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Status, exploitation and resource management of alginophytes in India: an account and way forward

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Abstract

The biodiversity of Indian seaweeds comprises ca. 865 taxa, of which the alginophytes *Sargassum* spp., *Cystoseira* spp. and *Turbinaria* spp. are traditionally exploited. The alginate trade in India evolved as a cottage industry in the rural coastal regions of Tamil Nadu. The resource surveys have assured sufficient feed-stock availability, but landing data between 1978 and 2019 revealed a 54.85 and 33.59% decline in biomass of *Sargassum* spp. and *Turbinaria* spp., respectively. Despite this, alginate production continues to register incremental growth from 112 t in 2004–2005 to 262 t in 2018–2019. The higher production was due to feed-stock imported for domestic processing. Self-reliance in production can only be achieved by resource management and developing a viable farming protocol. This shall support sustainable trade by reducing dependency on wild harvesting. The complete valorisation of biomass by employing a high-throughput integrated bio-refinery protocol for sequential extraction of industrial products, viz. bio-stimulant, pigments, mannitol and alginates, is pivotal for profitable enterprise. Since the domestic industry is heavily depending on artisanal seaweed gatherers of the Gulf of Mannar, it is crucial to protect their rights by resolving issues pertaining to ownership of the resource coupled with conservation and sustainable utilisation. Seemingly, there is still a lot to be done on alginophytes in India. This review provides information and data on various domains of alginate trade aimed at developing a national programme and policy.

Keywords Alginophytes · Phaeophyceae · *Sargassum* · Biomass valorisation · Seaweed farming · Indian standards · Wild harvest

Introduction

Alginophytes make up one of most important and commercially exploited marine renewable algal resources of the world ocean. Besides economic importance, alginophytes form the dominant flora in intertidal and sub-tidal areas. These species provide shelter, diet, habitat and breeding grounds to several marine taxa and thus are perceived as keystone species responsible for structuring marine habitats and providing ecosystem services (Draisma et al. 2010). The algin (polysaccharides) from which their name has been derived primarily imparts adhesion to the substratum as well as flexibility and structure to the cell wall matrix of various parts (i.e. stipe vs blade). Alginates—salts of alginic acid—act as thickening agents; the most common are sodium, calcium and ammonium alginate. The extraction process for alginic acid was patented by Stanford in 1881 (British Patent No 142); however, several variations on the original method were described and employed to improve the quality and quantity (reviewed by Booth 1975). Alginophytes, due to their non-flammable properties, were used even during the Roman era for protection in warfare devices against incendiary missiles (Pérez-Lloréns et al. 2020). Nevertheless, recent applications encompass bio-medical and clinical (dental moulds, prosthetic impressions, chelating agents to purify heavy metal contamination from blood, bio-plotted hydrogel scaffolds for encapsulation of islets of Langerhans and myocardial implantation and targeted gene delivery); pharmaceutical and wellness (health, foods, face mask, treatment of gastroesophageal reflux,

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antacid); food and beverages (binders for fish feed, pet food and processed meats, thickeners for yoghurt, ice cream and sauces, foam stabilizing agent for beer); art and crafts (taxidermy moulds and body cast) beside being used routinely in welding rods, textile printing and dye separation, non-drip paints; and in the fertiliser industry as plant bio-stimulants (Clingerman and Franco Jr 1988; Rama Rao 1991; McHugh 2003; Paul and Sharma 2015; Burges Watson et al. 2018; Duin et al. 2019;).

Common brown seaweed genera, e.g. *Ascophyllum* in the UK and continental Europe (Guiry and Morrison 2013; Borges et al. 2019; Monagail and Morrison 2020), *Macrocystis* in the USA, Mexico, Chile (Gerard and North 1984; Stekoll and Else 1990; Hernández-Carmona et al. 2000; Gutierrez et al. 2006; Macchiavello et al. 2010; Robledo and Freile-Pelegrín 2011; Alemañ et al. 2019; Vázquez-Delfín et al. 2019), *Laminaria*/*Sacharina* in Europe, Asia-Pacific (Chengkui 1984; Tseng 2001; Peteiro et al. 2006; Phang 2006; Kerrison et al. 2015; Rolin et al. 2017; Stévant et al. 2017), *Ecklonia* in Africa (Papenfuss 1942; Bolton et al. 2012), *Lessonia* in the Americas (Zuniga-Jara and Soria-Barreto 2018), *Durvillaea* in Asia-Pacific and Chile (Santelices et al. 1980; Westermeier et al. 1994; Tala et al. 2019; Velásquez et al. 2020) and *Sargassum* in India and subcontinent (Sreenivasa Rao et al. 1964; Kalimuthu et al. 1991; Subba Rao and Mantri 2006) have been of great interest to the phycocolloid industry. Ireland, Scotland, Iceland, west coast of Norway, France (only for cattle feed), Australia, Chile, California (USA), Indonesia and South Africa are the important countries where natural harvesting of alginophytes has been reported (McHugh 2003). The global alginate industry utilizes 236,820 dry t of biomass to produce 24,644 t alginate worth 345 million US$. Qingdao Bright Moon Seaweed Group, China, is the single largest producer of alginate in the world, followed by FMC in Norway, Great Gather Ocean Company in China, and DuPont and Cargill in France. In addition, there are over 20 small-scale units currently operational in China, but water scarcity has been a limiting factor (Porse and Rudolph 2017).

Indian scenario

The alginate trade in India evolved from a cottage industry of artisans based on natural collections, in pockets of rural coastal Tamil Nadu. Although estimated at 500 t (Thivy 1964), actual production reached 200 t only in 2016 (Ganesan et al. 2019). The domestic demand is 1000 t, and currently 60–70% requirement is met through imports (Personal communication with Mr. Bose, President Agar and Alginate Manufacturers Welfare Association, India). M/s. SNAP Natural Products and Alginate (P). Ltd, Rani Peth, Tamil Nadu, is the major producer within India with approximately 90% of the market share, whilst the remainder is supplied by Agar and Alginate Manufactures Welfare Association, Madurai, Tamil Nadu (a conglomeration of small industries). Unlike agar and carrageenan, the domestic alginate industry is largely not constrained by a raw material deficit, but the resultant blend of alginate (20–50 mPa s) prepared locally does not compete favourably with international standards. Other technical issues include, much smaller processing capacities of individual factories without sophisticated machineries (majority are cottage units) and dominance of cost-conscious end-users who prefer procurement of low-quality product from un-organised sector, while larger processing units need to compete with imported products. These are some of the prime determinants for industry growth in India (personal communication with Mr. Bose). Further, these resources also act as feed-stock for other industrially important products such as mannitol, fucoidan, iodine and plant bio-stimulants albeit in very small proportion.

