GMR
The Original

PHYSIOCHEMICAL, BIOCHEMICAL AND PHYTOCHEMICAL PROFILING OF SODIUM ALGINATE AND ITS ROLE AS A SEED COATING POLYMER TO ENHANCING SEED QUALITY IN OKRA (ABELMOSCHUS ESCULENTUS)

Pravina K[1], K. Sujatha*[2], V. Alex Albert[3], P. Meenakshisundaram[4], G. Anand[5], B. Venudevan[6], R. Amutha[7]

[1]Research Scholar, Department of Seed Science and Technology, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai-625 104, Tamil Nadu, India
[2]*Professor, Department of Seed Science and Technology, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai-625 104, Tamil Nadu, India
[3] Associate Professor, Department of Seed Science and Technology, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai-625 104, Tamil Nadu, India
[4] Associate Professor and Head, Department of Biotechnology, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai-625 104, Tamil Nadu, India
[5] Associate Professor, ICAR-KVK, Tamil Nadu Agricultural University, Madurai-625 104, Tamil Nadu, India
[6] Assistant Professor, Department of Seed Science and Technology, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai-625 104, Tamil Nadu, India
[7]Professor, Crop physiology unit, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai-625 104, Tamil Nadu, India
Corresponding author: Dr. K. Sujatha, ORCID ID*: 0000-0003-2105-4617, E-mail: sujathakseed@tnau.ac.in

ABSTRACT
Sodium alginate, a naturally occurring polysaccharide extracted from brown marine algae, has emerged as a promising biopolymer for sustainable agricultural applications. This study investigated the extraction, characterization, and functional evaluation of sodium alginate derived from Sargassummyriocystum and assessed its potential as a biodegradable seed-coating polymer for improving seed quality traits in okra (Abelmoschusesculentus L.). The extraction yielded 25% sodium alginate. Physicochemical characterization revealed medium viscosity (90 cP), an alkaline pH (7.20), a blackish-brown colour, and high water-absorption capacity. Biochemical analysis indicated a high carbohydrate content (70%) with negligible protein and lipid fractions, while phytochemical screening detected only saponins, indicating high purity. ICP–MS analysis revealed a high sodium content (200,000 ppm), confirming the sodium alginate form, and FTIR analysis verified the structural integrity and purity of the extracted alginate through characteristic O–H and C=O absorption bands with high transmittance (>95%). The extracted alginate was infused with selected biomolecules and applied as a seed-coating polymer. Among the treatments, T_{14} exhibited the best performance, recording 96% germination, 40.58 cm seedling growth, 0.463 g dry matter production per 10 seedlings, higher vigour indices I and II, and only 2% abnormal seedlings. In contrast, the uncoated control (T_0) showed the lowest germination (86%), seedling growth (30.34 cm), dry matter production (0.343 g per 10 seedlings), vigour indices, and the highest proportion of abnormal seedlings (9%). These findings demonstrate that sodium alginate derived from S. myriocystum is an effective, eco-friendly alternative to synthetic polymer and microplastic-based seed coatings. As a natural hydrocolloid, it significantly enhances seed quality attributes and holds considerable promise for sustainable and environmentally responsible agricultural practices.
KEYWORDS: Okra, sodium alginate, seed coating, biopolymer, biomolecules, organic agriculture

1. INTRODUCTION

Okra (Abelmoschus esculentus), also known as bhendi or lady's finger, is a widely cultivated vegetable across tropical, subtropical, and warm temperate regions. It serves as both an important food source and a source of income for smallholder farmers. The crop's rich composition of fiber, vitamins, minerals, and antioxidants contributes significantly to nutrition and food security (Gemede et al., 2014). In recent years, the industrial demand for okra has increased, primarily due to the valuable mucilage extracted from its pods, which is used in food and pharmaceutical applications (Leng, 2018). Despite its economic and nutritional importance, okra productivity is often constrained by factors such as the limited use of improved varieties, poor seed management, low availability of high-quality seeds, and the presence of hard seeds that hinder uniform germination (Demir, 1997). Moreover, high temperature and humidity conditions during storage adversely affect seed viability and field performance. The relatively high oil content in okra seeds (20-40%) further accelerates lipid peroxidation, damaging cell membranes and resulting in slow or uneven germination (Jarret et al., 2011). The low adoption of high-yielding varieties also reduces the implementation of improved cultivation practices (Abayneh, 2019). To overcome these

challenges, seed invigoration and coating technologies have been developed to enhance germination, emergence, and early plant vigor. Conventional polymer-based coatings improve seed handling, ensure uniform pesticide or nutrient delivery, and facilitate better adhesion of treatment chemicals to seed surfaces (Ekebafe et al. 2011). Such coatings form a thin, uniform layer that that create micro environment around the seed and diffuses easily and is non-toxic to seeds. They act as physical barriers, reducing the leaching of inhibitory substances from seed coats and limiting excess oxygen diffusion to the embryo (Kumar et al. 2014). This controlled microenvironment around the seed improves stress tolerance, delays ageing, and enhances seedling establishment. Additionally, polymers act as temperature-sensitive coatings that regulate water uptake during imbibition, thereby improving germination uniformity under fluctuating environmental conditions (Johnson et al, 1999). However, growing awareness of the environmental impacts associated with synthetic polymers particularly their persistence in soil, disruption of microbial diversity (Mustapha et al., 2025), and contribution to agricultural microplastic pollution (Accinelli et al. 2019) has prompted a shift toward eco-friendly alternatives. Among the biodegradable options, natural polymers such as sodium alginate, derived from brown seaweeds, have gained significant attention. Sodium alginate is a non-toxic, renewable biopolymer composed of β-D-mannuronic and α-L-guluronic acid units, which confer excellent gel-forming ability, adjustable viscosity, and high water-retention capacity, making it particularly suitable for seed-coating applications (Ahmad et al., 1994). Research has shown that alginate-based coatings can enhance germination rate, seedling vigor, and stress tolerance while minimizing ecological risks compared to synthetic coatings (Skrzypczak et al., 2021). Brown seaweeds, especially Sargassum species, are rich sources of alginate, although extraction yield and quality vary depending on species, growth stage, and environmental conditions (Kalimuthu, 1980; Dobrincicet al., 2020). In addition to alginate extraction, seaweeds have long been used as organic soil amendments and natural biostimulants to improve seed germination, plant growth, and resilience to environmental stresses (Baweja et al., 2019; Norrie andKeathley, 2005). Sodium alginate is particularly advantageous in seed-coating due to its high water-uptake capacity, which supports proper seed imbibition and promotes germination (McHugh, 1987). It is widely used in agriculture for coating seeds, fruits, and stem tips (Cisneros-Zevallosand Krochta, 2006). Although most research has focused on its application in synthetic seed production, limited studies have explored its direct effects on germination indices and seedling traits in various crops. For instance, sodium alginate concentrations of 2% and 3% in Ferulagoangulata L. produced synthetic seeds with maximum germination (Sorbi &Moradi, 2018), while 3.5% sodium alginate improved germination percentage in synthetic seeds of Persian oak. (Fayzi, 2016). Similarly, plant-derived polymers in general offer advantages such as biodegradability, low cost, light weight, and wide availability, further supporting their use in sustainable agricultural practices (Kamath & Park, 1993). When enriched with bioactive substances like humic and fulvic acids, these coatings can stimulate root growth, enhance nutrient uptake, and improve seedling establishment (Chen et al., 2021). Humic substances are commonly applied to mitigate the harmful impacts of chemical fertilizers on soils, and numerous researchers have demonstrated their significant positive influence on plant growth (Ghabbour& Davies, 2001). Fulvic acids, in particular, are effective due to their small molecular size and chelating ability, enabling them to penetrate plant cell membranes and enhance nutrient transport (Bocanegra et al., 2006; Yu et al., 2023). Antioxidants such as ascorbic acid and α-tocopherol also improve seed physiological performance by reducing oxidative stress during germination (Sivasakthi and Renganayaki 2022). Moreover, the incorporation of plant growth regulators like brassinosteroids (BRs) further strengthens the benefits of biopolymer coatings. BRs interact synergistically with auxins to promote root growth, increase germination rate, and enhance biomass accumulation in both roots and shoots (Zhang et al., 2008; Pravina and Renganayaki 2025). They also regulate gene expression, enzyme activity, and nitrogen fixation, contributing to improved yield potential (Khan et al., 2015). Similarly, salicylic acid (SA) functions as an important signaling molecule that improves water potential, maintains pigment stability, and confers tolerance to abiotic stresses such as drought and salinity (Raskin, 1992; Hayat et al., 2010; Bakryet al., 2012). Glutathione and ascorbic acid are key antioxidants that support seed germination by managing reactive oxygen species (ROS) and maintaining cellular redox balance. During the early stages of germination, glutathione (GSH) typically rises temporarily, contributing to dormancy release and modulating abscisic acid (ABA) signalling both essential for successful germination and seedling establishment. Higher GSH levels are also linked with stronger antioxidant protection and better stress tolerance during this phase (Koramutlaet al., 2021).Ascorbic acid is a widespread non-enzymatic antioxidant that not only neutralizes reactive oxygen species (ROS) but also influences several essential physiological processes in plants (Akramet al., 2017).Overall, seed coatings enriched with bioactive compounds, antioxidants, and plant growth regulators can create a beneficial microenvironment around seeds, promoting rapid germination, uniform emergence, and improved seedling establishment. The integration of biodegradable polymers like sodium alginate with bioactive additives represents a sustainable approach to seed enhancement, ensuring high physiological performance while safeguarding soil health and ecological balance (Skrzypczak et al., 2021).The objectives of the present study were: i)To extract and characterize sodium alginate from Sargassum myriocystum, examining its physicochemical, biochemical, and phytochemical properties and ii) to evaluate its efficacy as a biodegradable seed-coating polymer, supplemented with biostimulants, growth regulators, and antioxidants, for improving germination, vigor and seedling establishment in okra. By combining seaweed-derived alginate with functional additives, this study aims to develop sustainable seed-coating approaches that enhance productivity while minimizing environmental impact.

