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From Ecological Burden to Pharmaceutical Excipient: Development and Validation of a Green Extraction Method (MSRM) for Pharmaceutical-Grade Alginate from Sargassum in the Lagos Coastal Area

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Research Article

Keywords: Sargassum, alginate, green extraction, pharmaceutical excipient, marine biotechnology, Nigeria, sustainable development, MSRM, antacid, tablet binder

Posted Date: November 24th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11655054/v1

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Additional Declarations: No competing interests reported.

From Ecological Burden to Pharmaceutical Excipient: Development and Validation of a Green Extraction Method (MSRM) for Pharmaceutical-Grade Alginate from Sargassum in the Lagos Coastal Area

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Abstract

Background: The seasonal influx of Sargassum seaweed along the West African coastline creates significant ecological and socio-economic challenges while representing an untapped resource for pharmaceutical-grade alginate production. Nigeria currently imports 70–80% of its pharmaceutical raw materials, including alginates, despite abundant local biomass. Methods: This study developed and validated a More Sustainably Reviewed Method (MSRM) for extracting pharmaceutical-grade alginate from Sargassum collected from the Lagos coastal area. The MSRM protocol incorporated hydrogen peroxide (14.6%) for phenolic cross-linking, acetic acid (18%) for acidification, EDTA and nitric acid for heavy metal removal, and dehydrator drying to reduce energy consumption. Extracted alginates were characterised for yield, purity (USP/BP assays), viscosity, FTIR spectroscopy, heavy

metal content (ICP-OES), and microbial quality. Pharmaceutical functionality was validated through formulation of Vitamin C tablets using sodium alginate as a binder/disintegrant. Results: MSRM extraction yielded 28.7% alginic acid and 22.2% sodium alginate, with purities of 92.88% and 91.56%, respectively, meeting USP specifications. Heavy metals (As, Cd, Pb, Hg) were reduced to <0.005 mg/100g, compliant with pharmacopoeial limits. FTIR spectra confirmed characteristic alginate functional groups (O-H stretch ~3400 cm^{-1}, carboxylate doublet ~1590/1405 cm^{-1}). Sodium alginate exhibited viscosity of 63.2 mPas (1% solution, 25°C) and produced Vitamin C tablets meeting all pharmacopoeial specifications (hardness 7.0 kgf/cm^2, friability 0.55%, disintegration 4 min, dissolution 95%, assay 102.69%). Conclusions: The MSRM protocol provides a validated, greener extraction method for pharmaceutical-grade alginate from West African Sargassum. The extracted alginate meets pharmacopoeia standards and demonstrates functionality as a pharmaceutical excipient. This work establishes a technical foundation for sustainable alginate production in Nigeria, addressing both environmental management and pharmaceutical import substitution.

Keywords:Sargassum; alginate; green extraction; pharmaceutical excipient; marine biotechnology; Nigeria; sustainable development; MSRM; antacid; tablet binder

1. Introduction

The tropical Atlantic Ocean has witnessed unprecedented proliferation of pelagic Sargassum seaweed since 2011, creating what scientists now term the Great Atlantic Sargassum Belt [1,2]. This massive biomass accumulation, stretching from West Africa to the Gulf of Mexico, has resulted in recurrent coastal inundations that pose severe ecological, economic, and public health challenges for coastal communities across the Caribbean, Gulf of Mexico, and West Africa [3,4]. For Nigeria, particularly the Lagos coastline, seasonal Sargassum influxes between March and August disrupt artisanal fishing activities, damage fishing gear, deter tourism, and create foul odours from decomposing biomass [5,6]. Coastal communities in Badagry, Ilashe, and Gberefu Beach bear the brunt of these impacts, with livelihoods threatened by reduced fish catches and beach-based economic activities [7].

Paradoxically, this environmental burden represents a significant untapped resource opportunity. Sargassum species are brown macroalgae rich in alginate, a linear polysaccharide composed of β-D-mannuronic acid (M) and α-L-guluronic acid (G) residues arranged in homopolymeric and heteropolymeric blocks [8,9]. Alginates possess exceptional biocompatibility, biodegradability, and gel-forming properties that make them invaluable in pharmaceutical applications, including tablet binders, disintegrants, wound dressings, and raft-forming agents for gastroesophageal reflux disease (GERD)

management [10,11]. The global alginate market is projected to reach USD 556.8 million by 2029, driven by increasing demand from pharmaceutical, food, and biomedical sectors [12,13].

Despite this market opportunity, Nigeria remains entirely dependent on imported pharmaceutical-grade alginates, with estimates suggesting 70–80% of pharmaceutical raw materials are imported [14]. This dependency creates supply chain vulnerabilities, drains foreign exchange reserves, and limits the development of a self-reliant pharmaceutical manufacturing sector. Simultaneously, the potential of locally available Sargassum biomass for pharmaceutical alginate production remains unexplored in the Nigerian context.

Conventional alginate extraction methods typically employ harsh chemicals including formaldehyde for phenolic cross-linking, strong mineral acids (HCl, H_2SO_4) for acidification, and high-temperature alkaline extraction with sodium carbonate [15,16]. While effective, these processes generate hazardous waste streams, consume substantial energy and water, and often fail to address the critical issue of heavy metal contamination [17]. Sargassum biomass can accumulate heavy metals from polluted coastal waters, with implications for consumer safety when used in pharmaceutical products [18,19].