Species diversity, distribution, nomenclature and taxonomy

Among the diversity of different alginophytes used globally, *Sargassum* is the largest genus with 358 taxonomically accepted species, followed by *Laminaria* (29), *Ecklonia* (13), *Lessonia* (11), *Durvillaea* (8), *Ascophyllum nodosum* and *Macrocystis pyrifera* (Fraser et al. 2020; Guiry and Guiry 2020). Specifically in Indian context, species of *Sargassum*, *Turbinaria*, *Cystoseira*, *Hormophysa*, *Spatoglossum*, *Rosenvingea* and *Chnoospora* are important. However, only the first three grow in harvestable quantities of which the former two are industrially exploited.

Species diversity and distribution

The prime monograph of 'Indian Phaeophyceae' was published by the Indian Council of Agricultural Research, New Delhi (Mishra 1966). The order Fucales is represented by two families, the Cystoseiraceae comprising the genera *Cystoseria* and *Hormophysa* and the Sargassaceae genera *Sargassum* and *Turbinaria* (Krishnamurthy and Ezhili 2013). *Hormophysa* is monotypic and represented by *Hormophysa cuneiformis* (Børgesen 1937). Among these taxa, *Sargassum* has a maximum diversity of 52 species and 22 varieties and forms (Oza and Zaidi 2001). Its earliest record was from the Tranquebar, Coromandal coast (modern day Tharangambadi in Tamil Nadu), by J.G. Koenig—a Danish Missionary, surgeon and naturalist (c.f. Sahoo et al. 2001). In addition, other eighteenth century collections are housed in the Herbaria of Hooker, Berol, Rudolph, Colsman, Areschoug and Haussk (c.f. Srinivasan 1967). Further, nineteenth century collections were from Cape Comorin (Kanyakumari), Bombay (Mumbai); Nicobar Island; Andaman Island (von Martens 1871); and

Dwarka, Mumbai and Southern India (Børgesen 1933, 1935). Srinivasan, (1967) published a monographic account of genus *Sargassum* from Indian territorial waters. An old report of *Turbinaria* from Indian waters recorded nine taxa in eight species (Shah and Vaidya 1967): *Turbinaria conoides* from Port Okha; *T. conoides* form *laticuspidata* from Tuticorin; *Turbinaria ornata* form *ecoronata* from Olakuda, Rameswaram; *Turbinaria decurrens* from Pamban, Akkalmadam and Pulli Island; *Turbinaria. murrayana* from Port Okha, *Turbinaria condensata* from Lakshdweep; *Turbinaria turbinata* from Port Okha; *Turbinaria trialata* (now *T. turbinata*); and *Turbinaria triquetra* from Nicobar. However, according to Krishnamurthy and Ezhili (2013), *T. murrayana*, *T. turbinata* and *T. trialata* were misidentifications. The genus *Cystoseira* has been represented by five species, namely *Cystoseira barbata* (now *Treptacantha barbata*), *Cystoseira indica*, *Cystoseira myrica* (now *Polycladia myrica*), *Cystoseira opuntioides* (now *Carpodesmia zosteroides*) and *Cystoseira trinodis* (now *Sirophysalis trinodis*) (Oza and Zaidi 2001). Nevertheless, only three species, namely *C. indica*, *C. myrica* and *C. trinodis*, are recognised today (Krishnamurthy and Ezhili 2013). The distribution of the most common species is provided in Supplementary table 1. It has been found that maximum diversity is recorded from Tamil Nadu and Gujarat. Gulf of Kutch (GoK) and Gulf of Mannar (GoM) islands harbour more than half of the species, followed by the Andaman and Nicobar islands.

Taxonomy, nomenclature and molecular studies

It may be noted that most of the taxonomic literature available prior to 2010 for *Sargassum* is not helpful for arriving at correct taxonomic credentials. Krishnamurthy and Ezhili (2013) provided complete description and taxonomic keys for all the species. *Sargassum johnstonii* and *Sargassum merrifieldii* were described from Indian coast (Thivy and Chauhan 1964). *Sargassum merrifieldii sensu* Thivy and Chauhan has been shown to be *Sargassum thivyae*. Likewise, Chauhan (1965) described *Sargassum prismaticum* from Porbandar. However, it has been reduced to variety *Sargassum tenerrimum* var. *prismaticum* (Krishnamurthy and Ezhili 2013). Most recently, a new record of *Sargassum zhangii* was reported from Palk Strait, Tamil Nadu, that was further confirmed at molecular level using cytochrome and oxidase 1 (COX 1) internal transcribed spacer1 (ITS1) gene (Bast et al. 2016). *Turbinaria indica* Gopalakrishnan was published without Latin diagnosis but was later validated by Krishnamurthy (2006). Among the species of *Cystoseira*, only two have been extensively studied, namely *C. indica* and *C. trinoides* (Krishnamurthy and Ezhili 2013). The former was originally described under new genus *Stokeyia indica* Thivy *et* Doshiand later synonymised to *C. indica*. However, currently this species is regarded as *Polycladia indica* (Thivy *et* Doshi) Draisma, Ballesteros, F. Rousseau *et* T. Thibaut (Draisma et al. 2010). It also is worth mentioning that there have been no further molecular studies in both *Turbinaria* and *Cystoseria* from Indian waters.

