation (Akter et al., 2024).  
882 ○ Applications: Wound dressings, anti-inflammatory gels  
883 ○ Function: Hydrating agent, bioactive polymer  
884 ○ Benefit: Supports tissue regeneration and reduces inflammation  
885

- 886 • Drug Delivery and Encapsulation  
887 Carrageenan's ability to form stable hydrogels makes it an ideal controlled-release drug carrier.  
888 Studies indicate that carrageenan enhances the bioavailability of curcumin and other hydrophobic  
889 drugs, ensuring sustained release (Thakur & Singh, 2024).  
890 ○ Applications: Oral drug delivery, nanoencapsulation  
891 ○ Function: Controlled-release carrier  
892 ○ Benefit: Improves drug stability and absorption  
893

### 894 *6.3 Sustainable Packaging and Biodegradable Materials*

895 Carrageenan-based films and coatings are emerging as sustainable alternatives to traditional  
896 plastics, particularly in biodegradable food packaging.  
897

- 898 • Edible Films and Bioplastics  
899 Carrageenan-based bioplastics have been developed as sustainable food packaging solutions. When  
900 combined with polysaccharides such as starch, these films provide strong moisture barrier properties and  
901 improved mechanical strength (El Asri et al., 2025).  
902 ○ Applications: Edible packaging, biodegradable films  
903 ○ Function: Moisture barrier, sustainable polymer  
904 ○ Benefit: Reduces plastic waste and extends food freshness  
905

- 906 • Personal Care and Cosmetics  
907 Carrageenan is widely utilized in cosmetic and personal care products due to its hydration,  
908 emulsification, and stabilizing properties. It functions as a thickening and film-forming agent in skincare  
909 and hair care formulations, helping to enhance product consistency and improve moisture retention  
910 (Trindade et al., 2024).

911 Key Applications of Carrageenan in Personal Care Products:

- 912 ○ Moisturizers: Provides a film-forming effect, preventing water loss from the skin and improving  
913 hydration.  
914 ○ Face Masks: Enhances the viscosity and texture of gel-based and peel-off masks, offering a smooth  
915 application.  
916 ○ Hair Gels and Shampoos: Acts as a natural thickener and hold-enhancing agent, offering a gel-like  
917 consistency in styling products.

918 Functional Benefits of Carrageenan in Cosmetics:

- 919 ○ Emulsification: Enhances stability of oil-in-water emulsions, preventing ingredient separation.

920 ○ Hydration and Moisture Retention: Forms a moisturizing barrier, keeping the skin hydrated for  
921 longer periods.

922 ○ Texture Improvement: Provides silky smooth consistency to lotions, gels, and creams.

923 Recent studies confirm that  $\kappa$ -carrageenan-based formulations contribute to better skin hydration,  
924 improved stability of bioactive compounds, and enhanced penetration of beneficial ingredients in dermal  
925 applications (Trindade et al., 2024). This highlights its growing role in next-generation cosmeceuticals.

926

### 927 *6.3 Future Research and Innovations*

928 Recent advancements indicate that carrageenan will continue to evolve in various innovative  
929 applications:

930 • Biomedical Engineering: Carrageenan hydrogels are being tested for use in 3D bioprinting and tissue  
931 regeneration (Carrasqueira et al., 2025).

932 • Hybrid Packaging Materials: Combining carrageenan with nanomaterials enhances the mechanical and  
933 antimicrobial properties of biodegradable films (Thakur et al., 2024).

934 Figure 8 outlines future innovations in carrageenan, particularly in biomedical engineering and hybrid  
935 packaging materials.

936

## 937 **7. Challenges and Future Directions**

938 The widespread application of carrageenan in food, pharmaceutical, and biopolymer industries  
939 continues to grow, but several challenges remain in terms of production sustainability, regulatory issues,  
940 quality consistency, and technological advancements. Addressing these limitations is essential for  
941 ensuring carrageenan's long-term viability and expanding its applications.

942

### 943 *7.1 Challenges in Carrageenan Production and Industrial Processing*

944 Figure 9 presents the principal challenges associated with carrageenan production and industrial  
945 processing, emphasizing the energy-intensive nature of conventional extraction methods, the  
946 environmental burden of chemical waste, and the variability in product quality, while also indicating the  
947 potential role of advanced monitoring and eco-friendly technologies in addressing these limitations.

948

#### 949 • High Production Costs and Energy-Intensive Extraction Methods

950 Carrageenan production is dominated by alkaline extraction and hot water processing, both of which  
951 require high energy input and produce significant chemical waste. The energy consumption of traditional  
952 methods increases the carbon footprint and operational costs, making large-scale production  
953 economically challenging (Khiari, 2024).

954 To address this, emerging eco-friendly technologies, such as ultrasound-assisted extraction (UAE) and  
955 deep eutectic solvent (DES) extraction, are being investigated for their ability to reduce processing time,  
956 solvent use, and environmental impact (Mingu et al., 2024). However, these methods require further  
957 industrial validation before being widely adopted.

958

#### 959 • Variability in Carrageenan Quality and Purity

960 One of the main obstacles in carrageenan commercialization is the variation in molecular composition,  
961 which depends on seasonal changes, seaweed species, and cultivation conditions (Victoria et al., 2024).

962 These inconsistencies affect gel strength, solubility, and viscosity, limiting carrageenan's standardization  
963 for pharmaceutical and biomedical applications (Khiari, 2024).

964 The development of real-time monitoring techniques using spectroscopic analysis (FTIR, Raman) and  
965 machine learning algorithms could provide solutions for quality control and process optimization (Zhao  
966 & Xu, 2024).

967

## 968 *7.2 Environmental and Sustainability Challenges*

969 Figure 10 illustrates the main environmental and sustainability challenges in carrageenan  
970 production, emphasizing ecological impacts from large-scale seaweed cultivation and the adoption of  
971 green extraction innovations to minimize waste and pollution.

972

### 973 • Ecological Concerns in Large-Scale Seaweed Cultivation

974 Although seaweed farming is considered environmentally friendly, large-scale cultivation has raised  
975 concerns about marine biodiversity loss, nutrient depletion, and habitat destruction (Mingu et al., 2024).  
976 In some regions, unregulated seaweed monoculture has led to ecosystem imbalances, reducing local  
977 fisheries' productivity.

978 Sustainable solutions include:

979 ○ Integrated Multi-Trophic Aquaculture (IMTA): Combining seaweed with fish and shellfish farming  
980 to balance nutrient cycles (Victoria et al., 2024).

981 ○ Selective Breeding & Genetic Improvement: Using biotechnological approaches (CRISPR-Cas9) to  
982 enhance seaweed resilience and yield while maintaining biodiversity (Khiari, 2024).

983

### 984 • Waste Management and Green Processing Innovations

985 Carrageenan extraction generates a large amount of alkaline wastewater, leading to environmental  
986 pollution. Sustainable extraction techniques such as:

987 ○ Supercritical CO<sub>2</sub> Extraction (low solvent use and high selectivity) (Victoria et al., 2024),

988 ○ Enzymatic hydrolysis (biodegradable catalysts with minimal chemical waste) (Mingu et al., 2024),

989 ○ Microwave-Assisted Extraction (MAE) (reduces processing time by up to 50%) (Mendes, Cotas,  
990 Gutiérrez, et al., 2024).

991 These technologies promise reduced environmental impact, but high initial investment costs remain a  
992 limiting factor for industrial-scale adoption.

993

## 994 *7.3 Expanding Functionalization and New Applications*

995 Figure 11 shows carrageenan's applications in biomedicine (drug delivery with hybrid composites  
996 and nanoparticle encapsulation) and in sustainable packaging (biodegradable films, nanotechnology-  
997 enhanced films, and active packaging).

### 998 • Carrageenan in Biomedical and Pharmaceutical Fields

999 Recent research highlights carrageenan's potential in drug delivery, bio-inks for 3D bioprinting, and  
1000 antiviral therapies (Khiari, 2024). However, low bioavailability and limited mechanical strength hinder its  
1001 widespread use in biomedical engineering.

1002 Possible solutions:

1003 ○ Hybrid Composites: Combining carrageenan with chitosan, alginate, or nanocellulose for  
1004 improved stability and drug-release control (Jayeoye et al., 2025).

1005       ○ Nanoparticle Encapsulation: Enhancing targeted drug delivery and improving bioactivity in  
1006       pharmaceutical formulations (Victoria et al., 2024).

1007

1008       • Sustainable Food Packaging and Edible Films

1009       Carrageenan-based biodegradable films are emerging as sustainable alternatives to petroleum-based  
1010       plastics, but improving mechanical strength and moisture resistance remains a challenge (Mingu et al.,  
1011       2024).