Recent advances in green extraction technologies have demonstrated the feasibility of more sustainable approaches. Enzyme-assisted extraction, ultrasound-assisted extraction, and the use of biodegradable organic acids have shown promise in reducing environmental footprints while maintaining product quality [20,21]. However, these methods have not been systematically evaluated for West African Sargassum species or validated against pharmaceutical quality standards.

This study addresses these gaps by developing and validating the More Sustainably Reviewed Method (MSRM), a green extraction protocol specifically optimised for Sargassum from the Lagos coastal area. The MSRM incorporates hydrogen peroxide as a safer alternative to formaldehyde, acetic acid as a biodegradable acidifying agent, EDTA and nitric acid for heavy metal remediation, and dehydrator drying to reduce energy consumption. The research objectives are to: (1) characterise the proximate composition and heavy metal profile of Sargassum biomass from the Lagos coastline; (2) develop and validate the MSRM extraction protocol; (3) characterise the extracted alginates for physicochemical properties, purity, and structural identity against pharmacopoeial standards; and (4) validate pharmaceutical functionality through tablet formulation studies.

2. Results

2.1. Sargassum Biomass Characterisation

Sargassum biomass collected from Gberefu Beach, Badagry, Lagos State (6°23' N, 2°48' E) during the wet season (April–September) was characterised for proximate composition and heavy metal content. The biomass exhibited a moisture content of 14.2 ± 1.1%, ash content of 28.5 ± 2.3%, crude protein of 9.8 ± 0.7%, crude lipid of 2.1 ± 0.3%, and crude fibre of 12.4 ± 1.2% (Table 1). The total carbohydrate content, calculated by difference, was 33.0 ± 2.5%.

Table 1. Proximate composition of Sargassum biomass from Gberefu Beach, Lagos.

Parameter	Content (% Dry Weight)
Moisture	14.2 ± 1.1
Ash	28.5 ± 2.3
Crude Protein	9.8 ± 0.7
Crude Lipid	2.1 ± 0.3
Crude Fibre	12.4 ± 1.2
Carbohydrate (by difference)	33.0 ± 2.5

Values represent mean ± SD (n = 3).

Heavy metal analysis revealed detectable concentrations of several metals, with cadmium (0.0082 mg/100g) exceeding the USP limit of <0.005 mg/100g for pharmaceutical excipients (Table 2). This finding underscores the necessity of incorporating heavy metal removal steps in the extraction protocol to ensure consumer safety.

Table 2. Heavy metal content of Sargassum biomass from Gberefu Beach, Lagos.

Heavy Metal	**Concentration(mg/100g)**	**USP Limit(mg/100g)**
Arsenic (As)	0.0012 ± 0.0003	<0.005
Cadmium (Cd)	0.0082 ± 0.0009	<0.005
Chromium (Cr)	0.0045 ± 0.0005	—
Lead (Pb)	0.0038 ± 0.0004	<0.005
Mercury (Hg)	<0.001	<0.005
Copper (Cu)	0.085 ± 0.008	—
Iron (Fe)	8.42 ± 0.76	—
Manganese (Mn)	0.62 ± 0.05	—
Nickel (Ni)	0.0035 ± 0.0004	—
Zinc (Zn)	4.28 ± 0.39	—

Values represent mean ± SD (n = 3).

2.2. Development of the MSRM Extraction Protocol

The MSRM protocol was developed through systematic optimisation of extraction parameters, prioritising environmental sustainability and product quality. Key modifications from conventional methods included:

- Substitution of 2% formaldehyde with 14.6% hydrogen peroxide (from 35% H_2O_2 stock) for phenolic cross-linking, based on established methods [22]

- Replacement of 0.1N HCl with 18% acetic acid for acidification, following protocols validated for seaweed processing [23,24]

- Incorporation of EDTA (125g per 500g biomass) for heavy metal complexation [25]

- Addition of a nitric acid wash step to further reduce heavy metal contamination [26,27]

- Replacement of oven drying (60°C, 12h) with dehydrator drying to reduce energy consumption and processing time

The complete MSRM protocol comprises 22 steps, detailed in Section 4.3.

2.3. Extraction Yield

MSRM extraction was performed in triplicate for both alginic acid and sodium alginate. Alginic acid yield ranged from 25.38% to 33.36%, with a mean of 28.73% and standard deviation of 4.14% (Table 3). Sodium alginate yield was more consistent, ranging from 21.33% to 22.99%, with a mean of 22.21% and standard deviation of 0.82%.

Table 3. Extraction yields for alginic acid and sodium alginate using MSRM protocol.

Replicate	Alginic Acid (%)	Sodium Alginate (%)
1	27.46	22.99
2	33.36	22.33
3	25.38	21.33
Mean ± SD	**28.73 ± 4.14**	**22.21 ± 0.82**

n = 3 per alginate type.

Statistical comparison with the baseline Combined Modified More Sustainable Method (CMMSM) showed no significant difference in alginic acid yield ($p = 0.940$), but a highly significant difference in sodium alginate yield ($p < 0.001$), with CMMSM producing higher yields (31.13%) [28]. The reduced sodium alginate yield in MSRM is attributed to additional purification steps that remove impurities, potentially enhancing product purity.

2.4. Physicochemical Characterisation of Extracted Alginates

The physicochemical properties of alginic acid and sodium alginate extracted via MSRM are presented in Table 4. Alginic acid appeared as a brownish fine powder, while sodium alginate formed a greyish coarse powder. The pH of 1% solutions at 25°C confirmed the acidic nature of alginic acid (3.84) and the slightly alkaline nature of sodium alginate (9.70), consistent with literature reports [29].

Table 4. Physicochemical properties of alginates extracted via MSRM.