Resource estimates, standing stock and landings

With the exception of China, where *Saccharina japonica* is cultivated (7.06 million t or 51% of total cultivated seaweed in China in 2015) (FAO 2018), the rest of the global alginophyte harvest comes from the natural gathering. The long-term supply seems to be inadequate for this resource; thus, countries like Norway and Chile are regulating the harvest. According to Porse and Rudolph (2017) *Saccharina* (*Laminaria*) spp. accounted for over half (52%) of the global harvest, followed by *Lessonia* spp. (28%), *Macrocystis* (9%), *Ascophyllum* (8%) and others (3%). It may be noted that, 122,000 dry t of *Saccharina* alone has been harvested in 2015.

Industrial biomass gathering and seasonality

The commercial exploitation of this resource in India started in 1966 with collection of a cast ashore *Sargassum*. Later, efforts were made for gathering biomass from islands of GoM by artisanal fishermen of nearby coastal villages. The efforts were further extended to *Turbinaria* in 1975. Traditionally, they have been collected from around 300 km of coastal belt between Kanyakumari to northwards peninsula that forms the Guf of Mannar. The biomass has been collected from intertidal as well as sub-tidal areas. It may be noted that, no tools are provided by the company. The collectors are mostly women who collect the seaweeds for 10–12 days every month coinciding with low tides throughout the year. The landing is gathered at 14 fishing villages of the Ramnathapuram District (Fig. 1). The industry sources do not tend to divulge the species, but the species are predominantly,*S.wightii*,*S.myriocystum*,*S.ilicifolium*,*S.swartzii*, *S. tenerrimum*, *S. merrifieldii* and *S. johnstonii* as well as *T. conoides* and *T. ornata*. The species of *Sargassum* show a peak growth according to their favourable season. The best season for *Turbinaria* at Kilakarai has been from January to March; Periapattanam from August to December; and Rameswaram, Pamban, Vedalai and Seeniappa Darga during April–July. *Cystoseira trinoidis* in GoM and Palk Bay has favourable growth during July/August–January (Kaliaperumal and Kalimuthu 1997; Subba Rao and Mantri 2006; Veeragurunathan and Sujatha 2013). The harvest is being brought in boatloads and visual estimation (no actual weight) is agreed by both the collectors and seaweed dealers. Nevertheless, dried seaweeds are weighed with a 30%

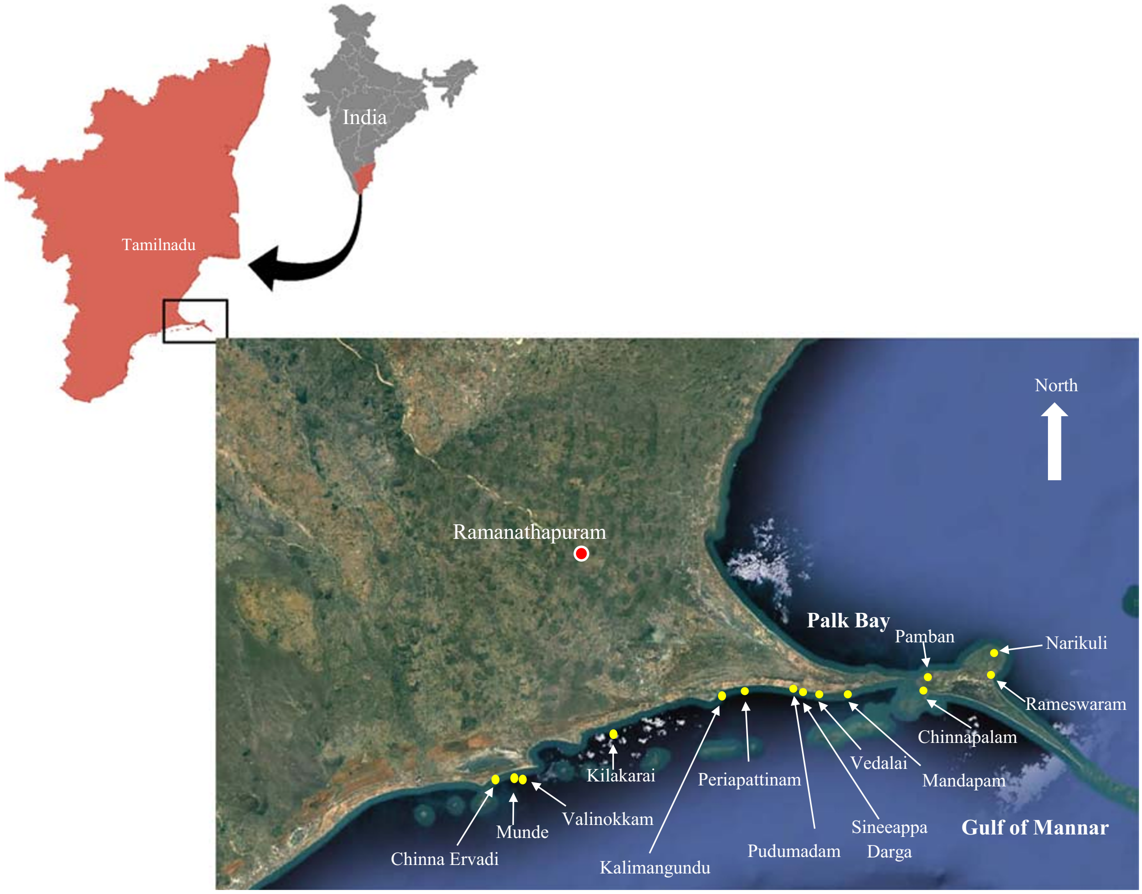


Fig. 1 Map dipicting landing centres of alginophytes in India

moisture content permissible in commercial purchase. The collection sector alone engages around 2000 fishermen of which 70% are women. The employment opportunities are seasonal, but daily assured income attracts greater participation of women during the peak seasons (Silas and Kalimuthu 1987). An income of 5.89–9.16 US$ day^{-1} (May 2020) is offered to the collector by agents. The wages vary based on the skill and experience of the collector. The market price is fixed and it is currently (May 2020) US$ 209.37 dry t^{-1} including all the species mentioned above (personal communication M/s. SNAP Naturals and Alginate (P) Ltd). The major post-harvest processing operations are carried out at the processing yard located in Thirupullani, Tamil Nadu. Here, drying, sorting and packaging take place before it is being dispatched to respective production units.