1012       Advancements include:

1013       ○ Nanotechnology-enhanced films: Infusing carrageenan with nanocellulose or polyphenols to  
1014       enhance strength and shelf stability (Victoria et al., 2024).

1015       ○ Active Packaging: Embedding antimicrobial and antioxidant agents into carrageenan films to  
1016       extend food shelf life (Khiari, 2024).

1017

1018       *7.4 Future Research Directions*

1019       • AI and Machine Learning in Carrageenan Processing

1020       AI-driven technologies can be integrated into carrageenan extraction and quality control to:

1021       ○ Predict optimal process conditions, reducing experimental trial-and-error (Imamoglu, 2024).

1022       ○ Automate batch monitoring, ensuring standardized product quality (Victoria et al., 2024).

1023

1024       • Genetic Engineering for Enhanced Seaweed Cultivation

1025       New breeding techniques, such as CRISPR gene editing, offer possibilities for:

1026       ○ Developing high-yield seaweed strains with improved carrageenan content (Kolandhasamy  
1027       Prabhuand Durairaj, 2025).

1028       ○ Increasing resistance to environmental stressors, such as temperature fluctuations and pathogens  
1029       (Sundarraaj Dinesh Kumarand Majumder, 2025).

1030

1031       • Regulatory Developments and Consumer Perception

1032       Despite its safety record, carrageenan remains controversial due to debates on gastrointestinal health  
1033       effects in certain food formulations. The need for:

1034       ○ Stronger global regulatory harmonization to address varying standards across markets (Zhang et  
1035       al., 2024).

1036       ○ Long-term human studies to reaffirm carrageenan's safety profile in food and pharmaceuticals  
1037       (David et al., 2018).

1038

1039       **8. Conclusion**

1040       Carrageenan continues to be an essential hydrocolloid with broad applications in food,  
1041       pharmaceuticals, and biomaterials. Its functional properties, including gelling, thickening, and stabilizing  
1042       abilities, have ensured its indispensable role in food formulation and biomedical advancements. However,  
1043       the focus has shifted towards eco-friendly extraction methods, novel applications in sustainable  
1044       packaging, and advanced biomaterial innovations.

1045

1046       *8.1 Advancements in Sustainable Carrageenan Extraction*

1047 Traditional alkaline extraction and alcohol precipitation methods, while effective, generate significant  
1048 chemical waste and energy consumption. Emerging green extraction technologies, such as enzyme-  
1049 assisted extraction, deep eutectic solvent (DES) extraction, and ultrasound-assisted extraction (UAE), have  
1050 been shown to improve carrageenan purity and sustainability (Horison & Surini, 2025; Pari et al., 2024).  
1051 These methods align with the increasing demand for clean-label, sustainable ingredients while reducing  
1052 the environmental footprint of seaweed processing (Cvetković et al., 2025).

1053

### 1054 *8.2 Innovative Applications in Food and Packaging*

1055 Carrageenan has moved beyond its conventional role in food stabilization to become a key component  
1056 in active and intelligent food packaging. Research has demonstrated that carrageenan-based films, when  
1057 combined with bioactive compounds like Chinese hawthorn extract or nanoparticles, can extend shelf life,  
1058 enhance food safety, and monitor freshness (Adhika et al., 2025; Murugan et al., 2025). These  
1059 advancements have positioned biodegradable carrageenan-based films as a sustainable alternative to  
1060 traditional plastic packaging, helping to reduce plastic waste and environmental impact (Lu et al., 2025).

1061

### 1062 *8.3 Biomedical and Cosmetic Innovations*

1063 Beyond food applications, carrageenan has shown promise in biomedical engineering and cosmetic  
1064 formulations. Recent studies indicate that  $\iota$ -carrageenan-based biomaterials can be used in wound  
1065 healing, tissue scaffolding, and controlled drug delivery systems due to their biocompatibility and antiviral  
1066 properties (Tariq et al., 2025b). In the cosmetics industry, marine algal polysaccharides, including  
1067 carrageenan, are being explored for their moisturizing, anti-aging, and bioactive properties in skincare  
1068 and pharmaceutical formulations (Balasundaram et al., 2025).

1069

### 1070 *8.4 Challenges and Future Directions*

1071 Despite these advancements, several challenges remain, including quality variability due to seasonal  
1072 fluctuations in seaweed biomass, regulatory concerns, and industrial-scale adoption of green processing  
1073 technologies (Hui et al., 2025). Future research should focus on:

- 1074 1. Scaling up green extraction methods for commercial applications.
- 1075 2. Developing hybrid biomaterials that combine carrageenan with other bioactive polysaccharides  
1076 for drug delivery and regenerative medicine.
- 1077 3. Enhancing regulatory standards to ensure consumer safety and consistency in carrageenan-based  
1078 food and biomedical applications.

1079 Exploring AI and machine learning applications for optimizing carrageenan processing and quality  
1080 control (Lu et al., 2025).

1081

### 1082 **Conflict of interest**

1083 The authors declare no conflict of interest.

1084

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1091

## 1092 Declaration of generative AI in scientific writing process

1093 During the preparation of this work, the author(s) used AI-assisted tools, including ChatGPT (OpenAI) and  
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1095 of the manuscript. The author(s) have reviewed and edited the content as needed. The author(s) will take  
1096 full responsibility for the content of the published article.

1097

## 1098 References

1099 A, F., E, C., R, B., LC, H., I, H., R, P., SWK, V. den B., T, P., AH, B., & EJ, C.-C. (2024). Ecosystem Services  
1100 Provided by Seaweed Cultivation: State of the Art, Knowledge Gaps, Constraints and Future Needs  
1101 for Achieving Maximum Potential in Europe. *Reviews in Fisheries Science & Aquaculture*, 1–19.  
1102 <https://doi.org/10.1080/23308249.2024.2399355>

1103 Adhika, D. R., Genecya, G., Habibah, A. A., Putri, A. N. A. R., & Arrozi, U. S. F. (2025). Carrageenan  
1104 bionanocomposite films incorporating Ag and Zn-Doped CeO<sub>2</sub> nanoparticles for active food  
1105 packaging applications. *OpenNano*, 22, 100234.  
1106 <https://doi.org/https://doi.org/10.1016/j.onano.2025.100234>

1107 Akter, A., Sobuj, M. K. A., Islam, Md. S., Chakroborty, K., Tasnim, N., Ayon, M. H., Hossain, Md. F., &  
1108 Rafiquzzaman, S. M. (2024). Seaweed polysaccharides: Sources, structure and biomedical  
1109 applications with special emphasis on antiviral potentials. *Future Foods*, 10, 100440.  
1110 <https://doi.org/https://doi.org/10.1016/j.fufo.2024.100440>

1111 Ali, M. Q., Azhar, M. A., Munaim, M. S. A., Ruslan, N. F., Alsubhi, L. M., Ahmad, N., & Noman, A. E. (2024).  
1112 Seaweed organic compounds source of hydrocolloids and sustainable food packaging: properties,  
1113 application, and future direction. *Discover Food*, 4(1), 101. [https://doi.org/10.1007/s44187-024-  
1114 00173-w](https://doi.org/10.1007/s44187-024-00173-w)

1115 Antonopoulos, A., Favetta, P., Helbert, W., & Lafosse, M. (2004). Isolation of κ-carrageenan  
1116 oligosaccharides using ion-pair liquid chromatography—characterisation by electrospray ionisation  
1117 mass spectrometry in positive-ion mode. *Carbohydrate Research*, 339(7), 1301–1309.  
1118 <https://doi.org/https://doi.org/10.1016/j.carres.2004.03.002>

1119 Awais, S., Munir, H., & Najeeb, J. (2025). Chapter 8 - Nanostructured surfaces in biopolymers—  
1120 characterization of nanostructures. In S. Ahmed & A. Soundararajan (Eds.), *Marine Biopolymers* (pp.  
1121 183–226). Elsevier. <https://doi.org/https://doi.org/10.1016/B978-0-443-15606-9.00008-5>

1122 Baghel, R. S., Reddy, C. R. K., & Singh, R. P. (2021). Seaweed-based cellulose: Applications, and future  
1123 perspectives. *Carbohydrate Polymers*, 267, 118241.  
1124 <https://doi.org/https://doi.org/10.1016/j.carbpol.2021.118241>