2.MATERIALS AND METHODS

2.1 Collection and authentication

The Mandapam coastal region, where the Sargassummyriocystum was collected, is located at approximately 9.2886° N latitude and 79.1329° E longitude. This area is part of the Gulf of Mannar, a coastal region known for its rich seaweed diversity. The freshly harvested seeds of Okra var. ArkaAnamika (Latitude: 10.12° N or 10° 07' 13" N and Longitude: 77.55° E or 77° 32' 50" E) were procured from Horticultural college and Research Institute, Periyakulam, Theni district. The variety was developed by the Indian Institute of Horticultural Research (IIHR), Bangalore and the laboratory experiment was conducted at the Department of Seed Science and Technology, Tamil Nadu Agricultural University, Madurai, Tamil Nadu, India during 2024-2025.

2.2 Design of the experiment

With four replications, the experiment was done in a completely randomized block design and statistical tool is ANOVA

2.3 Extraction of sodium alginate

Sodium alginate is extracted according to Calumpong et al., 1999 with some modifications. 25 g of dried seaweed (Sargassum myriocystum) powder was dissolved in 800 ml of 2 % formaldehyde for 24 hours to remove pigmentation. After such period supernant was decanted and seaweed was collected and washed twice by distilled water. Then seaweed was dissolved in 800 ml of 0.2 M HCl and leaved it for 24 hours to convert alginate into alginic acid, after such period again supernant was discarded and seaweed was collected, then washed by distilled water to remove acid. Collected seaweed was dissolved in 2 % Sodium carbonate solution and heated under water bath for 3 hours at 90-100^{0}c to dissolve the alginic acid into soluble sodium alginate. After that the solution was cooled and centrifuged under 5000 rpm for 30 min. Then supernant was collected carefully and added three volume of ethanol and it precipitate the sodium alginate. It was purified twice with100 ml of acetone and dried @ 65^{0}c. Dried sodium alginate powder was dissolved in distilled water and again precipitate with three volume of ethanol and dried @ 65^{0}c and grind it as fine powder and used for further studies.

2.4. Sodium alginate characteristics

2.4.1 Physiochemical Properties of Sodium Alginate

2.4.1.1 Yield (g)

. Extracted sodium alginate yield was calculated as follows: Weight of alginate/ Weight of seaweed dried biomass *100

2.4.1.2 Estimation of pH and Color

About one per cent w/v of sodium alginate polysaccharide powder was prepared in distilled water and the pH of thesolution was measured using pH meter. The color was evaluated by visual inspection

2.4.1.3 Moisture Content

The moisture of the alginates was determined according to AOAC (1995) through the
loss in mass of sodium alginate after heating at 105^{0}C for 24 h.

2.4.1.4 Viscosity

One gram of dried sodium alginate was dissolved in 100 ml of distilled water andthe viscosity was measured by using Brookfield viscometer.

2.4.1.5 Water absorbancy

To 25 ml of distilled water 0.5 g of sodium alginate powder was immersed and kept for 24 hours under room condition to reach absorption equilibrium. After specified time, the unabsorbed water was decanted and the swollen sodium alginate was weighed. The relative water absorbency was calculated (Chen et al., 2004),

Water absorbency (g/g) = $(M_2 – M_1) / M_1$

Where,

M_1 – initial weight of sodium alginate

M_2 – final weight of swollen sodium alginate after 24 hrs

2.4.1.5 Solubility behaviour

As per Sivasakthi (2022) the solubility behaviour of the polysaccharide was tested with different inorganicand organic solvents viz., warm water, cold water, ethanol (99.9%), methanol (99.85%),acetone (99.5%) and petroleum ether (99.0%). One gram of sample was taken and added to 25 ml ofsolvent and stirred with the help of glass rod for 1 min and then solubility behaviourwas observed and recorded.

2.4.2 Biochemical analysis of sodium alginate

2.4.2.1Carbohydrates analysis

The carbohydrate content of the sodium alginate was determined by the phenolsulphuric acid method described by Dubois et al., (1956)

2.4.2.2Proteins analysis

The proteins were tested following Lowry et al., (1951). The protein was calculatedusing bovine albumin serum as the standard.

2.4.2.3 Lipid's analysis

According to the AOAC methodologies (1950) the total lipids were estimated gravimetrically using chloroform–methanol

2.4.2.4Ash analysis

The ash content was measured by a gravimetric method using AOAC (1950) by burning. 1 g of the product taken in a silica crucible and kept in a muffle furnace at 575^{0}C for 24 h.After burning, the content was cooled, weighed, and expressed in terms of percentage.

2.4.3Phytochemical analysis

To assess the purity of the extracted alginate, qualitative phytochemical screening was performed for compounds such as flavonoids, alkaloids, tannins, terpenoids, steroids, saponins, glycosides, phenols, and phlorotannins, following the methods of Trease and Evans (1989) and Sofowora (1993). These assays serve as rapid tests to detect the presence of residual secondary metabolites from seaweed, which, if present, indicate possible co-extraction of non-target compounds along with alginate.

2.4.3.1 Test for flavonoids

To determine the presence of flavonoids, a qualitative assay was carried out. For this, 0.5 g of sodium alginate was dissolved in diluted NaOH, followed by the addition of HCl. The formation of a yellow coloration that subsequently disappeared upon acidification indicated the presence of flavonoids.

2.4.3.2 Test for alkaloids

To test for the presence of alkaloids, 0.5 g of sodium alginate was dissolved in 10 mL of 0.1 N HCl and filtered. The filtrate was then used for qualitative analysis. For the assay, 1 mL of 1% HCl was added to 3 mL of the filtrate, followed by a few drops of Mayer's reagent. The formation of a creamy white precipitatesconfirmsthe presence of alkaloids.

2.4.3.3 Test for tannins

To analyze the presence of tannins, a qualitative method was used. 0.5 g ofsodium alginate was boiled in 10 mL of distilled water and then filtered. A fewdrops of FeCl3 0.1% were added and observed for a blue-black or brownish green color,indicates the presence of tannins.

2.4.3.4 Test for terpenoids and Steroids

To analyze the presence of terpenoids and steroids, a qualitative method was used.Sodium alginate 0.5 g was added to 2 mL of chloroform. Then, 3 mL of conc.sulfuric acid was added carefully to a layer form. A reddish-brown color for the interfaceindicated terpenoids presence.

2.4.3.5 Test for saponins

To analyze the presence of saponins, a qualitative method was used. First, 0.5 gof sodium alginate was dissolved in 5 mL of distilled water. The solution was shakenspeedlyand observed for a stable persistent foam. The foaming was mixed with threedrop of olive oil and shaken strongly and the formation of a milky mass was observed, which indicates the existence of saponins.

2.4.3.6 Test for glycosides

The analysis of the presence of glycosides was done with a qualitative method using0.5 g of sodium alginate dissolved in 5 mL of distilled water. Then, 10 mL of 50% sulphuric acid was added to 1 mL of this extract. The mixture was heated in boiling water for 5 min.Then, 10 mL of Fehling's solution (5 mL of each solution A and B) was added and boiled.A brick red precipitate indicated the presence of glycosides.

2.4.3.7 Test for phenolic compounds

To analyze the presence of phenolic compounds, a qualitative method was used. 100 mg of sodium alginate was boiled with 1 mL of distilled water then filtered. Then, 2 mLof filtrate was taken and 2 mL of 1% FeCl3 solution was added. The establishment of bluishblack color indicated the existence of phenol.