Alginophyte landings and re-colonisation experiments

The annual distribution of wild harvest (not cast ashore/drift) from 1978 to 2019 is given in Fig. 2. The low landings have primarily reflected corresponding less demand by industry. The analysis from previous decades revealed a declining trend, with the highest biomass of 28,373 dry t of *Sargassum* reported during 1990–2019, whereas for *Turbinaria* it was 3751 dry t during 1980–1990. The lowest biomass for both genera was 15,565 and 1260 dry t, respectively, reported between 2010 till the end of 2019. Kaliaperumal et al. (2004) have reported that demand for overall alginophyte biomass was 33.82% lower in 2001 than previous year with a 31% decline in demand for *Sargassum* spp. and a 91% decline for *Turbinaria* spp.

Alginophyte resources have been over-exploited from selected area (GoM) due to improper collections practices in the past (prior to 2010). Re-colonisation studies have been carried out on *S. wightii* along the Mandapam coast. Thomas and Subbaramaiah, (1992) observed recruitment via zygotes on four coral stones covering an area of approximately 1 m^2 for 6 years. The experiment started in December and young germlings were observed within 2 months by February. The 1-cm plantlets in March reached 39 cm by December, with maximum growth of 14.5 cm month^{-1} in November. The length as well as growth extension was higher in plants arising from hold fast (2 - 70 cm length; 2 - 19.6 cm extension growth) in subsequent years than newly germinated zygotes (1–39 cm length; 1.1–14.5 cm extension growth). The density of plants varied from 35 to 46 plants in 0.5 m^2 quadrat. The study inferred that the new establishment of plants reduced

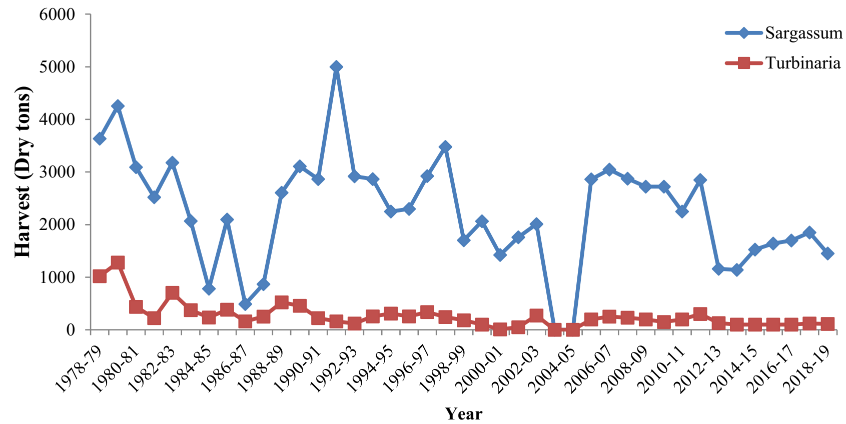


Fig. 2 Annual landings of alginophytes from Indian coast

after first 2 years which might be due shedding effect. Although it is a good study, artificial recruitment of young plants on hard substrates is not being generally practised by the fisherman due to the lack of adequate knowledge and training in the subject.

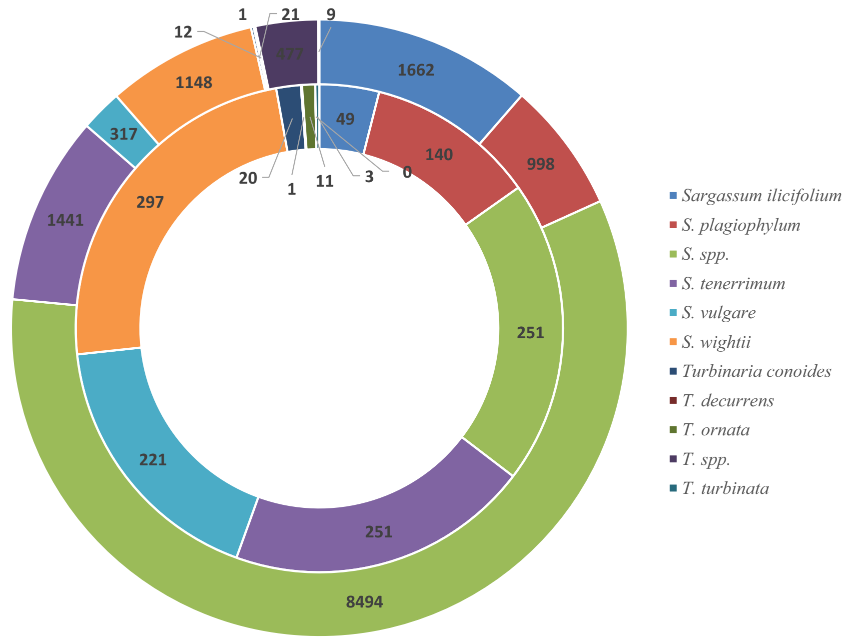
Resource estimates for alginophytes

The accurate biomass availability estimates are necessary for management and commercial exploitation. The initial surveys were preliminary, were fragmentary and rely on spot-surveys, while the values reported in this section are all estimated standing biomass (except drift survey). The availability of 11 dry t of *Sargassum* has been reported from Gulf of Kutch [GoK] (Desai 1967). Chauhan and Krishnamurthy (1968) have reported 4000 fresh t of alginophytes from 10.65 km^2 sub-tidal area of GoK. Coordinated efforts also have been made by CSIR-Central Salt and Marine Chemicals Research Institute (CSIR-CSMCRI). The first survey was carried out during 1965–1966 to estimate the drift seaweed potential of the country. Of the 343 km of coastline surveyed, 205 km reported the presence of drift seaweed. An availability of 980.43 fresh t alginophytes has been registered of which 84.65% reported from Idinthakarai (Krishnamurthy 1969).