- 1125 Balasundaram, H., Seethapathy, P., Sankaralingam, S., Mahendran, S., Mareeswaran, M., Pandiarajan, J.,  
1126 Maheswari, P., Venkatesh, S., Arunkumar, M., Pathade, G. R., Pandita, D., Pandita, A., Ullah, F.,  
1127 Elansary, H. O., Nazim, M., Fickak, A. A., Rashwan, M. A., & Moussa, I. M. (2025). *Isolation,*  
1128 *Characterization, and Biomedical Potential of Phycoerythrin Phycobiliprotein from Kappaphycus*  
1129 *alvarezii (Doty) Doty ex Silva: Antimicrobial, Antioxidant, and Anticancer Activities.*  
1130 <https://doi.org/10.21203/rs.3.rs-5880917/v1>
- 1131 Bandaru, S. S., & Kuchana, M. (2024). Synthesis, in-vitro antioxidant and anti-inflammatory properties of  
1132 novel amide derivatives of substituted 2-aminothiophenes and 3,4-dimethoxy cinnamic acid. *Journal*  
1133 *of Applied Pharmaceutical Science, 14*(6), 116–125. <https://doi.org/10.7324/JAPS.2024.180925>
- 1134 Bapuly, N., & Sharma, N. (2023). *Seaweed Cultivation as a Means to Realise the G20's Agenda for*  
1135 *Sustainability.* [https://t20ind.org/wp-content/uploads/2023/05/T20\\_PB\\_TF-6\\_646\\_Seaweed-](https://t20ind.org/wp-content/uploads/2023/05/T20_PB_TF-6_646_Seaweed-Cultivation.pdf)  
1136 [Cultivation.pdf](https://t20ind.org/wp-content/uploads/2023/05/T20_PB_TF-6_646_Seaweed-Cultivation.pdf)
- 1137 Bisht, B., Lohani, U. C., Kumar, V., Gururani, P., & Sinhmar, R. (2022). Edible hydrocolloids as sustainable  
1138 substitute for non-biodegradable materials. *Critical Reviews in Food Science and Nutrition, 62*(3),  
1139 693–725. <https://doi.org/10.1080/10408398.2020.1827219>
- 1140 Blikra, M. J., Altintzoglou, T., Løvdal, T., Rognså, G., Skipnes, D., Skåra, T., Sivertsvik, M., & Noriega  
1141 Fernández, E. (2021). Seaweed products for the future: Using current tools to develop a sustainable  
1142 food industry. *Trends in Food Science & Technology, 118,* 765–776.  
1143 <https://doi.org/https://doi.org/10.1016/j.tifs.2021.11.002>
- 1144 Carrasqueira, J., Bernardino, S., Bernardino, R., & Afonso, C. (2025). Marine-Derived Polysaccharides and  
1145 Their Potential Health Benefits in Nutraceutical Applications. *Marine Drugs, 23*(2), 60.  
1146 <https://doi.org/10.3390/md23020060>
- 1147 Ceaser, R., Bedzo, O. K. K., & Donkor, K. O. (2025). Biorefinery approach to producing polysaccharides  
1148 from seaweed: a focus on hydrocolloids and nanocellulose. *Biomass Conversion and Biorefinery.*  
1149 <https://doi.org/10.1007/s13399-024-06487-0>
- 1150 Chang, C.-W., Vo, T. H., Sheng, Y.-J., & Tsao, H.-K. (2025). Facile fabrication of 3D structure of carrageenan  
1151 gel at room temperature and spontaneous formation of carrageenan microgels. *Journal of the*  
1152 *Taiwan Institute of Chemical Engineers, 169,* 105953.  
1153 <https://doi.org/https://doi.org/10.1016/j.jtice.2025.105953>
- 1154 Chen, Q., Ji, H., Wang, Z., Wang, Y., Wang, X., & Chen, Z. (2025). Effects of different charged  
1155 polysaccharides on the gelation properties and in vitro digestibility of potato protein gel: Insight into  
1156 underlying mechanisms. *Food Hydrocolloids, 164,* 111187.  
1157 <https://doi.org/https://doi.org/10.1016/j.foodhyd.2025.111187>
- 1158 Cvetković, K., Đorđević, N., Karabegović, I., Danilović, B., Dordevic, D., Dordevic, S., & Kushkevych, I.  
1159 (2025). Production and Testing of Carrageenan-Based Films Enriched with Chinese Hawthorn Extract  
1160 in Strawberry Packaging. *Processes, 13*(2). <https://doi.org/10.3390/pr13020379>
- 1161 David, S., Shani Levi, C., Fahoum, L., Ungar, Y., Meyron-Holtz, E. G., Shpigelman, A., & Lesmes, U. (2018).  
1162 Revisiting the carrageenan controversy: do we really understand the digestive fate and safety of  
1163 carrageenan in our foods? *Food Funct., 9*(3), 1344–1352. <https://doi.org/10.1039/C7FO01721A>

- 1164 de Souza Mesquita, L. M. (2024). The perfect match between macroalgae and eutectic solvents as a  
1165 sustainable gateway to ready-to-use extracts towards a (blue + green) economy – A perspective  
1166 review. *Bioresource Technology*, 414, 131600.  
1167 <https://doi.org/https://doi.org/10.1016/j.biortech.2024.131600>
- 1168 Delattre, C., Pierre, G., Laroche, C., & Michaud, P. (2016). Production, extraction and characterization of  
1169 microalgal and cyanobacterial exopolysaccharides. *Biotechnology Advances*, 34(7), 1159–1179.  
1170 <https://doi.org/https://doi.org/10.1016/j.biotechadv.2016.08.001>
- 1171 Dong, Y., Wei, Z., & Xue, C. (2021). Recent advances in carrageenan-based delivery systems for bioactive  
1172 ingredients: A review. *Trends in Food Science & Technology*, 112, 348–361.  
1173 <https://doi.org/https://doi.org/10.1016/j.tifs.2021.04.012>
- 1174 Duan, F., Yu, Y., Liu, Z., Tian, L., & Mou, H. (2016). An effective method for the preparation of carrageenan  
1175 oligosaccharides directly from *Eucheuma cottonii* using cellulase and recombinant  $\kappa$ -carrageenase.  
1176 *Algal Research*, 15, 93–99. <https://doi.org/https://doi.org/10.1016/j.algal.2016.02.006>
- 1177 El Achkar, T., Fourmentin, S., & Greige-Gerges, H. (2019). Deep eutectic solvents: An overview on their  
1178 interactions with water and biochemical compounds. *Journal of Molecular Liquids*, 288, 111028.  
1179 <https://doi.org/https://doi.org/10.1016/j.molliq.2019.111028>
- 1180 El Asri, S., Ben Mrid, R., Zouaoui, Z., Roussi, Z., Ennoury, A., Nhiri, M., & Chibi, F. (2025). Advances in  
1181 structural modification of fucoidans, ulvans, and carrageenans to improve their biological functions  
1182 for potential therapeutic application. *Carbohydrate Research*, 549, 109358.  
1183 <https://doi.org/https://doi.org/10.1016/j.carres.2024.109358>
- 1184 Erge, A., & Dülger, B. D. (2024). A novel biodegradable film based on chicken gelatin and  $\kappa$ -carrageenan  
1185 cross-linked with oxidized phenolic compounds. *Environmental Science and Pollution Research*,  
1186 31(39), 51211–51221. <https://doi.org/10.1007/s11356-024-33988-2>
- 1187 Exarhopoulos, S., Krystallis, E., Rousi, E., Groztidou, O., Georgiou, D., Kalogianni, E. P., Goulas, A., &  
1188 Dimitreli, G. (2025). Effect of Thermal Treatment and the Addition of Texture Modifiers on the  
1189 Rheological Properties and the Microflora of Reconstituted Kefir Powder. *Macromol*, 5(1).  
1190 <https://doi.org/10.3390/macromol5010007>
- 1191 FAO. (2021). *SEAWEEDS AND MICROALGAE: AN OVERVIEW FOR UNLOCKING THEIR POTENTIAL IN GLOBAL*  
1192 *AQUACULTURE DEVELOPMENT FAO Fisheries and Aquaculture Circular NFIA/C1229 (En)*.  
1193 [https://doi.org/https://openknowledge.fao.org/server/api/core/bitstreams/43da43ad-be75-4aaa-](https://doi.org/https://openknowledge.fao.org/server/api/core/bitstreams/43da43ad-be75-4aaa-ba4a-e375b1c65cfc/content)  
1194 [ba4a-e375b1c65cfc/content](https://doi.org/https://openknowledge.fao.org/server/api/core/bitstreams/43da43ad-be75-4aaa-ba4a-e375b1c65cfc/content)
- 1195 Feng, Y., Sun, Z., Zhang, J., Shi, P., Kong, B., Cao, C., Sun, F., & Liu, Q. (2025). Proteomic analysis revealing  
1196 mechanisms of  $\kappa$ -carrageenan modulating the gelling properties of heat-induced microbial  
1197 transglutaminase cross-linked myofibrillar protein gels. *Food Hydrocolloids*, 159, 110693.  
1198 <https://doi.org/https://doi.org/10.1016/j.foodhyd.2024.110693>
- 1199 Gallego, R., Bueno, M., & Herrero, M. (2019). Sub- and supercritical fluid extraction of bioactive  
1200 compounds from plants, food-by-products, seaweeds and microalgae – An update. *TrAC Trends in*  
1201 *Analytical Chemistry*, 116, 198–213. <https://doi.org/https://doi.org/10.1016/j.trac.2019.04.030>