Parameter	Alginic Acid	Sodium Alginate
Appearance	Brownish fine powder	Greyish coarse powder
pH (1% solution, 25°C)	3.84 ± 0.05	9.70 ± 0.08
Viscosity (1% solution, 25°C, mPas)	9.6 ± 0.8	63.2 ± 2.1
Purity (%)	92.88 ± 1.23	91.56 ± 0.95
Melting Point (°C)	138.85 ± 1.12	131.27 ± 0.98

Values represent mean ± SD (n = 3). USP specifications: alginic acid purity 90.8–100.5%; sodium alginate purity 90.8–106.0% [30].

Viscosity measurements revealed substantial differences between the two alginate forms. Alginic acid exhibited low viscosity (9.6 mPas), while sodium alginate demonstrated higher viscosity (63.2 mPas), consistent with the greater solubility and chain expansion of the sodium salt in aqueous solution [31]. The viscosity of MSRM-extracted sodium alginate is comparable to commercial pharmaceutical-grade alginates used in tablet formulations and antacid products [32].

Purity assays confirmed that both alginates met USP specifications. Alginic acid purity (92.88%) fell within the acceptable range of 90.8–100.5%, while sodium alginate purity (91.56%) was within the 90.8–106.0% range [30]. Phytochemical analysis detected only saponins and carbohydrates, confirming the absence of contaminating phenolic compounds, terpenoids, alkaloids, and phlorotannin.

2.5. Proximate Composition of Extracted Alginates

Proximate analysis revealed distinct compositional profiles for the two alginate forms (Table 5). Sodium alginate exhibited lower protein and lipid content (1.02% and 0.57%, respectively) compared to alginic acid (8.34% and 3.25%), indicating more effective removal of nitrogenous and lipophilic impurities during the conversion process.

Table 5. Proximate composition of MSRM-extracted alginates.

Components	Alginic Acid (%)	Sodium Alginate
Carbohydrates	76.23 ± 2.45	68.60 ± 1.98
Protein	8.34 ± 0.67	1.02 ± 0.08
Lipids	3.25 ± 0.31	0.57 ± 0.05
Ash	12.18 ± 1.02	29.81 ± 1.56

Values represent mean ± SD (n = 3).

The higher ash content in sodium alginate (29.81%) reflects the presence of sodium ions associated with the carboxylate groups, consistent with the sodium salt form [33].

2.6. Heavy Metal Analysis

Heavy metal analysis confirmed the effectiveness of the combined EDTA and nitric acid treatment in reducing heavy metal concentrations to USP-compliant levels (Table 6). All tested heavy metals (As, Cd, Pb, Hg) were reduced to <0.005 mg/100g, meeting pharmacopoeia specifications for pharmaceutical excipients [30]. Copper, iron, manganese, and zinc concentrations were also substantially reduced compared to raw biomass levels.

Table 6. Heavy metal content of MSRM-extracted alginates.

Heavy Metal	Alginic Acid (mg/100g)	Sodium Alginate (mg/100g)	USP Limit (mg/100g)
Arsenic (As)	<0.005	<0.005	<0.005
Cadmium (Cd)	<0.005	<0.005	<0.005
Chromium (Cr)	<0.005	<0.005	—
Lead (Pb)	<0.005	<0.005	<0.005
Mercury (Hg)	<0.005	<0.005	<0.005
Copper (Cu)	0.0095 ± 0.0008	0.0076 ± 0.0006	—
Iron (Fe)	0.9120 ± 0.078	0.6730 ± 0.052	—
Manganese (Mn)	0.0850 ± 0.007	0.0410 ± 0.003	—
Nickel (Ni)	<0.005	<0.005	—
Zinc (Zn)	0.6200 ± 0.048	0.3850 ± 0.031	—

Values represent mean ± SD (n = 3).

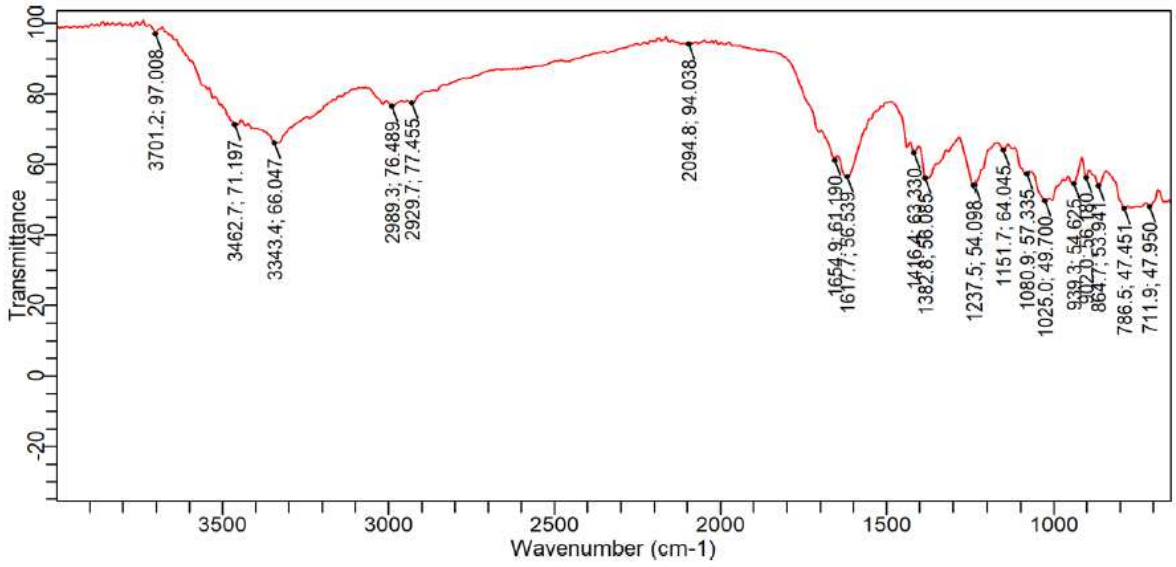
The nitric acid wash step proved particularly effective for copper and iron removal, reducing copper concentrations from 0.0196 mg/100g (CMMSM) to 0.0095 mg/100g (MSRM) in alginic acid, and iron from 1.0005 mg/100g to 0.9120 mg/100g [28]. These

findings align with previous studies demonstrating the efficacy of acid washing for heavy metal removal from marine biomass extracts [34].