The resource estimates for 11 species are available for the intertidal area for five coastal states, namely Gujarat, Maharashtra, Tamil Nadu, Andhra Pradesh and Lakshadweep. However, for sub-tidal waters, estimates are available only for Tamil Nadu (Subbaramaiah et al. 2006). Pan-Indian national mission 'Survey of economic seaweed resources' was undertaken during 1961–1991 and funded by the National Committee on Science and Technology, Government of India. The estimates ranged from 10.69 fresh t for Lakshadeep (lower limit) to 2750 tons fresh weight for Tamil Nadu sub-tidal waters (upper limit). Among the different species, *S. ilicifolium* had the highest reported biomass with 1612.50 fresh t in the sub-tidal waters of Tamil Nadu (Fig. 3). The species wise cumulative biomass availability for *Sargassum* and *Turbinaria* has been depicted in Supplementary figs. 1 and 2 respectively. Nevertheless, data related to commercial as well as non-commercial species showed that total biomass of 21680.8 fresh t was available. The maximum 10,532.9 fresh t (half of the total reported biomass) comprised of *Spatoglossum asperum* and lowest was that of *Chnoospora minima* and *Sphacelaria furcigera* (now *S. rigidula*) 0.1 fresh t each (Supplementary table 2). Nevertheless, no attempt was made in recent years to estimate standing biomass of alginophytes from India.

Preservation, pre-treatment and storage of biomass

Generally, seaweed feed-stock is collected from drift algae or harvested from natural beds (Fig. 4a–d). The collected biomass is stored in jute gunny bags in a warehouse before being processed for industrial utilisation. But the quality of the seaweed (in terms of product) deteriorates due to the natural microbial flora, if it is not processed immediately. The biomass has been processed by drying, ensilage or treated with bactericides, sodium tetraborate (borax), formalin, sodium chloride, calcium chloride (Tewari and Mody 2006). The air-dried as well as formalin-treated *S. tenerrimum* stored in cloth bags has been found to absorb more moisture than when stored in plastic containers, with slight decrease in alginic acid content and viscosity (Tewari et al. 1983). However, open-air sun-drying immediately after collection remains the most cost-effective technique. It may be noted that in *S. tenerrimum*, 2% formalin followed by sun-drying (23 cm or 5 kg m^{-1} bed) is most effective in removing 90% moisture within 100–108 h. The same biomass, when spread on inclined grids, takes 52–108 h and 20–36 h on horizontally suspended ropes (Tewari et al. 1987). A significant increase in viscosity of alginic acid has been recorded when formalin concentration was increased from 2 to 5%. The formalin acts as a bactericidal agent during storage and also removes phenolic compounds responsible for



Upper and lower limits displayed in outer and inner peripheries respectively

Fig. 3 The standing stocks of alginophytes along Indian coast. Source: Subbaramaiah et al. (2006)

discoloration. Similarly, 1% borax also is effective in terms of maintaining extractable quantity (Mody et al. 1992). The turnaround time for bigger industries (between collections to the sale to the processor) is generally 5–10 days. There are

Fig. 4 *Sargassum* collection and processing for alginate extraction. **a** Drift biomass along the Shivrajpur coast, Gujarat. **b** Naturally collected biomass unloaded from boat along GoM, Tamil Nadu. **c** Sun-drying the biomass by fisherwomen at at Tirupallani, Tamil Nadu. **d** Crushing of dried biomass as the part of pre-processing at Tirupallani, Tamil Nadu

several small-scale enterprises where stored biomass (as old as 1 year) is procured where formalin treatment (2%) is preferred. However, formalin is hazardous and its use is discouraged. The industry source confirmed that 95% of the biomass utilised by them is without any treatment and only sun-dried. However, in the case of pre-treated biomass, it is washed several times with fresh water to remove chemicals used in pre-treatment. It may also be noted that alginate used for production of food grade needs to comply with stringent quality control details are discussed in section dealing with quality, grade and product specifications.

Alginate extraction and chemical modification

The blooms of *Sargassum* in Caribbean islands in 2015 reported the availability of ~ 10,000 fresh t of biomass daily. This along with recurrence of this phenomenon along the beaches of the Gulf of Mexico, the Atlantic Coast of the USA, and the shoreline of western Africa from Morocco (south of Casablanca) to the Gulf of Guinea has generated enormous interest in sustainable utilisation of this resource for commercial gains (Milledge and Harvey 2016). The entire global alginate production is concentrated in China, whereas speciality food and pharma-grade alginate is produced in Europe. The Asia-Pacific accounted for 31,844 t industrial grade (23,500 t industrial and 8344 t food–pharma grade) and 1600 t propylene glycol alginate; this is followed by Europe (13,500 t industrial grade) and Americas (1000 t industrial grade and 200 t propylene glycol alginate) (Porse and Rudolph 2017).

Alginate production industrial protocol

Basically, alginate extraction comprises of rehydration and de-pigmentation of biomass, acid pre-treatment and extraction. In addition, the random distribution and molar ratio of the monomer blocks, i.e. β-D-mannuronic acid (M) and α-L-guluronic acid (G) affects the extraction procedure and characteristics of final products. This remains a challenge for developing a universally sustainable process. For instance, the number of acid pre-treatments increases the yield, but markedly affects the viscosity of final product (Hernández-Carmona et al. 1998). In India, extraction of alginates mostly takes place at cottage scale except at M/s. SNAP Alginate and Naturals Pvt. Ltd. The installed capacity of small-scale unit ranges from 1–3 t $month^{-1}$ while that of medium scale is 50 t $month^{-1}$, but it should be noted that actual manufacturing is inevitably low. The unit operations involved in industrial production are cleaning of seaweed, chemical pre-treatment, extraction of alginate and separation of the extract; after this, there exist two routes. The first option involves precipitation of alginic acid leading to production of sodium alginate. The second route comprises precipitation of calcium alginate, acidification/conversion to alginic acid and production of sodium alginate. The technical challenge involves demanding nature of the separation of product. The direct route of production of alginic acid from seaweed is not preferred due to the need to separate the slimy residue from the viscous solution where the bulk liquid is contained firmly within the alginic acid matrix which is difficult to handle. On the other hand, the fibrous nature of calcium alginate is easy to filter that can be converted into alginic acid by a simple acidification process (Fig. 5). The yield of alginic acid reported by several studies from different Indian samples is given in Table 1. It ranges from 1.5% in *Padina tetrastromatica* collected from Arockiapuram, Tamil Nadu (Stella Roslin 2003) to 36.5% in *S. wightii* collected from Mandapam, Palk Bay, Tamil Nadu (Thomas and Subbaramaiah 1991).