2.4.3.8 Test for phlorotannins

To analyze the presence of phlorotannins, a qualitative method was used. Sodium alginate 0.5 g was dissolved in 5 mL of distilled water and filtered. Then the filtrate was boiled with 2% HCl solution. A red precipitate indicated the presence of phlorotannins.

2.4.4 ICPMS analysis

One g of sodium alginate sample was induced into Inductively Coupled Plasma Mass Spectrometry (ICP-MS) quantifies trace elements by ionizing samples in Department of Forage crops, Tamil Nadu Agricultural University.

2.4.5 Identification of functional groups by Fourier Transforms Infra-Red (FTIR)

The functional groups of the isolated sodium alginatewere identified using an FTIR spectrophotometer (FT/IR-4600 Type A) equipped with an Attenuated Total Reflectance (ATR Pro One) sensor at the Central Instrumentation Centre, The American College, Madurai,Tamil Nadu, India. Spectral data were recorded in the range of 650–4000 cm^{-1}.

2.5 Preparation of seed coating polymer

After studying all the physiochemical, biochemical and phytochemical properties. Sodium alginate 2 g was taken and dissolves in 100 ml of distilled water (by magnetic strirrer) and 0.5 ml of glycerol was added to the polymer and different biostimulant, plant growth regulators and antioxidant were added at respective concentration to the polymer. For 1 kg of seed 250 ml of polymer is required for uniform seed coating.

Treatment details:

The Okrai seeds var. ArkaAnamika were coated with different treatments such as

T_0 - Control (Uncoated seed)
T_1 - Sodium alginate polymer (2%) 250 ml/kg of seed
T_2 - 0.2 g Humic acid infused to 100 ml of Sodium alginate polymer (2%)

T_3 - 0.3 g Humic acid infused to 100 ml of Sodium alginate polymer (2%)
T_4 - 0.4 g Fulvic acid infused to 100 ml of Sodium alginate polymer (2%)
T_5 - 0.5 g Fulvic acid infused to 100 ml of Sodium alginate polymer (2%)
T_6 - Salicylic acid 200 ppm to 100 ml of infused Sodium alginate polymer (2%)
T_7 - Salicylic acid 250 ppm infused to 100 ml of Sodium alginate polymer (2%)
T_8 - Brassinolide 0.5 ppm infused to 100 ml of Sodium alginate polymer (2%)
T_9 - Brassinolide 1.5 ppm infused to 100 ml of Sodium alginate polymer (2%)
T_{10} - 0.05 g Glutothione infused to 100 ml of Sodium alginate polymer (2%)
T_{11} – 0.10 g Glutothione infused to 100 ml of sodium alginate polymer (2%)
T_{12} - 0.2 g Ascorbic acid infused to 100 ml of Sodium alginate polymer (2%)
T_{13} - 0.4 g Ascorbic acid infused to 100 ml of Sodium alginate polymer (2%)
T_{14} - 0.3 g Humic acid + 250 ppm Salicylic acid + 0.4 g Ascorbic acid infused to 100 ml of Sodium alginate polymer (2%)
Seeds were coated with respective treatments and cross linked with 5 % $CaCl_2$ for 20 min. After that seeds were dried at room temperature for 24 hours.

2.6 Observations on seed quality parameters of okra

2.6.1 Seed germination (%)

The germination test was carried out in roll towel method according to ISTA, 2013 protocol. After 21 days of germination, the seedlings were evaluated and the normal seedlings were counted and germination percentage (GP) was calculated, according to the formula:

Germination percentage (GP) = (Total number of normal seedlings germinated / Total number of seeds evaluated) × 100

2.6.2 Abnormal seedlings (%)

The germination test was carried out in roll towel method according to ISTA, 2013 protocol. After 21 days of germination, the seedlings were evaluated and the abnormal seedlings were counted and expressed in percentage
Abnormal seedlings (%) = (Total number of abnormal seedlings / Total number of seeds evaluated) × 100

2.6.3 Root length (cm)

After the germination count, ten normal seedlings were randomly chosen from each replication and the length of the roots from the collar area to the tip of the primary root was measured.

2.6.4 Shoot length (cm)

Shoot length was measured on the same seedlings which is were used for measuring the length of the roots. The distance along the shoot from the collar to the tip of the primary leaf was measured.

2.6.5 Seedling Length (cm)

Seedling length generally refers to the total length of a young plant from the tip of the shoot to the tip of the root. It is usually measured in centimeters (cm) and is obtained by summing:
Seedling length=Shoot length (cm) + Root length (cm)

2.6.6 Dry matter production (g seedlings^{-10})

The seedlings which is used for seedling length measurement same seedlings were placed in a butter paper cover separately and dried in shade for 24 h and then kept in an oven maintained at 85 ± 2 ℃ for 24 h. Dry weight was recorded and the mean values were expressed in gram. (ISTA, 2013).

2.6.7 Vigour index (Abdul-Baki and Anderson, 1973)

Vigour index values were computed using the following formula and the mean values were expressed in whole number.
Vigour index I = Germination (%) x Root length (cm) + Shoot length (cm)
Vigour index II = Germination (%) x Drymatter production (g seedling^{-10})

3. RESULTS

3.1 Sodium alginate characteristics

3.1.1 Physiochemcial

Sodium alginate extracted from Sargassum myriocystum yielded 25%**,** demonstrating efficient recovery of the polysaccharide from the brown seaweed (Fig. 2). This yield falls within the range of 14.26–26.07% previously reported for S. myriocystum by Kalimuthu (1980), indicating that the extraction procedure employed in the present study was effective. Similar yields have also been reported in other Sargassum species (Dalal et al., 2021). Variations in alginate yield are mainly influenced by the seaweed species, maturity, seasonal growth stage, environmental conditions such as light intensity, water temperature, nutrient availability, and extraction methodology (Dobrincic et al., 2020). Therefore, the yield obtained in the present investigation confirms that S. myriocystum is a promising and sustainable source of sodium alginate for agricultural and industrial applications. The extracted sodium alginate exhibited a blackish-brown colour (Fig. 1) with a pH of 7.20**,** indicating its near-neutral nature. According to Coppen (1995), these characteristics are consistent with acceptable quality standards for sodium alginate. The darker colour observed in the present study may be attributed to the presence of residual natural pigments and saponins retained during extraction, whereas Rashedy et al., (2021) reported comparatively lighter alginate preparations obtained using different purification procedures. Although colour variation is

expected depending on the extraction process, it does not adversely affect the functional properties of sodium alginate intended for non-food applications such as seed coating. The viscosity of the 1% (w/v) sodium alginate solution was 90 cP**,** indicating a medium-viscosity grade suitable for seed-coating applications. According to the Food Chemicals Codex (FCC), the acceptable viscosity range for commercial sodium alginate varies from 10 to 5000 cP**,** depending on its intended application. The measured viscosity in the present study is therefore well within the recommended range. Viscosity is one of the most important rheological properties governing film formation, adhesion, gel strength, and coating uniformity. It is influenced by several factors, including alginate source, molecular weight, extraction procedure, polymer concentration, pH, temperature, and ionic composition of the solution. Similar observations regarding the importance of rheological behaviour in alginate applications have been reported by Fenoradosoa et al. (2018). The medium viscosity obtained in the present study is particularly advantageous for seed coating because it enables uniform polymer deposition without excessive solution thickness. The extracted sodium alginate contained 10% moisture, which is below the 15% maximum limit recommended by FAO standards (Coppen, 1995), indicating good storage stability and product quality. The polymer dissolved readily in both cold and hot water, whereas it remained insoluble in acetone, ethanol, methanol, and petroleum ether (Fig. 2). Similar solubility characteristics were reported by Zhou et al, (2020), who demonstrated that sodium alginate readily dissolves in water owing to its ionic and highly hydrophilic nature. Unlike several conventional polysaccharides that require heating for complete dissolution, sodium alginate forms a stable viscous colloidal solution under normal conditions, thereby facilitating its practical use in agricultural formulations, including seed-coating technologies. A remarkable property of the extracted alginate was its water absorption capacity of 5.5 g**,** with the polymer increasing from 1 g to 5.5 g after 24 h**.** This pronounced swelling behaviour reflects the hydrophilic nature of sodium alginate and its ability to retain large quantities of water through hydrogel formation. Ma et al., (2015) reported that sodium alginate hydrogels can absorb 200–300 times their own weight in water because of the abundance of hydroxyl and carboxyl functional groups within the polymer network. Such high water-retention capacity is particularly beneficial for seed-coating applications. Furthermore, Leandro et al., (2020) emphasized that comprehensive physicochemical characterization is essential to ensure the quality, safety and functionality of alginate intended for large-scale industrial applications, particularly in the food sector. The present findings satisfy these quality requirements and demonstrate the suitability of the extracted sodium alginate for further applications.