- 1202 Gereniu, C. R. N., Saravana, P. S., & Chun, B.-S. (2018). Recovery of carrageenan from Solomon Islands red  
1203 seaweed using ionic liquid-assisted subcritical water extraction. *Separation and Purification*  
1204 *Technology*, 196, 309–317. <https://doi.org/https://doi.org/10.1016/j.seppur.2017.06.055>
- 1205 Grant, N., & May, E. (2024). Seaweed to Sustainable Plastic: Bioengineering the Future of Materials.  
1206 *Embry-Riddle Aeronautical University Sustainability Conference Proceeding*.  
1207 <https://commons.erau.edu/sustainability-conference/2024/poster/4/>
- 1208 Gross, R. A. (2024). Seaweed Holds Great Potential to Provide Sustainable Solutions to Problems That  
1209 Threaten the Health of Our Planet. *Industrial Biotechnology*, 20(3), 99–100.  
1210 <https://doi.org/10.1089/ind.2024.20324.editorial>
- 1211 Hentati, F., Tounsi, L., Djomdi, D., Pierre, G., Delattre, C., Ursu, A. V., Fendri, I., Abdelkafi, S., & Michaud,  
1212 P. (2020). Bioactive polysaccharides from seaweeds. In *Molecules* (Vol. 25, Issue 14). MDPI AG.  
1213 <https://doi.org/10.3390/molecules25143152>
- 1214 Horison, R., & Surini, S. (2025). Utilization of glucomannan-xanthan gum-carrageenan based co-processed  
1215 excipients in the development of nutraceutical pomegranate (*Punica granatum* L.) peel extract jelly.  
1216 *Journal of Pharmacy and Pharmacognosy Research*, 13(3), 774–786.  
1217 [https://doi.org/10.56499/jppres24.2060\\_13.3.774](https://doi.org/10.56499/jppres24.2060_13.3.774)
- 1218 Huang, P.-H., Jian, C.-H., Lin, Y.-W., & Huang, D.-W. (2025). Impact of *Premna microphylla* Turcz leaf water  
1219 extracts on the properties of gelatin-carrageenan edible film and its application in cherry tomatoes  
1220 storage. *Food Chemistry: X*, 25, 102186.  
1221 <https://doi.org/https://doi.org/10.1016/j.fochx.2025.102186>
- 1222 Hui, Y., Liu, R., Mei, Z., & Xu, A. (2025). Engineering efficient carrageenan materials for simultaneously  
1223 removing herbicide, eight anionic/cationic dyes and metal ion contaminants and adsorption  
1224 mechanism. *International Journal of Biological Macromolecules*, 302, 140551.  
1225 <https://doi.org/https://doi.org/10.1016/j.ijbiomac.2025.140551>
- 1226 Imamoglu, E. (2024). Green extraction processes from renewable biomass to sustainable bioproducts.  
1227 *Bioresource Technology Reports*, 27, 101952.  
1228 <https://doi.org/https://doi.org/10.1016/j.biteb.2024.101952>
- 1229 James, J., Verma, M., & Sharma, N. (2023). Nanotechnology-driven improvisation of red algae-derived  
1230 carrageenan for industrial and bio-medical applications. *World Journal of Microbiology and*  
1231 *Biotechnology*, 40(1), 4. <https://doi.org/10.1007/s11274-023-03787-x>
- 1232 Jayeoye, T. J., Eze, F. N., Muangsin, N., & Singh, S. (2025). Carrageenan in Drug Delivery Therapeutics. In  
1233 *Handbook of Research in Marine Pharmaceutics* (1st ed.). Apple Academic Press.
- 1234 Khiari, Z. (2024). Recent Developments in Bio-Ink Formulations Using Marine-Derived Biomaterials for  
1235 Three-Dimensional (3D) Bioprinting. *Marine Drugs*, 22(3). <https://doi.org/10.3390/md22030134>
- 1236 Kolandhasamy Prabhu and Durairaj, K. R. and R. R. and S. S. K. (2025). From Sea to Super Crops: The  
1237 Expanding Horizons of Seaweed in Technology and Industry. In V. A. Rathore Mangal S. and Mantri  
1238 (Ed.), *Biotechnological Interventions to Aid Commercial Seaweed Farming* (pp. 19–49). Springer  
1239 Nature Singapore. [https://doi.org/10.1007/978-981-97-9427-0\\_2](https://doi.org/10.1007/978-981-97-9427-0_2)

- 1240 Kumar, S., Bhatt, A., & Purohit, P. (2025). Carrageenan Modifications: Improving Biomedical Applications.  
1241 *Journal of Polymers and the Environment*. <https://doi.org/10.1007/s10924-025-03501-y>
- 1242 Liang, B., Feng, S., Zhang, X., Ye, Y., Sun, C., Ji, C., & Li, X. (2024). Physicochemical properties and in vitro  
1243 digestion behavior of emulsion micro-gels stabilized by  $\kappa$ -carrageenan and whey protein: Effects of  
1244 sodium alginate addition. *International Journal of Biological Macromolecules*, 271, 132512.  
1245 <https://doi.org/https://doi.org/10.1016/j.ijbiomac.2024.132512>
- 1246 Liew, & Chin, Y. (2024). *Effect of Enzymatic Hydrolysis on the Physicochemical and Bioactive Properties of*  
1247 *Edible Bird Nest Hydrolysate-Oligocarrageenan Blend Gel*. Tunku Abdul Rahman University of  
1248 Management and Technology.
- 1249 Liu, C., Gao, J., Jiang, H., Sun, J., Gao, X., & Mao, X. (2024). Value-added utilization technologies for  
1250 seaweed processing waste in a circular economy: Developing a sustainable modern seaweed  
1251 industry. *Comprehensive Reviews in Food Science and Food Safety*, 23(6), e70027.  
1252 <https://doi.org/https://doi.org/10.1111/1541-4337.70027>
- 1253 Liu, Z., Ruan, M., Ha, S., Chitrakar, B., Li, H., Hu, L., & Mo, H. (2025). Effect of curcumin/cyclodextrin  
1254 composite on the gelation and 3D printability of  $\kappa$ -carrageenan in the sucrose co-solute field. *Journal*  
1255 *of Food Engineering*, 391, 112441. <https://doi.org/https://doi.org/10.1016/j.jfoodeng.2024.112441>
- 1256 Lomartire, S., Marques, J. C., & Gonçalves, A. M. M. (2022). An Overview of the Alternative Use of  
1257 Seaweeds to Produce Safe and Sustainable Bio-Packaging. *Applied Sciences*, 12(6).  
1258 <https://doi.org/10.3390/app12063123>
- 1259 Lu, S.-Y., Zhou, T., Shabbir, I., Choi, J., Kim, Y. H., Park, M., Aweya, J. J., Tan, K., Zhong, S., & Cheong, K.-L.  
1260 (2025). Marine algal polysaccharides: Multifunctional bioactive ingredients for cosmetic  
1261 formulations. *Carbohydrate Polymers*, 353, 123276.  
1262 <https://doi.org/https://doi.org/10.1016/j.carbpol.2025.123276>
- 1263 Lubowa, M., Shin Yong, Y., & Muhamad Shaban, M. (2024). Hydrocolloids in Rice Noodle Production:  
1264 Enhancing Texture, Cooking Quality, and Sustainability in Gluten-Free Formulations: A Review.  
1265 *Journal of Food Innovation, Nutrition, and Environmental Sciences*, 1(1), 30–46.  
1266 <https://doi.org/10.70851/qdw8d910>
- 1267 Luo, X., Wu, Y., Wang, S., Xiong, Z., Du, X., Zheng, M., Zhu, Y., Jiang, Z., Li, Q., Ni, H., Li, Z., & Chen, Z. (2024).  
1268 Frontier review of key reduction technologies and resource utilization of waste during the seaweed  
1269 gel production process. *Blue Biotechnology*, 1(1), 12. <https://doi.org/10.1186/s44315-024-00013-7>
- 1270 Mendes, M., Cotas, J., Gutiérrez, I. B., Gonçalves, A. M. M., Critchley, A. T., Hinaloc, L. A. R., Roleda, M. Y.,  
1271 & Pereira, L. (2024). Advanced Extraction Techniques and Physicochemical Properties of  
1272 Carrageenan from a Novel *Kappaphycus alvarezii* Cultivar. *Marine Drugs*, 22(11).  
1273 <https://doi.org/10.3390/md22110491>
- 1274 Mendes, M., Cotas, J., Pacheco, D., Ihle, K., Hillinger, A., Cascais, M., Marques, J. C., Pereira, L., &  
1275 Gonçalves, A. M. M. (2024). Red Seaweed (Rhodophyta) Phycocolloids: A Road from the Species to  
1276 the Industry Application. *Marine Drugs*, 22(10). <https://doi.org/10.3390/md22100432>