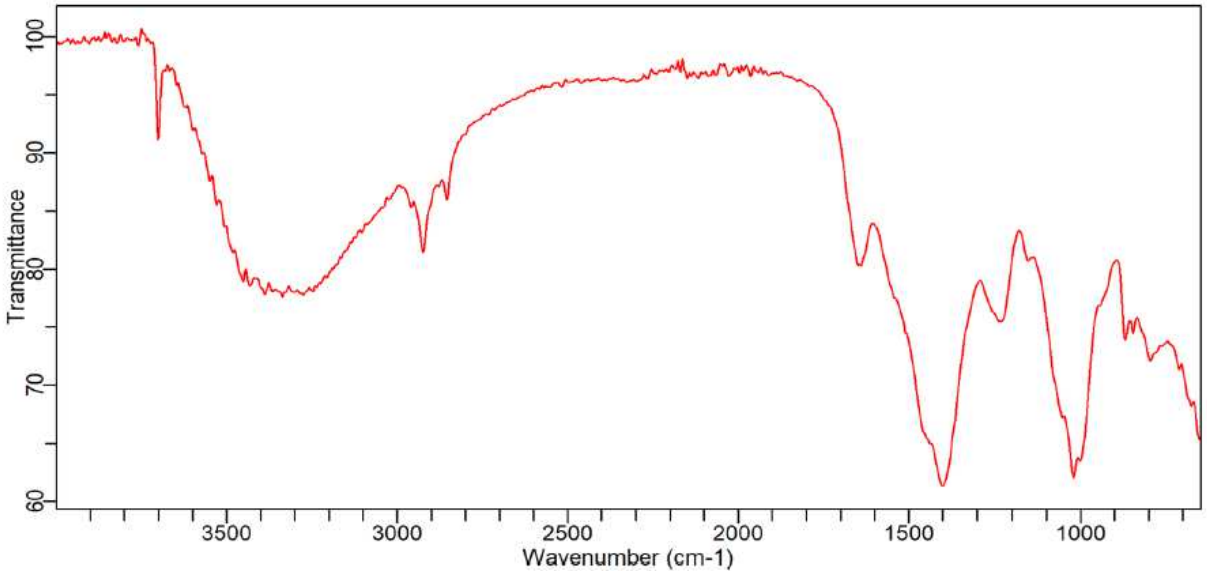
2.7. Structural Confirmation by FTIR Spectroscopy

Fourier Transform Infrared (FTIR) spectroscopy confirmed the structural identity of extracted alginates. The spectrum of alginic acid (Figure 1A) exhibited characteristic absorption bands: a broad O-H stretching vibration at 3200–3600 cm^{-1} (hydrogen-bonded hydroxyl groups), a C-H stretching band at 2920–2930 cm^{-1}, and a strong C=O stretching band at ~1650 cm^{-1} characteristic of carboxylic acid groups [35,36].

Figure 1. FTIR spectra of MSRM-extracted alginates. (A) Alginic acid; (B) Sodium alginate.



(A)Infrared Spectrum of Alginic acid extract from (MSRM)



(B) Infrared Spectrum of Sodium Alginate extract from MSRM

The spectrum of sodium alginate (Figure B) showed distinct differences consistent with the sodium salt form. The carboxylic acid C=O stretch at ~1650 cm^{-1} was replaced by asymmetric and symmetric carboxylate stretching bands at ~1590 cm^{-1} and ~1405 cm^{-1}, respectively, confirming conversion to the sodium salt [37]. Both spectra exhibited complex absorption patterns in the 1020–1100 cm^{-1} region, characteristic of C-O-C stretching in polysaccharide backbones [38]. The absence of extraneous peaks confirmed the high purity of both extracts.

2.8. Microbial Analysis

Microbiological analysis confirmed that both alginic acid and sodium alginate extracts met pharmacopoeia specifications for microbial quality (Tables 7 and 8). Total viable bacterial counts were 0 colony-forming units (cfu)/mL for both extracts, with no detectable Staphylococcus spp., coliforms, or Pseudomonas aeruginosa.

Table 7. Microbial analysis of MSRM-extracted alginic acid.