Improved green technologies

The current techniques routinely used for alginate production are water intensive. Furthermore, the length of the process, hefty chemical inputs and culminating environmental challenges require a sustainable solution for its uninterrupted and eco-friendly production. There are three main methods, namely ultrasound treatments, enzymatic treatments and microwave-assisted extraction emerging as potential alternatives to obtain alginate with a minimised chemical inputs. Chhatbar et al. (2009) have reported rapid hydrolysis of alginate using microwaves for M/G ratio determination and the results are in accordance with the conventional protocol. However, this process has not been scale up as yet. Ultrapure and amitogenic alginate utilised in bio-medical encapsulation applications is prepared following more arduous extraction techniques either employing free-flow electrophoresis (Zimmermann et al. 1992) or Ba-alginate gels (Klöck et al. 1994). These techniques, although not carried out in India, bring opportunity for advancement of skill set and product diversification for the domestic producers. Currently, the entire domestic requirement for ultrapure product is met through import.

Chemical modifications and emerging applications

The function modification of alginate has been attempted by targeted or fortuitously approaches (reviewed by Siddhanta et al. 2015). By a systematic approach, a series of alginic acid amide derivatives have been synthesised using mono-, di- and tri-nuclear aromatic amines. The thixotropic o-amino-benzoic (OABA) and m-amino benzoic (MABA) acid amides of sodium alginate Na–Alg have been obtained. The satisfactory viscosity under shear

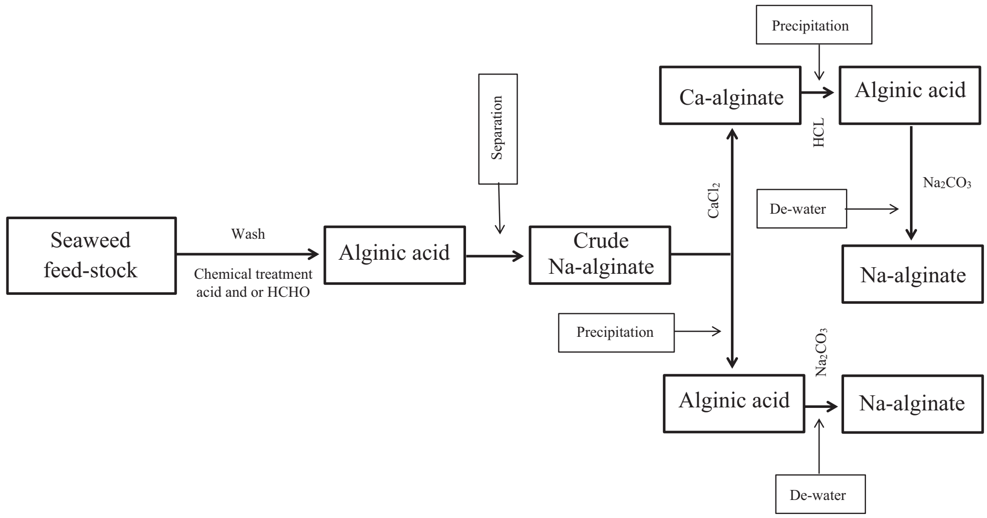


Fig. 5 Schematic representation of unit operations involved in industrial processing of sodium alginate

of ca. 32 mPa s at ca. 800 s^{-1} for Na–Alg/OABA has been found to be suitable in sprayable formulations. The hydrogel created by an agar/Na–Alg blend (1:3) and grafted with polyacrylamide (PAAm) exhibited superior swelling capacities of 24, 18 and 11 g g^{-1} in acidic, neutral and alkaline aqueous media, respectively. The swelling behaviour has been harnessed successfully, followed by the pH- and structure-dependent controlled-release of structurally different drugs, namely atenolol (ATN), indomethacin (IND), isoniazid (INH), paracetamol (PCT) and pravastatin (PST). The alginic acid and polyglucuronic acid (PGA) amide of ethylenediamine (EDA) have been used to synthesise novel water-soluble fluorogenic inter-polymeric diamide through a monoamide of PGCA and EDA. A yield of > 80% wt in each step has been achieved. TEMPO (2,2,6,6-tetramethyl piperidine-1-oxyl radical) oxidation of cellulose has been used to afford PGA. The monoamide of PGA has exhibited sevenfold higher fluorescence emission and recorded superior adsorption of divalent Pb^{2+} (398.8 mg g^{-1}) and Hg^{2+} (282.8 mg g^{-1}) metal ions than the inter-polymeric diamide. The ester and amide derivatives of alginate along with 9-chloromethyl anthracene and 2-amino anthracene in presence of an acceptor pyrene have displayed photosensitizer activity. An energy transforming efficiency of 63% and 37% has been recorded for ester and amide respectively. Further, significant hydrophilic–lipophilic balance factor (> 10.0) of these derivatives have made them excellent solubilizers having potential applications as sensor and photosensitizers (Siddhanta et al. 2015). It may be noted that these studies used alginate derived from *Sargassum* spp. of Indian waters. These chemical modifications are practical, but pilot-scale experiments are necessary to determine their cost-effectiveness to be adapted by industries.