3.1.2 Biochemical

The biochemical composition of the extracted sodium alginate is presented in Table 1. Carbohydrates were the predominant component, accounting for 70% of the extract, whereas protein (0.95%) and lipid (0.90%) contents were comparatively low. The ash content was determined to be 18.15%, representing the total mineral residue present in the extracted alginate. The predominance of carbohydrates indicates that the extracted product was rich in polysaccharides, whereas proteins and lipids were present only in minor quantities, suggesting effective enrichment of the alginate fraction during extraction. Although the polysaccharide content obtained in the present study was slightly lower than that reported by Osman et al., (2020), it was within the range reported for alginate extracted from various alginophyte species by Rioux et al., (2007), indicating that the extraction efficiency achieved in this study was comparable with previously published reports. The ash content (18.15%) was within the acceptable range reported for commercial sodium alginate. According to the Food Chemicals Codex (1981), sodium alginate should possess ash levels within specified quality standards, while Chapman and Chapman (1980) reported ash values of up to 23% for commercially prepared alginate. Therefore, the ash content obtained in the present investigation is consistent with internationally accepted standards, indicating the satisfactory quality of the extracted sodium alginate.

3.1.3 Phytochemical

Furthermore, qualitative phytochemical screening revealed the absence of flavonoids, alkaloids, tannins, phlorotannins, terpenoids, steroids, glycosides and phenolic compounds (Table 1), indicating that most secondary metabolites present in the seaweed biomass were effectively removed during extraction. . Only the saponins were detected in the extract. Since saponins are carbohydrate-based compounds, their presence is consistent with the structural composition of alginate. The absence of other phytochemicals indicates high purity of the extracted sodium alginate, which enhances its suitability for industrial use. Similar findings were reported by Sivagnanavelmurugan et al., (2018) and Kavitha et al., (2019), who also observed the absence of major metabolites in purified alginates, with saponins being the only detectable compound. The detection of only saponins suggests that the purified sodium alginate possesses a high degree of purity, making it suitable for subsequent applications where a clean polysaccharide matrix is required. Overall, the physiochemical, biochemical and phytochemical characteristics demonstrate that sodium alginate extracted from Sargassum myriocystum possesses desirable compositional properties for further utilization as a natural biopolymer, particularly as a seed-coating material.

3.1.4 ICP-MS elemental analysis

The elemental composition of the extracted sodium alginate, determined by ICP-MS and expressed in parts per million (ppm), is presented in Table 2. Sodium (Na) was the predominant element with a concentration of 200,390.405 ppm. The other major elements detected were calcium (Ca) (3,876.649 ppm), magnesium (Mg) (620.544 ppm), potassium (K) (200.573 ppm), phosphorus (P) (164.078 ppm), and iron (Fe) (158.246 ppm). Trace

elements, including aluminium (Al) (28.574 ppm), boron (B) (17.813 ppm), and titanium (Ti) (7.107 ppm), were present in comparatively lower concentrations. Heavy metals such as lead (Pb), arsenic (As), chromium (Cr), and cadmium (Cd) were detected at 8.685, 3.429, 2.075, and 0.158 ppm, respectively. Other elements including lithium (Li), beryllium (Be), vanadium (V), cobalt (Co), nickel (Ni), molybdenum (Mo), silver (Ag), antimony (Sb), cesium (Cs), and mercury (Hg) were detected only in trace quantities (≤1 ppm in most cases) (Table 2). The ICP-MS analysis demonstrated that sodium was the dominant element, accounting for 200,390.405 ppm, whereas all other elements were present at considerably lower concentrations. The predominance of sodium confirms the successful conversion of alginic acid into sodium alginate during extraction and indicates a high degree of purity of the extracted polymer. Similar elemental compositions have been reported for sodium alginate extracted from brown seaweeds such as Laminaria and Ascophyllum nodosum using ICP-OES and ICP-MS techniques (Marín et al., 2010). The comparatively low concentrations of heavy metals further support the suitability of the extracted alginate for agricultural and industrial applications.

3.1.5 FTIR spectral analysis

The FTIR spectrum of the extracted sodium alginate showed characteristic absorption bands corresponding to the functional groups of alginate (Table 3; Fig. 4). Broad peaks at 3699.764, 3584.056, 3295.750 and 3281.286 cm^{-1} were assigned to O–H stretching vibrations of hydroxyl groups associated with alcohols, phenols and carboxylic acids. The absorption band at 3100.011 cm^{-1} represented aromatic C–H stretching. Strong absorption bands between 1818.544 and 1717.300 cm^{-1} corresponded to C=O stretching vibrations of carboxylic acids, esters and anhydrides, confirming the presence of uronic acid residues that constitute the alginate backbone. In addition, the peaks observed at 1270.860, 1087.655 and 1050.050 cm^{-1} were attributed to C–O stretching vibrations of ester and alcohol groups, confirming the polysaccharide structure of the extracted sodium alginate. Fourier Transform Infrared Spectroscopy (FTIR) is a well-established analytical technique for identifying functional groups and characterizing biomaterials (Li et al., 2011). It has been widely employed for the identification of pure compounds (Stefanowicz et al., 2009), analysis of mixtures (Basiuk, 2001), detection of impurities (Pandey et al., 2016) and determination of material composition (Hakim and Shanks, 2011). The characteristic O–H and C=O absorption bands observed in the present study are in agreement with previously reported spectra of Sargassum-derived sodium alginate (Latifi et al., 2015), confirming the presence of mannuronic and guluronic acid residues that form the alginate polymer. The hydroxyl and carboxyl functional groups contribute to the excellent water absorption, gel-forming ability and calcium-mediated cross-linking properties of sodium alginate, making it an ideal hydrogel-forming biopolymer. These characteristics are particularly advantageous for seed-coating applications, where improved moisture retention and enhanced seed imbibition can promote better germination and seedling establishment under moisture-deficit conditions (Belattmania et al., 2020).

Overall, the biochemical, phytochemical, ICP-MS and FTIR analyses confirmed that the extraction procedure successfully produced high-quality sodium alginate from Sargassum myriocystum. The biochemical analysis revealed a carbohydrate-rich composition, phytochemical screening indicated minimal interference from secondary metabolites, ICP-MS confirmed sodium as the predominant element with only trace amounts of other elements, and FTIR verified the characteristic functional groups of sodium alginate. Collectively, these results demonstrate the purity and desirable physicochemical properties of the extracted alginate, supporting its suitability as a natural biopolymer for seed-coating applications. Accordingly, the purified sodium alginate was selected as the coating polymer for evaluating seed quality parameters in okra under moisture stress conditions.

After confirming with these parameters sodium alginate further used for seed coating and studied the seed quality parameters on okra.

3.2 Seed coating effect

The effect of different sodium alginate-based seed coating treatments on the physiological quality of okra seeds is presented in Table 4 and Fig 6. Significant differences were observed among the treatments for germination, abnormal seedlings, seedling growth, dry matter production and vigour indices. Germination percentage ranged from 86 to 93%, with the highest germination (93%) recorded in T_{14}. Treatments T_2, T_3, T_9 and T_{13} also exhibited relatively higher germination (89%), whereas the lowest germination (86%) was observed in T_0, T_1, T_{10} and T_{12} (Fig 3). The improved germination observed in T_{14} indicates the beneficial effect of sodium alginate incorporated with humic acid, salicylic acid and ascorbic acid on seed physiological quality. During the seed-coating process, sodium alginate was ionically crosslinked with calcium chloride, in which calcium ions (Ca^{2+}) interact with the guluronic acid residues of alginate to form a three-dimensional calcium alginate hydrogel through the well-established "egg-box" model (Lee and Mooney, 2012). This cross linked hydrogel enhances coating stability, increases water-holding capacity and enables the gradual release of the incorporated bioactive compounds, thereby creating a favourable microenvironment for seed imbibition and uniform germination (McHugh, 1987). In addition, seed coating has been reported to enhance nutrient availability, activate antioxidant enzymes and stimulate the accumulation of beneficial metabolites, resulting in improved seed metabolism and germination (Rocha et al., 2019).