- 1277 Mingu, N., Mail, N. H. A., Mamat, H., Siddiquee, S., Majid, M. H. A., & Sarjadi, M. S. (2024). Red Seaweed  
1278 Carrageenan: A Comprehensive Review of Preparation in Cosmetics - An In Depth Analysis. *Borneo*  
1279 *Journal of Resource Science and Technology*, 14(2), 156–172.  
1280 <https://doi.org/10.33736/bjrst.7290.2024>
- 1281 Mohamed, R. R. (2024). Hydrogel-Nanocomposite in Sustained Drug Release: Synthesis and Properties. In  
1282 K. Sharma, S. K. Tiwari, V. Kumar, & S. Kalia (Eds.), *Novel Bio-nanocomposites for Biomedical*  
1283 *Applications* (pp. 227–260). Springer International Publishing. [https://doi.org/10.1007/978-3-031-](https://doi.org/10.1007/978-3-031-69654-1_9)  
1284 [69654-1\\_9](https://doi.org/10.1007/978-3-031-69654-1_9)
- 1285 Murugan, G., Khan, A., Priyadarshi, R., Nilswan, K., Benjakul, S., & Rhim, J.-W. (2025). Smart packaging  
1286 films based on gelatin/k-carrageenan integrated with gromwell root extract rich in shikonin and  
1287 carbon dots for real-time monitoring of shrimp freshness. *Journal of Food Science*, 90(2), e70011.  
1288 <https://doi.org/https://doi.org/10.1111/1750-3841.70011>
- 1289 Nakhate, P., & van der Meer, Y. (2021). A Systematic Review on Seaweed Functionality: A Sustainable Bio-  
1290 Based Material. *Sustainability*, 13(11). <https://doi.org/10.3390/su13116174>
- 1291 Nunes, A., Azevedo, G. Z., & de Souza Dutra, F. (2024). Uses and applications of the red seaweed  
1292 *Kappaphycus alvarezii*: a systematic review. *J Appl Phycol*, 36, 3409–3450.
- 1293 Oliyaei, N., Moosavi-Nasab, M., & Mazloomi, S. M. (2022). Therapeutic activity of fucoidan and  
1294 carrageenan as marine algal polysaccharides against viruses. *3 Biotech*, 12(7), 154.  
1295 <https://doi.org/10.1007/s13205-022-03210-6>
- 1296 Parab, P., Khandeparker, R., Amberkar, U., & Khodse, V. (2017). Enzymatic saccharification of seaweeds  
1297 into fermentable sugars by xylanase from marine *Bacillus* sp. strain BT21. *3 Biotech*, 7(5), 296.  
1298 <https://doi.org/10.1007/s13205-017-0921-4>
- 1299 Pari, R. F., Uju, U., Hardiningtyas, S. D., Ramadhan, W., Wakabayashi, R., Goto, M., & Kamiya, N. (2024).  
1300 *Ulva Seaweed-Derived Ulvan: A Promising Marine Polysaccharide for Biomaterial Design*.  
1301 <https://doi.org/10.20944/preprints202412.2541.v1>
- 1302 Pari, R. F., Uju, U., Hardiningtyas, S. D., Ramadhan, W., Wakabayashi, R., Goto, M., & Kamiya, N. (2025).  
1303 *Ulva Seaweed-Derived Ulvan: A Promising Marine Polysaccharide as a Sustainable Resource for*  
1304 *Biomaterial Design*. *Marine Drugs*, 23(2). <https://doi.org/10.3390/md23020056>
- 1305 Pereira, L., Mendes, M., Hillinger, A., Ihle, K., Cascais, M., Andrade, P., Cotas, J., Pacheco, D., Carlos  
1306 Marques, J., & Marta Mendes Gonçalves, A. (2024). Seaweed Aquaculture Importance in Sustainable  
1307 Economy in an Era of Climate Change. In L. Pereira & M. A. Pardal (Eds.), *Oceanography -*  
1308 *Relationships of the Oceans with the Continents, Their Biodiversity and the Atmosphere*. IntechOpen.  
1309 <https://doi.org/10.5772/intechopen.114366>
- 1310 Pinto Tiago C. and Sabet, S. and K. G. A. and K. S. and V. F. (2024). Oleogel Preparation Methods and  
1311 Classification. In F. Palla Camila and Valoppi (Ed.), *Advances in Oleogel Development,*  
1312 *Characterization, and Nutritional Aspects* (pp. 77–114). Springer International Publishing.  
1313 [https://doi.org/10.1007/978-3-031-46831-5\\_4](https://doi.org/10.1007/978-3-031-46831-5_4)

- 1314 Prado-Fernández, J., Rodríguez-Vázquez, J. A., Tojo, E., & Andrade, J. M. (2003). Quantitation of  $\kappa$ -,  $\iota$ - and  
1315  $\lambda$ -carrageenans by mid-infrared spectroscopy and PLS regression. *Analytica Chimica Acta*, *480*(1),  
1316 23–37. [https://doi.org/https://doi.org/10.1016/S0003-2670\(02\)01592-1](https://doi.org/https://doi.org/10.1016/S0003-2670(02)01592-1)
- 1317 Puspita, M., Setyawidati, N. A. R., & Pangestuti, R. (2020). Hydrocolloid Production of Indonesian  
1318 Seaweeds. In *Encyclopedia of Marine Biotechnology*.  
1319 <https://onlinelibrary.wiley.com/doi/abs/10.1002/9781119143802.ch12>
- 1320 Rawiwan, P., Peng, Y., Paramayuda, I. G. P. B., & Quek, S. Y. (2022). Red seaweed: A promising alternative  
1321 protein source for global food sustainability. *Trends in Food Science & Technology*, *123*, 37–56.  
1322 <https://doi.org/https://doi.org/10.1016/j.tifs.2022.03.003>
- 1323 Rezaei, M., Naji-Tabasi, S., Ghorani, B., & Emadzadeh, B. (2025). Studying the impact of zein microfibers  
1324 on the physicochemical and microstructural properties of bi-gels based on  $\iota$ -carrageenan hydrogels  
1325 and beeswax oleogels. *Current Research in Food Science*, *10*, 100985.  
1326 <https://doi.org/https://doi.org/10.1016/j.crfs.2025.100985>
- 1327 Rhein-Knudsen, N., & Meyer, A. S. (2021). Chemistry, gelation, and enzymatic modification of seaweed  
1328 food hydrocolloids. In *Trends in Food Science and Technology* (Vol. 109, pp. 608–621). Elsevier Ltd.  
1329 <https://doi.org/10.1016/j.tifs.2021.01.052>
- 1330 Rosmawati, R., Sari, S. F., Asnani, A., Embe, W., Asjun, A., Wibowo, D., Irwan, I., Huda, N., Nurdin, M., &  
1331 Umar, A. A. (2025). Influence of Sorbitol and Glycerol on Physical and Tensile Properties of  
1332 Biodegradable–Edible Film From Snakehead Gelatin and  $\kappa$ -Carrageenan. *International Journal of*  
1333 *Food Science*, *2025*(1), 7568352. <https://doi.org/https://doi.org/10.1155/ijfo/7568352>
- 1334 Rupert, R., Rodrigues, K. F., Thien, V. Y., & Yong, W. T. L. (2022). Carrageenan From *Kappaphycus alvarezii*  
1335 (Rhodophyta, Solieriaceae): Metabolism, Structure, Production, and Application. In *Frontiers in Plant*  
1336 *Science* (Vol. 13). Frontiers Media S.A. <https://doi.org/10.3389/fpls.2022.859635>
- 1337 Salazar, L., Dresdner, J., Figueroa, Y., Araya, A., & Palta, E. (2024). Sustainability of seaweed supply and  
1338 price dynamics in the Chinese hydrocolloid industry. *Aquaculture Economics & Management*, *28*(4),  
1339 537–551. <https://doi.org/10.1080/13657305.2024.2368783>
- 1340 Salengke, S., Hasizah, A., Waris, A., Mahendradatta, M., & Laga, A. (2017). Optimization of Carrageenan  
1341 Extraction from *Eucheuma Spinosum* Using Pilot Scale Ohmic Technology. *Hasanuddin University*  
1342 *Journal*. <https://doi.org/https://core.ac.uk/download/pdf/132584242.pdf>
- 1343 Santana, I., Felix, M., & Bengoechea, C. (2024). Seaweed as Basis of Eco-Sustainable Plastic Materials:  
1344 Focus on Alginate. *Polymers*, *16*(12). <https://doi.org/10.3390/polym16121662>
- 1345 Sedayu, B. B., Cran, M. J., & Bigger, S. W. (2019). A Review of Property Enhancement Techniques for  
1346 Carrageenan-based Films and Coatings. *Carbohydrate Polymers*, *216*, 287–302.  
1347 <https://doi.org/https://doi.org/10.1016/j.carbpol.2019.04.021>
- 1348 Sharifi, M., Ghiasi, F., Zare, M., Hedayati, S., & Abbasi, A. (2025). Production of bigel based on  $\kappa$ -  
1349 carrageenan and monoglyceride for potential application as a shortening replacer in cookie. *Food*  
1350 *Hydrocolloids*, *164*, 111160. <https://doi.org/https://doi.org/10.1016/j.foodhyd.2025.111160>