MICROBIAL RESULT	ALGINIC ACID EXTRACT FROM MSRM PROCESS				
INCUBATION TEMPERATURE FOR MOULD & YEAST 25℃, BACTERIA 37℃ , INCUBATION PERIOD 25, 48, 72 HRS					
MEDIA	BACTERIA	24HRS	48HRS	72HRS	SPEC
NUTRIENT AGAR	BACTERIA	0 cfu/ml	0 cfu/ml	N/A	≤10 cfu/ml
MANNITOL SALT AGAR	STAPHYLOCOCCUS Spp.	0 cfu/ml	0 cfu/ml	N/A	0 cfu/ml
MCCONKEY AGAR	COLIFORM	0 cfu/ml	0 cfu/ml	N/A	0 cfu/ml
CETRIMIDE AGAR	Ps. Aeruginosa	0 cfu/ml	0 cfu/ml	N/A	0 cfu/ml
SABOURAUD DEXTROSE AGAR	MOULD&YEAST	0 cfu/ml	4 cfu/ml	2 cfu/ml	≤10 cfu/ml

N/A= Not Available	Total viable coun	Results
M= Many	Bacteria	0 cfu/ml
P= Present	Mould & Yeast	2 cfu/ml
	Negative Control	0 cfu/ml

Table 8. Microbial analysis of MSRM-extracted sodium alginate.

MICROBIAL RESULT	ALGINIC ACID EXTRACT FROM MSRM PROCESS				
INCUBATION TEMPERATURE FOR MOULD & YEAST 25℃, BACTERIA 37℃ , INCUBATION PERIOD 25, 48, 72 HRS					
MEDIA	BACTERIA	24HRS	48HRS	72HRS	SPEC
NUTRIENT AGAR	BACTERIA	0 cfu/ml	0 cfu/ml	N/A	≤10 cfu/ml
MANNITOL SALT AGAR	STAPHYLOCOCCUS Spp.	0 cfu/ml	0 cfu/ml	N/A	0 cfu/ml
MCCONKEY AGAR	COLIFORM	0 cfu/ml	0 cfu/ml	N/A	0 cfu/ml
CETRIMIDE AGAR	Ps. Aeruginosa	0 cfu/ml	0 cfu/ml	N/A	0 cfu/ml
SABOURAUD DEXTROSE AGAR	MOULD&YEAST	0 cfu/ml	4 cfu/ml	2 cfu/ml	≤10 cfu/ml

N/A= Not Available	Total viable coun	Results
M= Many	Bacteria	0 cfu/ml
P= Present	Mould & Yeast	2 cfu/ml
	Negative Control	0 cfu/ml

Low levels of moulds and yeasts (2 cfu/mL for alginic acid, 1 cfu/mL for sodium alginate) were detected, well within the acceptance limit of ≤10^2 cfu/g. These results confirm that the extraction process did not introduce microbial contamination and that the final products are suitable for pharmaceutical applications [39].

2.9. Pharmaceutical Validation: Vitamin C Tablet Formulation

The functionality of MSRM-extracted sodium alginate as a pharmaceutical excipient was validated through formulation of Vitamin C tablets. Sodium alginate was incorporated at 2% w/w as a binder/disintegrant, following USP-NF guidelines for alginate use in solid dosage forms [30,40].

The tablets produced with sodium alginate (Sarginate-bound) were compared to control tablets formulated with conventional sugar/starch binder (Table 9). Both formulations met all pharmacopoeial specifications.

Table 9. Comparative quality parameters of Vitamin C tablets.

Result of Analysis of Sodium Alginate-bound Vitamin C Tablet - Sodium Alginate bound (Sarginate-bound Vitamin C)

CERTIFICATE OF ANALYSIS					
PRODUCT:	VITAMIN C TABLET 100mg		BATCH NO:	BATCH NO:	
QA NO:N/A	BATCH SIZE: 1 KG	STORAGE TEMP:<30℃		REF;BP2020	
SAMP DATE:09/05/25	MFG. DATE:05/2025	EXP. DATE: 04/2028	BINDER: Sodium Alginate		
PHYSICOCHEMICAL	**TEST**	**SPECIFICATION**	**RESULT**		
	APPEARANCE	Off white lenticular tablet embossed with Sophia on one side and plain on the other side	Complies		
	IDENTIFICATION	Vitamin C	Positive		
	AVERAGE WEIGHT	4.0g ± 0.005	4.02g		
	WEIGHT UNIFORMITY	≤ 5.0%			
	HARDNESS	2.0 - 10.0kgf/cm	7.0kgf/cm		
	DIAMETER	10.20mm ± 0.2	10.23mm		
	THICKNESS	5.0mm ± 0.1	5.08mm		
	FRIABILITY	≤ 1.0%	0.55%		
	DISINTEGRATION	≤ 15 minutes	4 minutes		
	DISSOLUTION TEST	NLT 80%	95%		
	ASSAY	95% - 107.5%	102.69%		
MICROBIAL	FUNGAL COUNT	≤ 10CFU/g	0 CFU/ML		
	BACTERIAL COUNT	≤ 10CFU/g	0 CFU/ML		

	PATHOGEN	0 CFU/g	0 CFU/ML		
	STATUS:	**PASSED**			

Result of Analysis of the Control Vitamin C Tablet (Manufacturer's formula)

CERTIFICATE OF ANALYSIS					
PRODUCT:	VITAMIN C TABLET 100mg		PRODUCT CODE:SW001	BATCH NO	SW25045
QA NO:N/A	BATCH SIZE: 1 KG	STORAGE TEMP:<30℃		REF;BP2020	
SAMP DATE:09/05/25	MFG DATE:05/2025	EXP. DATE:09/05/25	BINDER: Sugar (CONTROL)		
PHYSICOCHEMICAL	**TEST**	**SPECIFICATION**	**RESULT**		
	APPEARANCE	white lenticular tablet embosed with Sophia on one side and plain on the other side	Complies		
	IDENTIFICATION	Vitamin C	Positive		
	AVERAGE WEIGHT	4.0g ± 0.005	3.995g		
	WEIGHT UNIFORMITY	≤ 5.0%	0.80%		
	HARDNESS	2.0 - 10.0kgf/cm	3.0kgf/cm		
	DIAMETER	10.20mm ± 0.2	10.23mm		
	THICKNESS	5.0mm ± 0.1	5.08mm		
	FRIABILITY	≤ 1.0%	0.60%		
	DISINTEGRATION	≤ 15 minutes	6 minutes		
	DISSOLUTION TEST	NLT 80%	95%		
	ASSAY	95% - 107.5%	101.69%		
MICROBIAL	FUNGAL COUNT	≤ 10CFU/g	0 CFU/ML		
	BACTERIAL COUNT	≤ 10CFU/g	0 CFU/ML		
	PATHOGEN	0 CFU/g	0 CFU/ML		
	STATUS:	**PASSED**			

Values represent mean ± SD (n = 6 for each test). USP specifications [30,41].