The percentage of abnormal seedlings ranged from 2 to 9%, with T_{14} recording the lowest abnormal seedlings (2%), while T_0, T_1, T_{10} and T_{12} recorded the highest abnormality (9%). The reduction in abnormal seedlings under T_{14} suggests that the cross linked sodium alginate matrix provided a protective environment for normal embryo development while ensuring the sustained release of the incorporated bioactive compounds throughout germination. Significant differences were also observed in seedling growth among the treatments. Root length

ranged from 17.23 cm in the control (T_0) to 22.36 cm in T_{14}, while shoot length increased from 13.11 cm in T_0 to 18.22 cm in T_{14}. Consequently, the highest total seedling length (40.58 cm) was recorded in T_{14} compared with 30.34 cm in the control. The enhanced seedling growth can be attributed to the synergistic action of humic acid, salicylic acid and ascorbic acid delivered through the sodium alginate coating. Besides serving as a biodegradable carrier, sodium alginate maintains adequate moisture around the seed and supports early metabolic activity owing to its high polysaccharide content. Humic acid further promotes root elongation by improving nutrient availability and exhibiting auxin-like activity (Chen et al., 2004; Mackowiak, 2001). Similar improvements in germination, seedling length and vigour following humic acid-infused polymer coatings were reported by Sivasakthi and Renganayaki (2022). Moreover, humic substances enhance membrane permeability, ion transport, respiration and ATP synthesis through increased enzymatic activity in the Krebs cycle, thereby promoting vigorous seedling growth (Zandonadi et al., 2007).

Dry matter production varied from 0.343 g in T_0 to 0.463 g in T_{14}, whereas T_2, T_3, T_7 and T_{13} recorded intermediate values of approximately 0.398 g. The greater dry matter accumulation in T_{14} indicates enhanced biomass production resulting from improved metabolic activity and nutrient utilization. Salicylic acid contributes to these responses by regulating photosynthesis, nitrogen metabolism, osmotic balance and antioxidant defence mechanisms (Miura and Tada, 2014). It also stimulates antioxidant enzymes, including superoxide dismutase, catalase and peroxidase, which protect germinating seeds against oxidative stress (Sedghi, 2010). Similar improvements in germination and early seedling growth following salicylic acid application have been reported in Arabidopsis, alfalfa and ginger (Alonso-Ramírez et al., 2009; Wang et al., 2009; Ghasemzadeh and Jaafar, 2013). Vigour Index I followed a trend similar to seedling growth, with T_{14} recording the highest value among all treatments. Likewise, Vigour Index II reached a maximum value of 43 in T_{14}, whereas the control recorded the lowest value of 29 (fig 3). The improved vigour indices reflect enhanced physiological activity and seedling robustness under the combined treatment. These responses are further supported by the role of ascorbic acid as a non-enzymatic antioxidant, which scavenges reactive oxygen species, protects cellular structures from oxidative damage and regulates physiological processes associated with seed germination and seedling development (Akram et al., 2017). Similar enhancement in seedling vigour following ascorbic acid treatment has been reported in alfalfa (Chen et al., 2021).

Overall, T_{14} consistently outperformed all other treatments by producing the highest germination percentage, longest seedlings, greatest dry matter production and vigour indices, together with the lowest percentage of abnormal seedlings. The superior performance of this treatment can be attributed to the synergistic effects of humic acid, salicylic acid and ascorbic acid encapsulated within the calcium-crosslinked sodium alginate matrix. This biodegradable hydrogel not only enhances water availability and regulates the release of bioactive compounds but also promotes nutrient uptake, metabolic activity and antioxidant defence, thereby improving seedling establishment and early growth. Such integrated seed-coating systems represent an environmentally sustainable approach for enhancing seed physiological quality and crop establishment (Skrzypczak et al., 2021).

4. Future Thrust

Future research should focus on optimizing the extraction and purification methods to improve the yield and functional quality of sodium alginate from Sargassummyriocystum. The integration of this biopolymer with different bioactive compounds, micronutrients, and beneficial microorganisms can be explored to enhance its efficiency as a multifunctional seed-coating material. Further studies under field conditions are essential to validate its performance across various crops and environments. Long-term investigations on soil health, microbial dynamics, and biodegradability will provide insights into its environmental safety and sustainability. Additionally, developing low-cost and scalable production techniques will support its industrial application and promote the replacement of synthetic polymers with natural, eco-friendly alternatives in sustainable agriculture.

5. CONCLUSION

The present investigation demonstrated that sodium alginate extracted from Sargassum myriocystum possesses desirable physicochemical and biochemical properties suitable for agricultural use. The moderate viscosity, high carbohydrate content, and excellent water absorption capacity, combined with its biodegradability, make it an efficient and sustainable seed-coating polymer. The biopolymer and additives had a significant effect on the physiological seed performance in okra. Among the treatments, T_{14} (sodium alginate biopolymer 2 % + humic acid 0.3 g + 250 ppm Salicylic acid + ascorbic acid 0.4 g) showed superior performance by improving stand establishment parameters such as germination, root length, shoot length, dry biomass production, vigour index I and II, and by reducing abnormal seedlings compared to the control. These findings highlight that seed coating with S. myriocystum-derived sodium alginate infused with biomolecules effectively enhances seed quality attributes and seedling growth. Thus, sodium alginate biopolymer represents an eco-friendly and sustainable alternative to synthetic polymers, supporting greener practices in modern seed technology.

Acknowledgments

The authors are thankful to Department of Seed Science and Technology, Tamil Nadu Agricultural University for providing the facilities that enabled them to conduct the research successfully.

Declarations

Funding
The authors received no external funding for this research.

Competing interests
The authors declare that they have no competing interests.

Availability of data and material
The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Code availability
Not applicable.

Authors' contributions
Pravina K. conducted the experiments, analyzed the data, and prepared the manuscript. All authors reviewed and approved the final manuscript.

REFERENCES

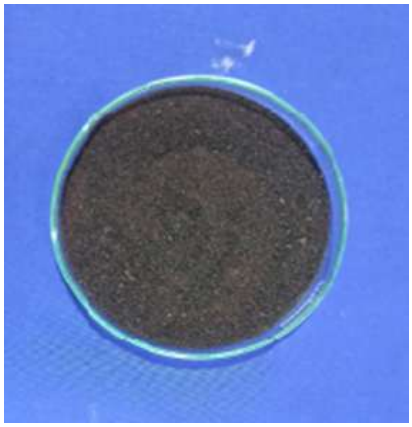
1. Abayneh, K. (2019). Review on adoption of improved agricultural technologies in Ethiopia. Int. J. Health Econ. Policy. 4:11-19. doi: 10.11648/j.hep.20190401.12
2. Abdul-Baki A. A. and Anderson J. D. 1973. Vigour deterioration of soybean seeds by multiple criteria. Crop Science. 13:630-633.
3. Accinelli, C.; Abbas, H. K.; Shier, W. T.; Vicari, A.; Little, N. S.; Aloise, M. R. and Giacomini, S. (2019). Degradation of microplastic seed film-coating fragments in soil. Chemosphere, 226, 645-650.
4. Ahmad, F.B.; Omar, S.; Williams, P.A. (1994). Physicochemical Characterisation of Alginate from Malaysian Brown Seaweeds. In: Nishinari, K., Doi, E. (eds) Food Hydrocolloids. Springer, Boston, MA. https://doi.org/10.1007/978-1-4615-2486-1_28
5. Akram, N. A.; Shafiq, F. Ashraf, M. (2017). Ascorbic Acid-A Potential Oxidant Scavenger and Its Role in Plant Development and Abiotic Stress Tolerance. Front Plant Sci. 8:613. doi: 10.3389/fpls.2017.00613.
6. Alonso-Ramírez, A.; Rodríguez, D.; Reyes, D.; Jiménez, J. A.; Nicolás, G.; López-Climent, M.; Gómez-Cadenas, A. and Nicolás, C. (2009). Cross-talk between gibberellins and salicylic acid in early stress responses in Arabidopsis thaliana seeds. Plant Sign. Behav. 4:750-751. doi: 10.4161/psb.4.8.9175.
7. Anilkumar, L. and Malarkodi, K. (2019). Combined seed enhancement technique involving seed priming and coating for improvised anatomical potential and vigour of okra seeds (Abelmoschusesculentus L.). Journal of Phytology, 11(1), 25–30.
8. AOAC (1995). International. Official Methods of Analysis, 16th ed.; AOAC International: Washington, DC, USA.
9. AOAC (2000). International. Official Methods of Analysis, 17th ed; AOAC International: Washington, DC, USA.
10. Bakry, B.; El-Hariri, D.; Sadak, M. and. El-Bassiouny, H. (2012). "Drought stress mitigation by foliar application of salicylic acid in two linseed varieties grown under newly reclaimed sandy soil." J. Appl. Sci. Res., 8(7):3503-3514.
11. Basiuk, V.A. (2001). Quantum chemical calculations of infrared spectra for the identification of organic compounds in complex mixtures by GC/FTIR/MS. Advances in Space Research, 27(2), 255–260.doi: 10.1016/s0273-1177(01)00055-2. PMID: 11605640.
12. Baweja P, Kumar S, Kumar G. (2019). Organic fertilizer fromalgae: a novel approach towards sustainable agriculture.Biofertil. Sustain. Agric. Environ., 353-370.
13. Belattmania Z, Kaidi S, El Atouani S, Katif C, Bentiss F, Jama C, Reani A, Sabour B, Vasconcelos V (2020). Isolation and FTIR-ATR and ^{1}H NMR Characterization of Alginates from the Main Alginophyte Species of the Atlantic Coast of Morocco. Molecules. 22;25(18):4335. doi: 10.3390/molecules25184335.
14. Blalogoe, J. S., Ayenan, M. A. T., Aglinglo, L. A., N'Danikou, S., Schafleitner, R., &Achigan-Dako, E. G. (2025). Challenges and opportunities in the okra (Abelmoschus spp.) seed system in Benin. Front. Sustain. Food Syst., 9, Article 1614338. https://doi.org/10.3389/fsufs.2025.1614338
15. Bocanegra, M. P., Lobartini, J. C., &Orioli, G. A. (2006). Plant Uptake of Iron Chelated by Humic Acids of Different Molecular Weights. Commun. Soil Sci. Plant Anal., 37(1-2), 239=248. https://doi.org/10.1080/00103620500408779.
16. Calumpong, H. P.; Maypa, A. P. and Magbanua, M. (1999). Population and alginate yield and quality assessment of four Sargassum species in Negros Island, central Philippines.Hydrobiologia, 398-399:211-215. doi:10.1023/A:1017015824822
17. Chapman, V.J. and Chapman, D.J. (1980). Seaweeds and Their Uses; Springer: Dordrecht, ThemNetherlands, ISBN 978-94-009-5808-1. https://archive.org/details/in.ernet.dli.2015.11954.
18. Chen P.; Zhang, W.; Luo, W. and Fang Y. (2004). Synthesis of superobsorbannt polymers by irradiation and their applications in agriculture. J. Appl. Polym. Sci., 93(4):1748-1755.