- 1351 Singh, P. K., Agrawal, N., Srivastav, N., Srivastav, A., Niranjana, A. K., Yadav, S., Singh, R., Shukla, S., & Garg,  
1352 A. (2024). Biodegradable packaging of food: An alternative to synthetic polymers for sustainable  
1353 development. *INDIAN JOURNAL OF ANIMAL HEALTH*, 63(2-Spl).  
1354 <https://doi.org/10.36062/ijah.2024.spl.00324>
- 1355 Sundarraj Dinesh Kumar and Majumder, A. and R. S. H. and I. E. and S. S. M. I. (2025). Spore-Based  
1356 Seaweed Propagation for Germplasm Selection and Cultivation. In V. A. Rathore Mangal S. and  
1357 Mantri (Ed.), *Biotechnological Interventions to Aid Commercial Seaweed Farming* (pp. 257–293).  
1358 Springer Nature Singapore. [https://doi.org/10.1007/978-981-97-9427-0\\_12](https://doi.org/10.1007/978-981-97-9427-0_12)
- 1359 Sutrisno, D., Rifaie, F., Rudiastuti, A. W., Rahadiati, A., Purwandani, A., Rahman, A., & Pratama, B. B.  
1360 (2024). A Systematic Review of the Scientific Literature to Identify Challenges for the Sustainable  
1361 Development of Seaweed Farming in Indonesia. In *Journal of Marine and Island Cultures* (Vol. 13,  
1362 Issue 3, pp. 136–159). Plate Media. <https://doi.org/10.21463/jmic.2024.13.3.08>
- 1363 Tan, I. S., & Lee, K. T. (2014). Enzymatic hydrolysis and fermentation of seaweed solid wastes for  
1364 bioethanol production: An optimization study. *Energy*, 78, 53–62.  
1365 <https://doi.org/https://doi.org/10.1016/j.energy.2014.04.080>
- 1366 Tariq, T. B., Karishma, Umer, M., & Mubeen-ur-Rehman. (2025a). The potential of seaweed-derived  
1367 polysaccharides as sustainable biostimulants in agriculture. *International Journal of Biological*  
1368 *Macromolecules*, 298, 140009. <https://doi.org/https://doi.org/10.1016/j.ijbiomac.2025.140009>
- 1369 Tariq, T. B., Karishma, Umer, M., & Mubeen-ur-Rehman. (2025b). The potential of seaweed-derived  
1370 polysaccharides as sustainable biostimulants in agriculture. *International Journal of Biological*  
1371 *Macromolecules*, 298, 140009. <https://doi.org/https://doi.org/10.1016/j.ijbiomac.2025.140009>
- 1372 Thakur, N., & Singh, B. (2024). Designing carrageenan-based functional biomaterials by supra-molecular  
1373 and covalent interactions for biomedical applications. *Medicine in Novel Technology and Devices*, 24,  
1374 100338. <https://doi.org/https://doi.org/10.1016/j.medntd.2024.100338>
- 1375 Thakur, N., Singh, B., Sharma, S., & Kanwar, S. S. (2024). Designing carrageenan-based hydrogels for drug  
1376 delivery applications: Evaluation of physicochemical and biomedical properties. *Bioactive*  
1377 *Carbohydrates and Dietary Fibre*, 32, 100439.  
1378 <https://doi.org/https://doi.org/10.1016/j.bcdf.2024.100439>
- 1379 Trindade, G. A. de M., Alves, L. A., Lazo, R. E. L., Dallabrida, K. G., Reolon, J. B., Bonini, J. S., Nunes, K. C.,  
1380 Garcia, F. P., Nakamura, C. V., Rego, F. G. de M., Pontarolo, R., Sari, M. H. M., & Ferreira, L. M. (2024).  
1381 Polysaccharide-Stabilized Semisolid Emulsion with Vegetable Oils for Skin Wound Healing: Impact of  
1382 Composition on Physicochemical and Biological Properties. *Pharmaceutics*, 16(11).  
1383 <https://doi.org/10.3390/pharmaceutics16111426>
- 1384 van Oort, P. A. J., Verhagen, A., & van der Werf, A. K. (2023). Can seaweeds feed the world? Modelling  
1385 world offshore seaweed production potential. *Ecological Modelling*, 484, 110486.  
1386 <https://doi.org/https://doi.org/10.1016/j.ecolmodel.2023.110486>
- 1387 Victoria, N. J., Ulac, A. P., & Marie Dayag, D. C. (2024). *POTENTIAL OF CARRAGEENAN PGP AND SYNTHETIC*  
1388 *FERTILIZER IN IMPROVING GROWTH AND YIELD OF AEROBIC RICE*. *Proceedings of the International*  
1389 *Conference on Strengthening Capacities of Multi-sectors toward Sustainable Development*, 399-408.

1390 Villanueva, R. D., Romero, J. B., Montaña, M. N. E., & de la Peña, P. O. (2011). Harvest optimization of four  
1391 Kappaphycus species from the Philippines. *Biomass and Bioenergy*, 35(3), 1311–1316.  
1392 <https://doi.org/https://doi.org/10.1016/j.biombioe.2010.12.044>

1393 Wang, C., Shen, Z., Cui, X., Jiang, Y., & Jiang, X. (2020). Response surface optimization of enzyme-assisted  
1394 extraction of R-phycoerythrin from dry Pyropia yezoensis. *Journal of Applied Phycology*, 32(2), 1429–  
1395 1440. <https://doi.org/https://doi.org/10.1007/s10811-019-01963-x>

1396 Wang, Y., Jiang, Y., Chen, X., Zou, Y., Lei, L., Zhao, G., & Zhou, Y. (2025). Dispersion stabilization of proteins  
1397 by carrageenan in baked milk: A quantitative separation study. *Food Chemistry*, 472, 142835.  
1398 <https://doi.org/https://doi.org/10.1016/j.foodchem.2025.142835>

1399 Waseem, M., Khan, M. U., Majeed, Y., Ntsefong, G. N., Kirichenko, I., Klopova, A., Trushov, P., & Lodygin,  
1400 A. (2023). Seaweed-based films for sustainable food packaging: properties, incorporation of  
1401 essential oils, applications, and future directions. *Potravinarstvo Slovak Journal of Food Sciences*, 17,  
1402 899–917. <https://doi.org/https://doi.org/10.5219/1908>

1403 Webb, P., Somers, N. K., & Thilsted, S. H. (2023). Seaweed’s contribution to food security in low- and  
1404 middle-income countries: Benefits from production, processing and trade. *Global Food Security*, 37,  
1405 100686. <https://doi.org/https://doi.org/10.1016/j.gfs.2023.100686>