Indian standard specifications

The US Food and Drug Administration (FDA) has approved the use of alginates as generally recognized as safe (GRAS) as an emulsifier, thickener and stabilizer in food applications. Further sodium alginate is extensively studied polymer for pharmaceutical as well as bio-medical applications globally. Therefore, its monograph is available in both the European Pharmacopeia and the United States Pharmacopeia (The United States Pharmacopeia, 2011; The European Pharmacopoeia, 2011). The Indian standards are also available for alginophytes—seaweed material—both *Sargassum* (grades I and II) and *Turbinaria* (grades I and II) as well as for alginic acid, sodium alginate and calcium alginate: food grade and sodium alginate for textile grade. The requirement of the raw material of alginophyte allows the use of a material having alginic acid of minimum 15–25% by mass, min 100–190 cP viscosity, maximum 15–20% moisture and maximum 3–7% extraneous matter and other seaweed impurities depending on grade and type of seaweed (Table 2). The food-grade alginic acid, sodium alginate and calcium alginate required purity of min 90–106%, max 15% moisture, max 0.2% insoluble matter, max ash content 12–27%, minimum viscosity of 30 cP, presence of heavy metals between 10 and 40 mg kg^{-1} and absence of *Escherichia coli* and *Salmonella* in 1 g and 10 g samples respectively (Table 3). Standards for sodium alginate for sodium alginate for textile grade are low due to its application in non-food industry. While, compared while the United States Pharmacopeia as well as the European Pharmacopoeia, purity and ash content are found to be similar, but other standards are found to be different (Szekalska et al. 2016). This has been attributed to the different standard regime operated in these countries, as well as the Indian standards being quite old and in need of re-examination in light of the fast changing global scenario.

Table 1 Yield of alginic acid reported from Indian seaweeds

Name of the species	Geographic location	Yield (%)	Reference
Sargassum swartzii *S. tenerrimum*	Okha, Gujarat	10.92–19.71 6.29–11.02	Chauhan 1970
S. tenerrimum *S. johnstonii*		10.08 22.34	Kappanna et al.1962
Sargassum spp.		19.88	
S. tenerrimum	Adatra, Gujarat	8	Sreenivasa Rao et al. 1964
S. tenerrimum *Sargassum spp.*	Sikka, Gujarat	14.77 21.28	Kappanna et al. 1962
Cystophyllum muricatum		19.74	
Dictyota spp.		5.50	
Sargassum spp.	Porbandar, Gujarat	7.12	Kappanna et al. 1962
Cystoceraceae spp.	Veraval, Gujarat	19.34	Kappanna et al. 1962
S. tenerrimum *Sargassum* spp.	Dwarka, Gujarat	4.85 27.49	Kappanna et al. 1962
S. cinereum var *berberifolium*		29.17	
Sargassum spp. *Turbinaria conoides*	Gulf of Mannar, Tamil Nadu	17.55 15.96	Valsan 1955
Cystophyllum muricatum		13.58	
Hormophysa triquerta		16.87	
Padina spp.		8.45	
T. decurrens	GoM, Tamil Nadu	16.3–26.3	Kaliaperumal and Kalimuthu 1976
S. myriocystum	Pudumadam, GoM, Tamil Nadu	14.26–26.07	Kalimuthu 1980
Colpomenia sinuosa *Hydroclathrus clathratus*	Mandapam, Tamilnadu	9.8–14.1 9.7–14.7	Kalimuthu et al. 1991
Rosenvingea intricata		10.4–20.5	
S. ilicifolium *S. myriocystum*		34.9 34.5	Chennubhotla et al. 1982
Padina boergesenii *T. ornata*	Agatti, Lakshadweep	9.2 24.1	Kaliaperumal et al, 1989
P. boergesenii	Bangaram, Lakshadweep	4.4	
T. ornata		23.3	
P. boergesenii	Androth, Lakshadweep	4.5	
T. ornata		22.4	
P. boergesenii	Minicoy, Lakshadweep	4.6	
T. ornata		22.4	
P. boergesenii	Suheli, Lakshadweep	8.0	
T. ornata		19.1	
S. duplicatum		19.1	
P. boergesenii	Kalpeni, Lakshadweep	6.6	
T. ornata		24.4	
Chnoospora implexa		10.6	
T. conoides		27.3	
S. tenerrimum *D. dumosa*	Goa	15.16 13.34	Solimabi and Naqvi 1975
C. sinuosa		16.65	
P. tetrastomatica		8.48	
D. bartayresii		22.94	
Spatoglossum asperum		17.14	
P. gymnospora	Pudumadam, Tamilnadu	9.4–24.8	Chennubhotla et al. 1978
T. decurrens	Mandapam, Tamilnadu	16.3–26.3	Kaliaperumal and Kalimuthu 1976

Table 1 (continued)

Name of the species	Geographic location	Yield (%)	Reference
S. wightii	Pudumadam, Tamilnadu	12.10–26.32	Jayasankar 1993
S. wightii	Mandapam, Tamilnadu Krusadai Island	23–36.5 15–29	Thomas and Subbaramaiah 1991
Stoechospermum marginatum	Pudumadam, Tamilnadu	14.5–23.8	Kalimuthu et al. 1980
Sargassum myriocystum	Pudumadam, Tamilnadu	14.26–26.07	Kalimuthu 1980
C. indica	Porbandar, Okha, Gujarat	8.16–16.39	Umamaheswara Rao, 1994
S. tenerrimum		12.53–20.0	
S. johnstonii		15.64–25.5	
S. polycystum	Rameswaram, Tamil Nadu	17.12–27.64	Jothisaraswathi et al. 2003
T. conoides	Kilakarai, South India	11–24	Jothisaraswathi et al. 2006
T. ornata	Palk Bay, Mandapam, Tamil Nadu	20–35	Umamaheswara Rao and Kalimuthu 1972
P. boergesenii	Arockiapuram, Tamil Nadu	5–20	Stella Roslin 2003
P. tetrastromatica		1.5–26.2	
Lobophora variegata		2.5–16	
S. marginatum		5–20	
Colpomenia sinuosa		4.1–14.6	
Chnoospora minima		4.5–26.4	
S. ilicifolium		5–27.5	
S. wightii		9.4–26.2	
S. linearifolium		7.5–24.8	

Valorisation and other value-added products

Brown seaweeds besides alginate produce other industrially important products such as mannitol, fucoidan, plant biostimulants and secondary metabolites.