19. Chen, Q.; Gao, F.; Meng, Q.M.;Li, M.Y.; Zhang, Y.; Zhang, P., Zhang, M.; Liu, Z.G. (2021). Controlled-release urea combined with fulvic acid enhanced carbon/nitrogen metabolic processes and maize growth. J. Sci. Food Agric., 102:3644-3654. doi: 10.1002/jsfa.11711
20. Cisneros-Zevallos, L. and Krochta, J. M. (2006). Internal modified atmospheres of coated fresh fruits and vegetables: Understanding relative humidity effects. Journal of Food Science 67: 2792-2797
21. Coppen, J.J.W. (1995). Gums, Resins and Latexes of Plant Origin; FAO: Rome, Italy, ISBN 9251037574.
22. Dalal, S. R.; Hussein, M, H.; El-Naggar, N.E.; Mostafa, S. I. and Shaaban-Dessuuki, S. A.(2021). Characterization of alginate extracted from Sargassumlatifolium and its use in Chlorella vulgaris growth promotion and riboflavin drug delivery. Sci Rep., 11(1):16741. doi: 10.1038/s41598-021-96202-0. PMID: 34408229;
23. de Souza Machado, A.A.; Werner K.; Chirstiane Z.; Stefan H.; Rillig, M.C. (2018). Microplastics as an emerging threat to terrestrial ecosystems. Global Change Biology, 24(4), 1405-1416. Demir, I. and Mavi, K. (2004). The effect of priming on seedling emergence of differentially matured watermelon (Citrulluslanatus (Thunb.) Matsum. andNakai) seeds. Seed Science and Technology. 32: 71-76.
24. Dobrincic, A.; Balbino, S.; Zori´c, Z.; Pedisi´c, S.; Bursa´cKova˘cevi´c, D.; ElezGarofuli´c, I.; Dragovi´c-Uzelac, V. (2020). Advanced technologies for the extraction of marine brown algal polysaccharides. Mar. Drugs. 18:168.
25. DuBois, M.; Gilles, K. A.; Hamilton, J. K. and Rebers, P.A. (1956). Smith, F. Colorimetric method for determination of sugars and related substances. Anal. Chem., 28: 350-356.
26. Ekebafe, L.; Ogbeifun, D.; and Okieimen, F. (2011). "Polymer applications in agriculture." Biokemistri 23(2).
27. Fayzi, E. (2016). Somatic embryogenesis and seed production in Iranian Oak (QuerCusbrantii L.). Master's Thesis, Yasuj University, Yasuj, Iran.
28. Fenoradosoa, T.A.; Ali, G.; Delattre, C.; Laroche, C.; Petit, E.; Wadouachi, A. and Michaud, P. (2010). Extraction and characterization of an alginate from the brown seaweed SargassumturbinarioidesGrunow. J. Appl. Phycol., 22:131-137.
29. Food Chemicals Codex; National Academies Press: Washington, DC, USA, 1981; ISBN 978-0-309-03090-8.
30. Gemede, H. F.; Ratta, N.; Haki, G. D.; Woldegiorgis, A. Z. and Beyene, F. (2015). Nutritional Quality and Health Benefits of Okra (Abelmoschusesculentus): A Review.J. Food Process. Technol., 6(6):458. https://doi.org/10.4172/2157-7110.1000458
31. Ghabbour E. A. and Davies G. (2001). Humic substances: Structures, models and functions. Royal Society of Chemistry, England.
32. Ghasemzadeh, A. and Jaafar, H. Z. (2013). Interactive effect of salicylic acid on some physiological features and antioxidant enzymes activity in ginger (Zingiberofficinale Roscoe). Molecules. 18(5): 5965-5979. https://doi.org/10.3390/molecules18055965
33. Hayat, Q.; Hayat, S.; Irfan, M. and Ahmad. A (2010). "Effect of exogenous salicylic acid under changing environment: a review." Environ. Exp. Bot., 68(1):14-25.
34. ISTA. (2013) International rules for seed testing. switzerland: The International Seed Testing Association (ISTA).
35. Jarret, R. L.; Wang, M. L. and Levy, I. J. (2011). Seed oil and fatty acid content in okra (Abelmoschusesculentus) and related species. J Agric Food Chem., 59(8):4019-24. doi: 10.1021/jf104590u.
36. Johnson, G. A.; Hicks, D. H.; Stewart, R. F. and Duan, X. (1999). Use of temperature-responsive polymer seed coating to control seed germination. In VI Symposium on Stand Establishment and ISHS Seed Symposium (ActaHorticulturae). ISHS., 504:229-236. https://doi.org/10.17660/ActaHortic.1999.504.24
37. Kalimuthu, S. (1980). "Variations in growth and mannitol and alginic acid contents of Sargassummyriocystum J. Agardh." Indian J. Fish. 27, (1&2):265-266.
38. Kamath, K. R. and Park K. (1993). Biodegradable hydrogels in drug delivery. Advances in Drug Delivery Review. 11:59-84.
39. Kavitha, N.; Karunya, T.P.; Kanchana, S.; Mohan, K.; Sivaramakrishnan, R.; Uthra, S.; Kapilan, K.; Yuvaraj, D.; (2019). Arumugam, M. Formulation of alginate based hydrogel from brown seaweed, Turbinariaconoides for biomedical applications. Heliyon. 5:e02916. Doi: https://doi.org/10.1016/j.heliyon.2019.e02916
40. Khan, M. I., Fatma, M., Per, T. S., Anjum, N. A. and Khan, N. A. (2015). Salicylic acid-induced abiotic stress tolerance and underlying mechanisms in plants. Front. Plant Sci., 6:462. https://doi.org/10.3389/fpls.2015.00462
41. Koramutla, M. K., Negi, M. and Ayele, B. T. (2021). Roles of Glutathione in Mediating Abscisic Acid Signaling and Its Regulation of Seed Dormancy and Drought Tolerance. Genes, 12(10):1620. https://doi.org/10.3390/genes12101620
42. Kumar, S. V., Vyakaranahal, B., Deshpande, V., Raikar, S., Nadaf, H. and Kumar, B. A. (2014). Effect of seed polymer coating on growth and yield of pigeonpea. Karnataka J. Agric. Sci., 27(4):469-471.
43. Larrea-Marín, M. T., Pomares-Alfonso, M. S., Gomez-Juaristi, M., & Sánchez-Muniz, F. J. (2010). Validation of an ICP-OES method for macro and trace element determination in Laminaria and Porphyra seaweeds from four different countries. Journal of Food Composition and Analysis, 23(8), 814–820.https://doi.org/10.1016/j.jfca.2010.03.015