1406 Yong, W. T. L., Thien, V. Y., Misson, M., Chin, G. J. W. L., Said Hussin, S. N. I., Chong, H. L. H., Yusof, N. A.,  
1407 Ma, N. L., & Rodrigues, K. F. (2024). Seaweed: A bioindustrial game-changer for the green revolution.  
1408 *Biomass and Bioenergy*, 183, 107122.  
1409 <https://doi.org/https://doi.org/10.1016/j.biombioe.2024.107122>

1410 Yousouf, L., Lallemand, L., Giraud, P., Soulé, F., Bhaw-Luximon, A., Meilhac, O., D’Hellencourt, C. L.,  
1411 Jhurry, D., & Couprie, J. (2017). Ultrasound-assisted extraction and structural characterization by  
1412 NMR of alginates and carrageenans from seaweeds. *Carbohydrate Polymers*, 166, 55–63.  
1413 <https://doi.org/https://doi.org/10.1016/j.carbpol.2017.01.041>

1414 Zainal-Abidin, M. H., Hayyan, M., Hayyan, A., & Jayakumar, N. S. (2017). New horizons in the extraction of  
1415 bioactive compounds using deep eutectic solvents: A review. *Analytica Chimica Acta*, 979, 1–23.  
1416 <https://doi.org/https://doi.org/10.1016/j.aca.2017.05.012>

1417 Zhang, J., Waldron, S., Langford, Z., Julianto, B., & Komarek, A. M. (2024). China’s growing influence in the  
1418 global carrageenan industry and implications for Indonesia. *Journal of Applied Phycology*, 36(2), 639–  
1419 660. <https://doi.org/https://doi.org/10.1007/s10811-023-03004-0>

1420 Zhao, H., & Xu, C. (2024). Machine Learning-Driven Raman Spectroscopy Techniques for Rapid Detection  
1421 of Chemical Compounds and Contaminants in Foods. In *Raman Spectroscopy in the Food Industry*  
1422 (1st ed.). Taylor and Francis.

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1429 **Tables and Figures**

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1431 Table 1. Green and Advanced Extraction Techniques.

Extraction Method	Mechanism	Advantages	Disadvantages
Enzymatic Hydrolysis	Uses enzymes to break down seaweed cell walls	High purity, mild conditions, reduce chemical waste	Expensive, requires precise enzyme control
Ultrasound-Assisted Extraction (UAE)	Uses high-frequency sound waves to enhance cell rupture	Fast, energy-efficient, improves yield	Requires specialized equipment
Microwave-Assisted Extraction (MAE)	Uses microwave heating to accelerate carrageenan release	Rapid process, low energy use, high purity	Potential for molecular degradation
Supercritical Fluid Extraction (SFE)	Uses supercritical CO <sub>2</sub> or water for solvent-free extraction	High purity, eco-friendly, minimal chemical residues	High operating costs
Deep Eutectic Solvent (DES) Extraction	Uses biodegradable eutectic solvents	Green chemistry approach, highly selective	Limited scalability
Instant Controlled Pressure Drop (DIC)	Applies sudden steam pressure drop to rupture seaweed cells	High yield, improves gel strength, eco-friendly	High initial cost, limited industrial use

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1434 Table 2. Effect of Temperature on Carrageenan Extraction Efficiency and Yield.

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Parameter	Effect on Extraction
Low Temp. ( $\leq 60^{\circ}\text{C}$ )	Incomplete extraction, lower yield
Moderate Temp. ( $60\text{--}80^{\circ}\text{C}$ )	Optimal yield and gel properties
High Temp. ( $>90^{\circ}\text{C}$ )	Degradation, lower molecular weight

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Note:

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➤ Extended extraction ( $>120$  min) increases yield but damages molecular structure.

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➤ Short-time extraction ( $\leq 30$  min) is efficient only if coupled with alternative techniques.

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(Duan et al., 2016).

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1444 **Table 3.** Comparative Analysis of Advanced Carrageenan Extraction Techniques: Mechanisms, Benefits,  
1445 and Challenges.

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Method	Mechanism	Advantages	Challenges
Ultrasound-Assisted Extraction (UAE)	Uses high-frequency sound waves to break seaweed cells	Faster extraction, higher yield	Requires specialized equipment
Microwave-Assisted Extraction (MAE)	Uses microwave radiation for rapid heating	Energy-efficient, preserves molecular weight	May cause overheating
Ohmic Heating Extraction	Electric currents heat the seaweed matrix	Less chemical use, enhances diffusion	High initial cost (Salengke et al., 2017)
Supercritical CO <sub>2</sub> Extraction (SFE)	Uses pressurized CO <sub>2</sub> to dissolve carrageenan	Solvent-free, high purity	Expensive, not widely used
Deep Eutectic Solvent (DES) Extraction	Uses biodegradable, non-toxic solvents	Eco-friendly, highly selective	Limited industrial application
Instant Controlled Pressure Drop (DIC) Extraction	Sudden steam pressure drop ruptures cell walls	Higher yield, better gel properties, energy-efficient	High equipment cost, process needs optimization (Rupert et al., 2022)

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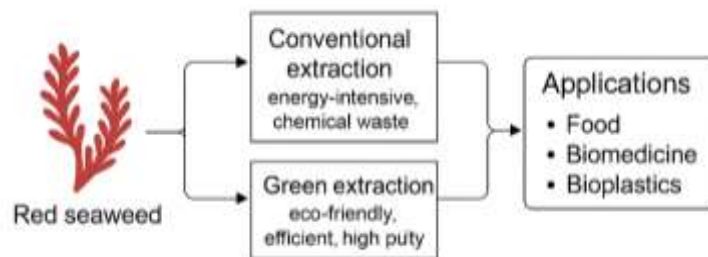
1448 **Table 4.** Comparison of Drying Methods for Carrageenan Processing: Benefits and Limitations  
1449  
1450

<b>Drying Method</b>	<b>Pros</b>	<b>Cons</b>
Spray Drying	Fast, uniform drying	High energy cost
Freeze Drying	Preserves bioactivity	Expensive, slow
Sun Drying	Low cost	Microbial contamination risk

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1452 Figure 1. Carrageenan production from red seaweed and its significance in sustainable applications.

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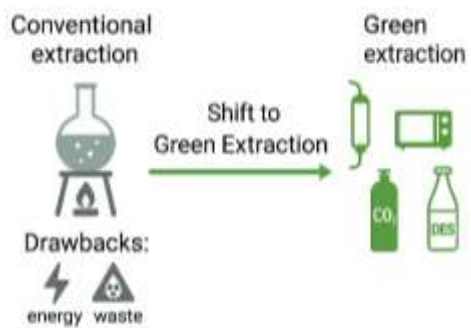


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1456 Figure 2. Transition from conventional to green extraction techniques highlighting sustainability benefits.

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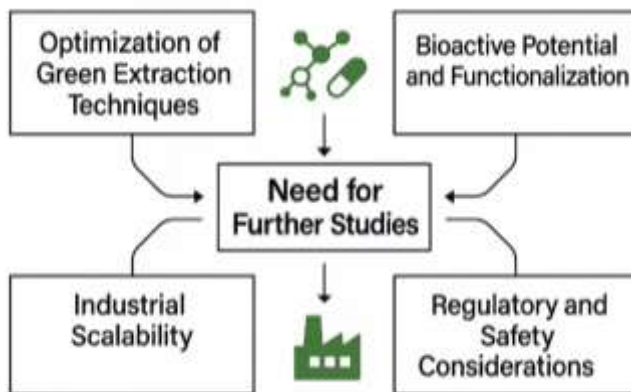


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1460 Figure 3. Key research gaps in carrageenan extraction.

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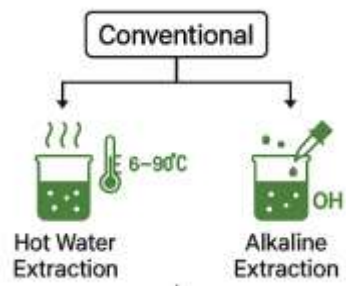


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1464 Figure 4. Overview of conventional carrageenan extraction techniques.

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1468 Figure 5. Green and Advanced Extraction Techniques.