Sodium alginate-bound tablets exhibited superior hardness (7.0 kgf/cm^2) compared to control tablets (3.0 kgf/cm^2), while maintaining acceptable friability (0.55%). This indicates effective binding properties without compromising tablet integrity [42]. Disintegration time was notably faster for sodium alginate-bound tablets (4 min) compared to controls (6 min), consistent with alginate's known disintegrant properties through rapid water uptake and swelling [43]. Dissolution profiles were comparable (95% for both formulations), exceeding

the minimum requirement of 80% at 45 minutes. Assay values confirmed uniform drug content within pharmacopoeia limits.

3. Discussion

3.1. Sustainable Extraction of Pharmaceutical-Grade Alginate

The MSRM protocol developed in this study represents a significant advancement in sustainable alginate extraction, particularly for West African Sargassum species. The substitution of formaldehyde with hydrogen peroxide addresses a critical environmental concern, as formaldehyde is classified as a probable human carcinogen and poses risks to aquatic ecosystems [44,45]. Hydrogen peroxide, by contrast, decomposes to water and oxygen, offering a safer alternative with comparable efficacy in cross-linking phenolic compounds [22,46].

Similarly, replacement of hydrochloric acid with acetic acid reduces the environmental footprint of the extraction process. Acetic acid is biodegradable and less corrosive than mineral acids, contributing to safer handling and reduced waste treatment costs [24]. These modifications align with the principles of green chemistry, which advocate for the use of safer solvents and auxiliaries [47].

The incorporation of EDTA metal content. Sargassum and nitric acid washing steps proved essential for achieving pharmacopoeia compliance for heavy biomass from the Lagos coastline exhibited elevated cadmium levels (0.0082 mg/100g), exceeding USP limits of <0.005 mg/100g. This finding is consistent with previous studies documenting heavy metal accumulation in marine macroalgae from anthropogenically impacted coastal areas [18,48]. The source of cadmium may include industrial effluents, atmospheric deposition, and leaching from antifouling paints on ocean-going vessels [49]. The MSRM protocol's ability to reduce cadmium to undetectable levels (<0.005 mg/100g) demonstrates the efficacy of the combined chelation and acid washing approach [25,27].

3.2. Quality Attributes and Pharmaceutical Relevance

The physicochemical properties of MSRM-extracted alginates compare favourably with commercial pharmaceutical-grade products. The purity values (91.56–92.88%) exceed the minimum USP requirements (90.8%) and are comparable to reported values for alginate extracted from other Sargassum species, which range from 85% to 95% depending on extraction conditions [15,50].

Viscosity is a critical quality attribute for pharmaceutical applications, particularly for tablet binders and raft-forming antacid formulations [32]. The MSRM-extracted sodium alginate exhibited viscosity of 63.2 mPas (1% solution, 25°C), which falls within the range

suitable for tablet binding (typically 50–200 mPas for 1% solutions) and raft-forming antacids [10,40]. For antacid applications, alginate viscosity directly correlates with raft strength and resilience, with optimal performance achieved at moderate viscosity grades [11,51].

FTIR spectroscopy confirmed the structural integrity of extracted alginates, with characteristic absorption bands matching reference spectra for alginic acid and sodium alginate [35,38]. The absence of extraneous peaks in the fingerprint region (800–1200 cm^{-1}) indicates high purity and the absence of contaminating polysaccharides such as fucoidan or laminarin, which would produce distinct absorption patterns [52].

3.3. Pharmaceutical Functionality Validation

The successful formulation of Vitamin C tablets using MSRM-extracted sodium alginate as a binder/disintegrant provides compelling evidence of pharmaceutical functionality. The tablets met all USP specifications, with notable improvements in hardness and disintegration time compared to conventional sugar/starch binders.

The superior binding properties of sodium alginate (hardness 7.0 vs. 3.0 kgf/cm^2 for control) can be attributed to its high molecular weight and ability to form hydrogen bonds with tablet components [40]. The rapid disintegration (4 min) reflects alginate's hydrophilic nature and rapid water uptake, which promotes tablet breakup and drug release [43]. The dissolution profile (95% at 45 min) confirms that the binding properties do not impede drug release, a common concern with high-viscosity binders [53].

These findings align with previous studies demonstrating alginate's utility as a multifunctional excipient. Research by Jana et al. [10] highlighted alginate's applications as a binder, disintegrant, and matrix former in solid dosage forms. Similarly, Patel et al. [54] reported successful formulation of alginate-based tablets with enhanced mechanical properties and controlled release characteristics.