44. Latifi, A.M., SadeghNejad, E. and Babavalian, H. (2015). Comparison of extraction different methods of sodium alginate from brown alga Sargassum sp. localized in the southern of Iran. Journal of Applied Biotechnology Reports, 2(2): 251–255
45. Leandro, A.; Pacheco, D.; Cotas, J.; Marques, J.C.; Pereira, L. and Gonçalves, A. M. M. (2020). Seaweed's bioactive candidate compounds to food industry and global food security. Life. 10:140. Doi: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7459772/.
46. Lee, K. Y., & Mooney, D. J. (2012). Alginate: Properties and biomedical applications. Progress in Polymer Science, 37(1), 106–126. https://doi.org/10.1016/j.progpolymsci.2011.06.003
47. Leng, P. H., (2018). Okra: A potential future bioenergy crop. BioEnergy Research, 11(1):1-9.
48. Lowry, O. H.; Rosebrough, N. J.; Farr, A. L.; Randall, R. J. (1951). Protein measurement with the Folin phenol reagent. J. Biol. Chem., 193:265-275.
49. Ma, G.; Ran, F.; Yang, Q.; Feng, E. and Lei, Z. (2015). Eco-friendly superabsorbent composite based on sodium alginate and organo-loess with high swelling properties. RSC Advances, 5(66):53819-53828.
50. Mackowiak, C. L.; Grossl, P. R. and Bugbee. B. G. (2001). Beneficial effects of humic acid on micronutrient availability to wheat. Soil Sci. Soc. Am. J., 56:1744-1750.
51. McHugh, D. J. (1987). Production and utilization of products from commercial seaweeds. 1th Ed. FAO fisheries
52. Miura, K. and Tada, Y. (2014). Regulation of water, salinity, and cold stress responses by salicylic acid. Front. Plant Sci., 5(4). DOI: 10.3389/fpls.2014.00004.
53. Mustapha, H.; Sonja, R.; Benjamin, R.; Robin, S.; Raphael, C.; Charlotte, S. and Natacha B. (2025). "Agronomic Performance and Microbial Diversity of Wheat Following Organic and Synthetic Seed Treatments: A Swiss Field Study."
54. Norrie, J. and Keathley, J. P (2005). Benefits of Ascophyllumnodosummarine-plant extract applications to Thompson Seedlessgrape production. X International Symposium on PlantBioregulators in Fruit Production; pp 727. https://www.ishs.org/ishs-article/727_27
55. Pravina, K. and P R. Renganayaki. (2025). "Unveiling the Impact of Plant Growth Regulator Infused Tamarind Seed Polysaccharide (TSP) Polymer Coating on Seed Quality Behaviour of Cowpea Var. VBN 3". Int. J. Plant Soil Sci., 37(11):220-227. https://doi.org/10.9734/ijpss/2025/v37i115837
56. Rashedy, S. H. (2019). Spatial and Temporal Variations in Nutritional Composition, Antioxidant and Antimicrobial Activities of Some Seaweeds from Red Sea, Egypt. Ph.D. Thesis, Suez Canal University, El Sheikh Zayed, Egipt.
57. Raskin, I. (1992). "Role of salicylic acid in plants." Annu. Rev. Plant Biol., 43(1):439-463.
58. Rioux, L. E.; Turgeon, S. L. and Beaulieu, M. (2007). Characterization of polysaccharides extracted from brown seaweeds. Carbohydr. Polym., 69: 530-537. https://doi.org/10.1016/j.carbpol.2007.01.009
59. Rocha, I.; Ma, Y.; Souza-Alonso, P.; Vosátka, M.; Freitas, H. and Oliveira, R. S. (2019). Seed Coating: A Tool for Delivering Beneficial Microbes to Agricultural Crops. Front. Plant Sci., 10: 1357.
60. Sivagnanavelmurugan, M.; Radhakrishnan, S.; Palavesam, A.; Arul, V.; Immanuel, G. (2018). Characterization of alginic acid extracted from Sargassumwightii and determination of its anti-viral activity of shrimp Penaeus monodon post larvae against white spot syndrome virus. Int. J. Curr. Res. Life Sci., 7:1863-1872.
61. Sivasakthi S. and P.R. Renganayaki (2022). Studies on Seed Quality Parameters of TSP Polymer Coated Ridge Gourd (Luffa acutangula) var. PKM 1. Biol. Forum – Int. J., 14(2):193-201.
62. Skrzypczak, D.; Jarzembowski, Ł.; Izydorczyk, G.;Mikula, K.; Hoppe, V.; Mielko, K. A.; Pudełko-Malik, N.;Młynarz, P.;Chojnacka, K. and Witek-Krowiak, A. (2021). Hydrogel Alginate Seed Coating as an Innovative Method for Delivering Nutrients at the Early Stages of Plant Growth. Polymers, 13(23), 4233. https://doi.org/10.3390/polym13234233
63. Sofowora, A. (1993). Medicinal Plants and Traditional Medicine in Africa, 2nd ed.; Spectrum Books Limited, Sunshine House: Ibadan, Nigeria.
64. Sorbi, E. and Moradi, A. (2018). Synthetic hydrated seed production in medicinal plant of Chavil (Ferulago angulate L.) through encapsulation of somatic embryos. J. Gen. Plant., 31: 232-241.
65. Spoel, S. H. and Dong, X. (2024). Salicylic acid in plant immunity and beyond. The Plant cell. 36(5):1451-1464. https://doi.org/10.1093/plcell/koad329
66. Spoel, S. H. and Dong, X. (2024). Salicylic acid in plant immunity and beyond. The Plant cell, 36(5), 1451–1464.
67. Stefanowicz, Z., Stefanowicz, J. and Mulas, K. (2009). Determination of tropicamide and its major impurity in raw material by the HPLC-DAD analysis and identification of this impurity using the off-line HPLC–FT-IR coupling. Journal of Pharmaceutical and Biomedical Analysis, 49(2): 214–220.
68. Trease, G. E.; Evans, W. C. (1989). Pharmacognosy, 13th ed.; Baillière Tindall: London, UK,
69. Wang W. B.; Kim Y. H.; Lee H. S.; Kim K. Y.; Deng X. P. and Kwak S. S. (2009). Analysis of antioxidant enzyme activity during germination of alfalfa under salt and drought stresses. Plant Physiol. Biochem., 47:570-577. doi: 10.1016/j.plaphy.2009.02.009.
70. Yu, B.; Wang, L.; Cui, D.; Gao, W.; Xue, X. and Nie, P. (2023). Effects of Fulvic Acid on Growth and Nitrogen Utilization Efficiency in M9T337 Seedlings. Plants (Basel, Switzerland), 12(23), 3937. https://doi.org/10.3390/plants12233937

71. Zandonadi, D. B.; Monda, H.; Gralian, J.; James, A.; Lamar, R. T. and Santos. M. P. (2025). Humic acids as drivers of plant growth: Regulating root development and photobiology through redox modulation. Chem. Biol. Technol. Agric., 12:71. https://doi.org/10.1186/s40538-025-00789-9
72. Zhang, L.;Gao, M.; Li, S.; Alva, A.K. and Ashraf. M (2014). "Potassium fertilization mitigates the adverse effects of drought on selected Zea mays cultivars." Turk. J. Bot., 38(4):713-723.
73. Zhou, W.; Zhang, H.; Yu, Y.; Zou, X.; Shi, J.; Zhao, Y. and Ye, Y. (2020) Dissolution mechanism of sodium alginate and properties of its regenerated fiber under low temperature. Int J BiolMacromol., 162:810-819. doi: 10.1016/j.ijbiomac.2020.06.192.

Figures



(Fig.1Color of sodium alginate)

Warm water **Cold water** **Acetone** **Ethanol** **Methanol** **Petroleum ether**

(Fig. 2 Solubility behaviour of sodium alginate)

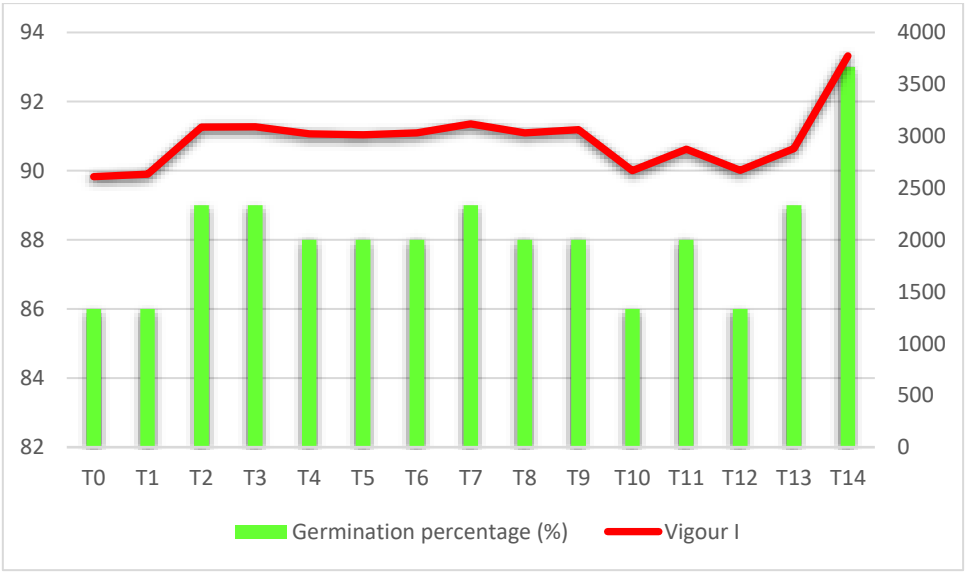


Fig. 3 Impact of biomolecules infused sodium alginate coating on germination percentage and vigour index I on Okra