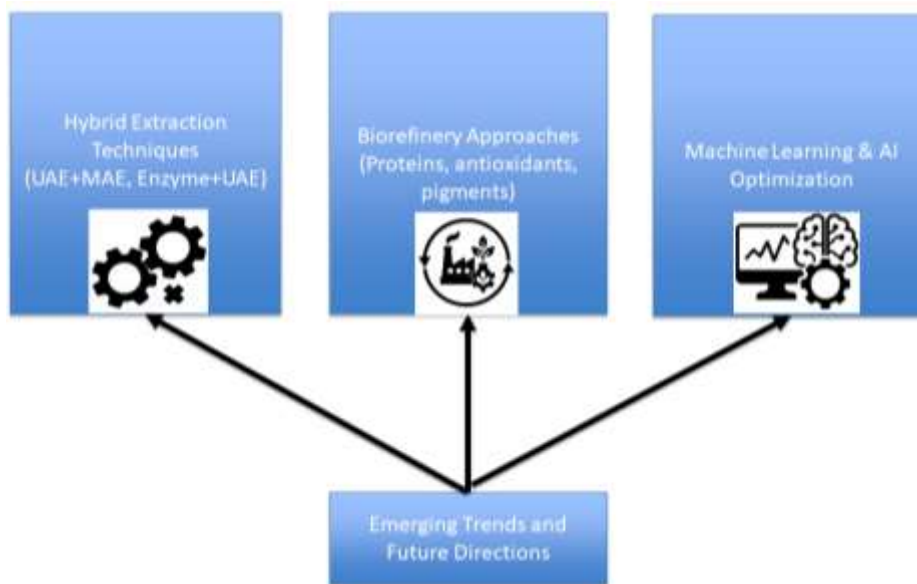
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1472 Figure 6. Emerging Trends and Future Directions.

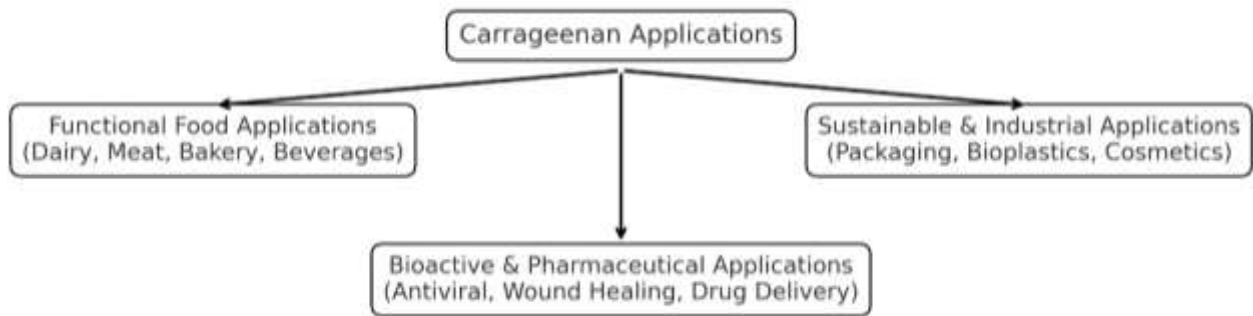


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1475 Figure 7. Applications of Carrageenan.

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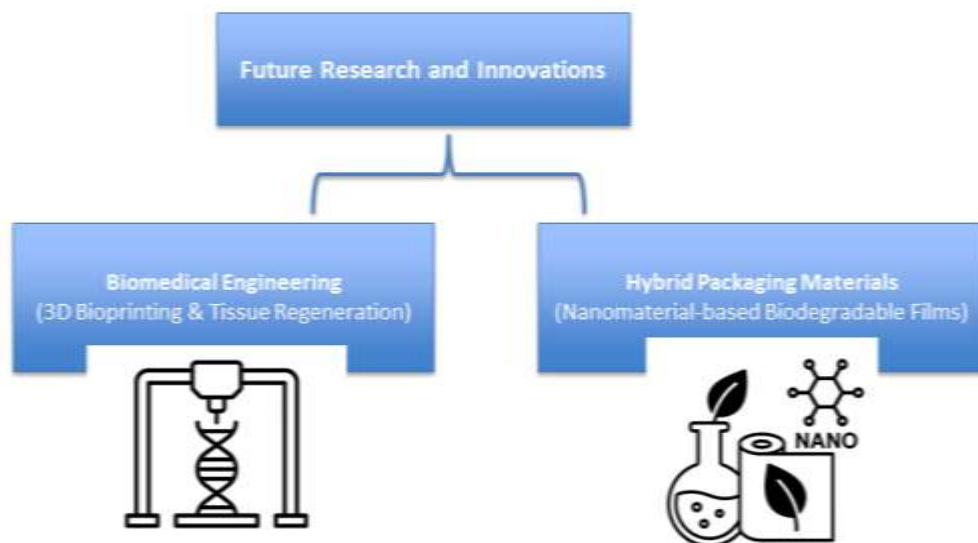


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1479 Figure 8. Future Research and Innovations in Carrageenan Applications.

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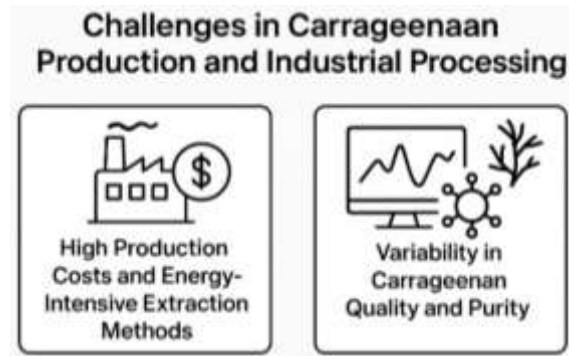


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1483 Figure 9. Key Challenges in Carrageenan Production: Energy Demands, Quality Variability, and  
1484 Technological Limitations

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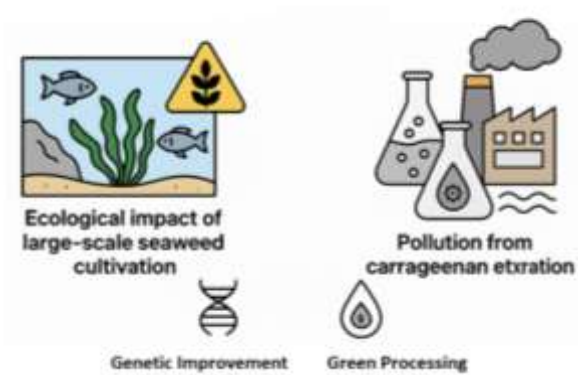
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1488 Figure 10. Environmental and Sustainability Challenges

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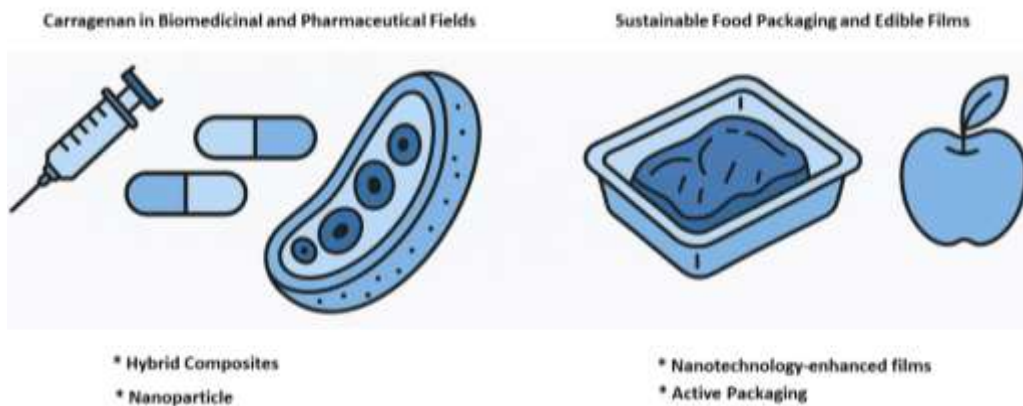
### Environmental and Sustainability Challenges



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1492 Figure 11. Expanding Functionalization and Applications of Carrageenan.



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8<sup>th</sup> December 2025

Authors: Agustriyanto R, Fatmawati A, Setyoprato P, Sapei L

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Yang bertanda tangan di bawah ini :

Nama : Dr.rer.nat. LANNY SAPEI S.T, M.Sc.

Alamat : -

berdasarkan Surat Keputusan Nomor 0419/C3/DT.05.00/2025 dan Perjanjian / Kontrak Nomor 128/C3/DT.05.00/PL/2025 mendapatkan Anggaran Penelitian Aplikasi Karagenan sebagai Ko-agen Penyalut dalam Proses Enkapsulasi Minyak Kelapa Murni menggunakan Pengeringan Semprot Sebesar Rp. 119.950.000

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Realisasi ( 100 % )			Rp. 119.950.000

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Demikian surat pernyataan ini dibuat dengan sebenarnya.



Surabaya, 12-12-2025, Ketua

Dr.rer.nat. LANNY SAPEI S.T, M.Sc.

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