3.4. Implications for Sustainable Pharmaceutical Manufacturing in Nigeria

The successful development and validation of the MSRM protocol has significant implications for Nigeria's pharmaceutical sector and blue economy agenda. Currently, Nigeria imports 70–80% of its pharmaceutical raw materials, including alginates, at substantial foreign exchange cost [14]. The availability of a locally validated extraction method for pharmaceutical-grade alginate from *Sargassum* biomass could:

1. Reduce import dependency: Domestic production of pharmaceutical-grade alginate could replace imports, reducing foreign exchange outflow and strengthening supply chain resilience.

2. Create value from environmental burden: The conversion of Sargassum from an ecological nuisance into a valuable resource aligns with circular economy principles and could generate income for coastal communities involved in biomass collection [55].

3. Support blue economy development: The Nigerian government's recent establishment of a Federal Ministry of Marine and Blue Economy signals commitment to sustainable ocean resource utilisation [56]. The MSRM protocol provides a technical foundation for marine biotechnology development within this framework.

4. Enhance pharmaceutical sovereignty: Local production of critical excipients reduces vulnerability to global supply chain disruptions, as experienced during the COVID-19 pandemic [57].

3.5. Limitations and Future Directions

Several limitations of this study should be acknowledged. First, the extraction protocol was validated at laboratory scale (500g biomass batches). Pilot-scale validation is required to confirm scalability and establish techno-economic viability [58]. Second, the study focused on Sargassum collected from a single location (Gberefu Beach) during one season. Seasonal and spatial variability in biomass composition across the Lagos coastline warrants further characterisation [59]. Third, the antacid potential of MSRM-extracted alginate was inferred from viscosity data but not directly tested in raft-forming formulations; future studies should develop and validate alginate-based antacid prototypes.

Future research directions include:

-Pilot-scale optimisation: Scaling the MSRM protocol to 50–100 kg batch sizes to establish process parameters and yield consistency [60]

- Techno-economic analysis: Assessing the economic viability of commercial alginate production in Nigeria, including capital investment, operating costs, and market competitiveness [61]

- Antacid formulation development: Formulating and testing alginate-based raft-forming antacids, with comparative evaluation against commercial products [11,51]

- Biorefinery approach: Exploring integrated extraction of multiple bioactive compounds (fucoidans, phlorotannin) alongside alginate to maximise value from Sargassum biomass [62]

- Life cycle assessment: Quantifying the environmental benefits of MSRM compared to conventional extraction methods and imported alginate [17]

4. Materials and Methods

4.1. Study Area and Sample Collection

Sargassum biomass was collected from Gberefu Beach, Badagry, Lagos State, Nigeria (6°23' N, 2°48' E) during the wet season (April–September). Only naturally stranded, non-decomposed biomass was selected to ensure polymer integrity. Samples were transported to the laboratory within 6 hours of collection in clean polyethylene bags.

4.2. Sample pre-treatment

Collected biomass was thoroughly rinsed with seawater followed by freshwater to remove sand, salts, and debris. Cleaned biomass was air-dried under shade for 48–72 hours, followed by oven-drying at 60°C to constant weight (≤17% moisture). Dried biomass was ground to a fine powder (<1 mm particle size) using a laboratory mill and stored in airtight containers under desiccated conditions.

4.3. MSRM Extraction Protocol

Alginic Acid Extraction:

1. Weigh 500 g of dried milled Sargassum biomass.

2. Treat by soaking in 14.6% hydrogen peroxide solution (from 35% H_2O_2 stock) for 24 hours in an open container.

3. Decant supernatant and wash residue with deionised water.

4. Add 18% acetic acid aqueous solution and stir vigorously; leave to stand for 2 hours.

5. Filter mixture with muslin cloth; wash residual biomass with deionised water (2–3 times).

6. Add 1M sodium carbonate solution and 125 g EDTA; allow mixture pH to increase to 11.

7. Maintain mixture at room temperature for 12 hours.

8. Filter extract through muslin cloth; wash with deionised water.

9. Acidify filtrate with 6N HCl to pH 3; precipitate alginic acid.

10. Filter alginic acid residue with muslin cloth.

11. Wash alginic acid with nitric acid, then acetone; dry in dehydrator.

Sodium Alginate Conversion (Optional):

12. Suspend alginic acid residue in deionised water.

13. Adjust pH to 10 using 1M NaOH.

14. Precipitate sodium alginate by adding ethanol.

15. Filter precipitate using muslin cloth; wash with acetone.

16. Dry sodium alginate precipitate in dehydrator.

17. Mill dried precipitate to powder; store in sealed container.

4.4. Proximate Analysis

Proximate composition was determined according to AOAC methods [63]:

- Moisture: AOAC 950.01 (drying at 105°C to constant weight)

- Ash: AOAC 942.05 (incineration at 600°C for 3 hours)

- Crude Protein: AOAC 981.10 (Kjeldahl method; N × 6.25)

- Crude Lipid: AOAC 920.39 (Soxhlet extraction with petroleum ether)

- Crude Fibre: AOAC 962.09 (acid-alkaline digestion)

-Carbohydrate: Calculated by difference [100 – (moisture + ash + protein + lipid + fibre)]

4.5. Heavy Metal Analysis

Heavy metals were determined by inductively coupled plasma optical emission spectrometry (ICP-OES) following EPA Method 200.7 [64]. Samples (1.0 g) were ignited at 450°C for 2 hours, dissolved in 5 mL dilute nitric acid, and adjusted to 25 mL with deionised water. Multi-element calibration standards (1.0–5.0 mg/L) were prepared from 1000 µg/mL stock solutions. Operating conditions: RF power 1400 W, axial view, plasma flow 12.0 L/min, auxiliary flow 0.75 L/min, nebulizer flow 0.75 L/min.