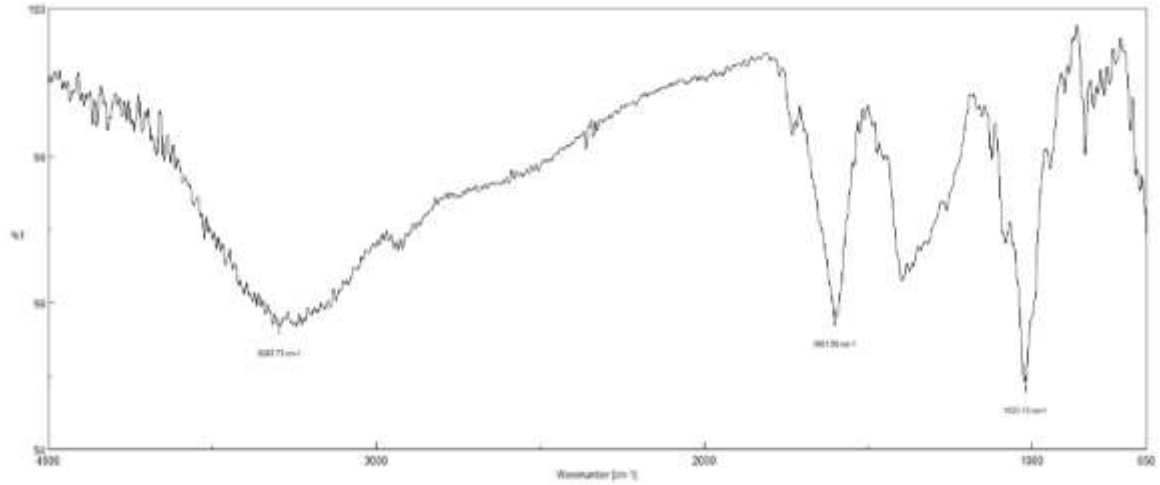


Fig. 4 FTIR spectrum of sodium alginate isolated from Sargassum myricocystum

T_0	T_{14}

Fig.6 Visualized difference in seedling

Tables

Table. 1 Represent the physiochemical, biochemical and phytochemical analysis of sodium alginate from seasweedsargassum myriocystum

PHYSIOCHEMICAL ANALYSIS		**BIOCHEMICAL ANALYSIS**		**PHYTOCHEMICAL ANALYSIS**	
Yield	25 g	**Carbohydrates**	70 %	**Flavonoids**	–
pH	7.20	**Proteins**	0.95 %	**Alkaloids**	–
Viscocity	90 cp	**Lipid's**	0.90 %	**Tannins**	– (Absent)
Moisture content	10 %	**Ash content**	18.15 %	**Phlorotannins**	–
Water absorbancy	5.5 g			**Terpenoids and Steroids**	–
Solubility Behaviour	Dissolves in both warm and cold water			**Saponins**	+ (Present)
				Glycosides	–
				Phenolic Compounds	–

Table. 2 Represent the IC-PMS analysis

Element (Isotope)	Element Name	Sodium Alginate Sample (ppm)
7 Li	Lithium	0.022
9 Be	Beryllium	0.009
11 B	Boron	17.813
23 Na	Sodium	200390.405
24 Mg	Magnesium	620.544
27 Al	Aluminium	28.574
31 P	Phosphorus	164.078
39 K	Potassium	200.573
44 Ca	Calcium	3876.649
48 Ti	Titanium	7.107
51 V	Vanadium	0.184
52 Cr	Chromium	2.075
55 Mn	Manganese	4.100
57 Fe	Iron	158.246
59 Co	Cobalt	0.125
60 Ni	Nickel	0.876
63 Cu	Copper	2.013
66 Zn	Zinc	3.237
75 As	Arsenic	3.429
95 Mo	Molybdenum	0.084
107 Ag	Silver	0.021

Element (Isotope)	Element Name	Sodium Alginate Sample (ppm)
111 Cd	Cadmium	0.158
118 Sn	Tin	3.413
121 Sb	Antimony	0.010
133 Cs	Cesium	0.001
137 Ba	Barium	9.444
202 Hg	Mercury	0.007
208 Pb	Lead	8.685

Table. 3 FTIR frequency peak (cm^{-1}) and functional groups of the extracted sodium alginate from seasweedsargassummyriocystum

S. No.	Wave number (cm^{-1})	% Transmittance	Functional Group (Vibration)	Bond Type / Assignment
1.	3699.764	98.5061	O-H stretching (free)	phenol, alcohol
2.	3584.056	97.6994	O-H stretching (free)	alcohol, phenol
3.	3295.75	95.6635	O-H stretching (hydrogen-bonded)	alcohol
4.	3281.286	95.7942	O-H stretching	carboxylic acid
5.	3100.011	96.2868	C-H stretching (aromatic)	aromatic hydrocarbon
6.	2906.2	96.9026	O-H stretching	alcohol
7.	1818.544	99.3767	C=O stretching	anhydride
8.	1780.939	99.2866	C-H bending	aromatic compound
9.	1775.154	99.1976	C=O stretching	conjugated anhydride
10.	1760.69	99.156	C=O stretching	carboxylic acid
11.	1742.37	98.6035	C=O stretching	esters
12.	1717.3	98.3983	C=O stretching	Carboxylic acids
13.	1601.592	95.7818	C=C stretching	Aromatic Compounds
14.	1395.246	96.3114	O-H bending	carboxylic acid
15.	1310.393	96.8924	O-H bending	phenol
16.	1270.86	97.3679	C-O stretching	aromatic ester
17.	1087.655	96.9291	C-O stretching	secondary alcohol
18.	1050.05	96.5043	C-O stretching	primary alcohol
19.	1020.159	94.885	CO-O-CO stretching	anhydride
20.	900.5941	98.8529	C-H out-of-plane bending	aromatic substitution
21.	830.205	98.8992	C-H bending	1,2,3,4-tetrasubstituted benzene

22.	720.2824	99.4072	aromatic out-of-plane C–H bending	benzene derivative
23.	680.7488	97.7695	C-H out-of-plane bending	aromatic substitution
24.	600.7175	96.2547	M–O stretching	metal–oxygen (inorganic)

Table. 4 Impact of biomolecules infused Sodium alginate polymer on seed quality parameters of Okra

Treatments	**Abnormal seedlings (%)**	**Root length (cm)**	**Shoot length (cm)**	**Seedling length (cm)**	**Dry matter production (g/ 10 seedlings**	**Vigour index II**
T_0	9	17.23	13.11	30.34	0.343	29
T_1	9	17.59	13.29	30.88	0.351	30
T_2	6	19.46	15.21	34.67	0.398	36
T_3	6	19.46	15.23	34.69	0.393	36
T_4	7	19.21	15.12	34.33	0.394	35
T_5	7	19.17	15.09	34.26	0.392	34
T_6	7	19.37	15.26	34.43	0.391	34
T_7	6	19.68	15.37	35.05	0.398	35
T_8	7	19.29	15.18	34.47	0.394	35
T_9	7	19.49	15.32	34.81	0.396	34
T_{10}	9	17.49	13.53	31.02	0.353	30
T_{11}	7	19.39	15.27	34.66	0.397	32
T_{12}	9	17.78	13.25	31.03	0.351	30
T_{13}	6	19.42	15.31	34.73	0.398	32
T_{14}	2	22.36	18.22	40.58	0.463	43
Mean	7	20.05	15.88	35.93	0.410	35
S.Ed	0.088	0.265	0.203	0.415	0.006	0.388
CD (0.05%)	0.178*	0.535*	0.409*	0.839*	0.013*	0.784*

(**T_0** – control, **T_1**– Sodium alginate Polymer 2 % 250 ml, **T_2** - 0.2 g Humic acid, **T_3**- 0.3 g Humic acid, **T_4** - 0.4 g Fulvic acid, **T_5**- 0.5 g Fulvic acid, **T_6** - Salicylic acid 200 ppm, **T_7** - Salicylic acid 250 ppm, **T_8** – Brassinolide 0.5 ppm, **T_9** - Brassinolide 1.0 ppm, **T_{10}**- 0.05 g Glutothione, **T_{11}** - 0.20 g Glutothione, **T_{12}** - 0.2 g Ascorbic acid, and **T_{13}** - 0.4 g Ascorbic acid **T_{14}** - 0.3 g Humic acid + 250 ppm Salicylic acid + 0.4 g Ascorbic acid)