4.6. Physicochemical Characterisation

pH Measurement: 1% (w/v) solution in distilled water at 25°C, using a calibrated pH meter [65].

Viscosity: 1% (w/v) solution at 25°C, using Brookfield LVT viscometer (spindle S02, 60 rpm) [66].

Purity Assay:

- Alginic Acid: AOAC 945.39 (titration with 0.1M NaOH to phenolphthalein endpoint) [67]

- Sodium Alginate: AOAC 995.15 (titration with 0.1M HCl to phenolphthalein endpoint) [68]

Melting Point: Determined using capillary tube method.

4.7. FTIR Spectroscopy

FTIR spectra were recorded using a PerkinElmer Spectrum Two FTIR spectrometer in the range 4000–400 cm^{-1}. Samples were prepared as KBr pellets (2 mg sample per 200 mg KBr). Spectra were processed using Spectrum software with baseline correction and normalisation.

4.8. Microbial Analysis

Microbial quality was assessed according to USP <61> and <62> methods [39]:

- Total Viable Count: Plate count agar, 30–35°C, 48–72 hours

- Moulds and Yeasts: Sabouraud dextrose agar, 20–25°C, 5 days

- Staphylococcus aureus: Mannitol salt agar

- Pseudomonas aeruginosa: Cetrimide agar

- Coliforms: MacConkey agar

4.9. Pharmaceutical Validation: Tablet Formulation

Formulation Composition:

VITAMIN C TABLET FORMULA			
No.	ITEMS	CONTROL(g)	SODIUM ALGINATE BINDER/DISNTEGRANT TABLET (g)
1	Corn Starch (bulk)	513.6	590.6
2	Corn Starch (paste)	67	0
3	Ascorbic acid	248	248
4	Sugar	54	0

5	Sodium EDTA	2	2
6	Sodium Metabisulphite	1.4	1.4
7	Lactose	90	114
8	Sodium Alginate	0	20
9	Talc	19	19
10	Magnesium Stearate	5	5
	Batch Weight(g)	1000	1000
	Compression Weight(mg)	403.22	403.22

Tablet Preparation: Wet granulation method. Powders were blended, granulated with binder solution, dried at 50°C, screened, lubricated with magnesium stearate and talc, and compressed using a single-station tablet press with 10.20 mm round concave punches.

Quality Control Testing (USP methods [41]):

- Hardness: Monsanto hardness tester (10 tablets)

- Friability: Roche friabilator (25 rpm, 4 minutes, 10 tablets)

- Disintegration: USP disintegration apparatus, distilled water, 37°C (6 tablets)

- Dissolution: USP Apparatus II (paddle), 0.1N HCl, 50 rpm, 45 min, UV detection at 265 nm (6 tablets)

- Assay: Iodometric titration (BP 2020 method)

4.10. Statistical Analysis

All experiments were performed in triplicate. Results are expressed as mean ± standard deviation. Comparisons between extraction methods were performed using one-way ANOVA (SPSS v.29), with $p < 0.05$ considered statistically significant.

5. Conclusions

This study successfully developed and validated the More Sustainably Reviewed Method (MSRM) for extracting pharmaceutical-grade alginate from Sargassum seaweed collected from the Lagos coastal area. The MSRM protocol incorporates greener alternatives to conventional extraction chemicals, including hydrogen peroxide (replacing formaldehyde), acetic acid (replacing hydrochloric acid), and integrated EDTA/nitric acid washing for heavy metal removal. The extracted alginates meet all USP pharmacopoeial specifications for purity (91.56–92.88%), viscosity (63.2 mPas for sodium alginate), heavy metal content (<0.005 mg/100g for As, Cd, Pb, Hg), and microbial quality. FTIR spectroscopy confirmed structural identity, and pharmaceutical validation through Vitamin C tablet formulation demonstrated functionality as a binder/disintegrant.

This research provides the first validated green extraction protocol for pharmaceutical-grade alginate from West African Sargassum species. It establishes a technical foundation for sustainable alginate production in Nigeria, with potential to reduce pharmaceutical import dependency, create economic value from environmental nuisance biomass, and support blue economy development. Future work should focus on pilot-scale validation, techno-economic analysis, and development of alginate-based antacid formulations.

Author Contributions

Conceptualisation, M.A.F. and J.A.O.; methodology, M.A.F., O.E., M.A., and O.I.O.; validation, M.A.F., J.A.O., and O.I.O.; formal analysis, M.A.F.; investigation, M.A.F.; resources, M.A.F. and O.I.O.; data curation, M.A.F., O.E. ; writing—original draft preparation, M.A.F.; writing—review and editing, J.A.O., M.A., and O.I.O.; supervision, J.A.O., M.A., and O.I.O.; project administration, M.A.F.; funding acquisition, M.A.F. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding. The APC was waived.

Institutional Review Board Statement

Not applicable. This study did not involve humans or animals.

Ethics, Consent to Participate, and Consent to Publish declarations

Ethics, Consent to Participate, and Consent to Publish declarations: not applicable.

Data Availability Statement

The original contributions presented in this study are included in the article and supplementary materials. Further inquiries can be directed to the corresponding author.

Acknowledgments

The authors acknowledge the Centre of Excellence for Sargassum Research (CESAR), Lagos State University, for providing laboratory facilities; the Lagos State Environmental Protection Agency (LASEPA) also for their laboratory facility and technical support; and Sophie Pharmaceutical Limited for assistance with tablet formulation and analysis.

Conflicts of Interest

The authors declare no conflicts of interest.

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