Source of mannitol

Mannitol is a diuretic and has been used to treat or prevent medical conditions, e.g. cerebral oedema, glaucoma and kidney failure where accumulation body fluids takes place. Mehta and Parekh (1978) reported mannitol content of 35 samples representing 15 seaweed species collected from 4 different locations of Saurashtra coast of India. This ranged from 1.22 to 16%. The mannitol from 5 seaweeds collected from 8 different islands of Lakshdweep ranged from 1.4 to 9.5% (Kaliaperumal et al. 1989a, b). Seasonally, the mannitol in *S. wightii* and *T. conoides* from GoM varied from 1.2 to 5.5% in former and 1.78 to 7% in the latter (Umamaheswara Rao 1969). The mannitol in *T. decurrens* from GoM ranged from 1.5 to 8.7% (Kaliaperumal and Kalimuthu 1976) and in *S. myriocystum* ranged 1.8 to 5% (Kalimuthu 1980).

Source of fucoidan

Fucoidan compounds have been marketed as a dietary supplement as well as nutraceutical (Marinova, Australia). Due to its low toxicity, bioavailability through oral dosage and multiple

Table 2 Bureau of Indian Standards (BIS) specifications for alginophytes

Characteristics	Requirement				Method of test ref to appendix
	Sargassum		*Turbinaria*		
	Grade I	Grade II	Grade I	Grade II	
Alginic acid, % by mass, *Min*	25	15	25	15	C-1
Viscosity[a], cP	190	150	150	100	C-2
Moisture, %, *Max*	15	20	18	20	C-3
Dirt, dust, mud and sand % by mass, *Max*	5	7	5	7	C-4
Other seaweed, % by mass, *Max*	3	5	3	5	C-5

[a] Viscosity of 1% sodium alginate solution at 27 °C

Table 3 Bureau of Indian Standards (BIS) specifications for food grade alginic acid (IS 7928:1993); food grade sodium alginate (IS 5191:1993) and food grade calcium alginate (IS 7905:1975)

Characteristics	Alginic acid			Sodium alginate			Calcium alginate			
	Requirement	Method of test Annex of this standard	Ref to appendix other Indian standards	Requirement	Method of test annex of this standard	Ref to appendix other Indian standards	Requirement	Method of test annex of this standard	Method of test appendix of IS 7928: 1975[a]	Ref to appendix clause of IS 1699: 1974[b]
Purity, as ($C_6H_8O_6$) % by mass, *Min*	91	A-1	–	19 to 106	A	–	90	A	–	
Moisture % by mass, on drying at 105 °C for 4 h, *Max*	15	A-2	–	15	B	A-2 of IS 7928: 1992	15	–	–	
Insoluble matter, % by mass, *Max*	0.2	A-3	–	1.0	–	A-3 of IS 7928: 1992	0.2	–	A-2	
Viscosity of 1% solution (m/m) cP, *Min*	–	–	–	30	C	–	–	–	–	
Ash (on dry basis) % by mass, *Max*	–	–	–	18–27	–	A-4 of IS 7928: 1992	12–18	–	A-3	
Acid insoluble ash (on dry basis), % by mass, *Max*	0.5	A-5	–	0.5	–	A-5 of IS 7928: 1992	–	–	–	
Lead (as Pb), mg kg^{-1}, *Max*	10	–	9 of IS 1699:1974	10	–	9 of IS 1699:1974	10	–	–	
Arsenic (as As), mg kg^{-1}, *Max*	3	–	10 of IS 1699:1974	3	–	8 of IS 1699:1974	3	–	–	
Lead (as Pb), mg kg^{-1}, *Max*	10	A-6	–	40	–	A-5 of IS 7928: 1992	–	–	–	
E. coli	Absent (in 1 g)	–	IS 5887 (part 1): 1976	Absent (in 1 g)	–	IS 5887 (part 1): 1976	–	–	–	
Salmonella	Absent (in 1 g)	–	IS 5887 (part 1): 1976	Absent (in 1 g)	–	IS 5887 (part 3): 1976	–	–	–	

[a] Specification for alginic acid, food grade

[b] Methods of sampling and test for food colours (first revision)

modes of action indicate the potential in the treatments including inflammation, vascular physiology, carcinogenesis, etc. (Chale-Dzul et al. 2015; Lowenthal and Fitton 2015; Shanura Fernando et al. 2018; Mohan et al. 2019). Recently, antigenotoxicity effect of fucoidan on 4-nitroquinolin-1-oxide (4-NQO) induced genetic damage and apoptosis in mice bone marrow cells was reported (Arumugam et al. 2020). A study on *Sargassum* sp. showed that at 100 °C temperature, 5 h extraction time and pH 8 resulted in maximum yield of 9.4 ± 1.9%, while the carbohydrate content was 320.23 ± 1.68 mg g^{-1}. The sulphate content in the crude extract was 37 ± 4.45 mg g^{-1}. The maximum emulsification of 72.09 ± 0.61% was recorded in crude oil, followed by 67.44 ± 0.93% in neem oil and least 6.82 ± 0.89% in mustard oil (Narayani et al. 2016). The other lesser-known uses of alginophyte biomass such as bio-medical applications, secondary metabolites and source of iodine are listed in Supplementary material table 3.

Utilisation of industrial spent biomass

Sudhakar et al. (2017) evaluated utilisation of alginate industry spent biomass obtained from commercial processing plants of for ethanol production. The saccharification was carried out using mild acid (1% (v/v) H_2SO_4 at 121 °C for 15 min) and or marine bacterial consortia yielding 7.25 ± 0.44% DW carbohydrate and 15.27 ± 1.02 g L^{-1} reducing sugar (the protocol for ethanol production is given in Supplementary table 4). The ethanol production of 2.60 ± 0.42 g L^{-1} was achieved from spent biomass. The study confirmed spent alginate biomass as novel and renewable resource for production of value-added ethanol. The quantification of antioxidant properties of fucoxanthin extracted from *S. wightii*, *S. ilicifolium*, *S. longifolium* and *P. gymnospora* has been attempted (Sudhakar et al. 2017).

Source of plant bio-stimulants

Rama Rao (1991) has prepared plant bio-stimulant from *S. wightii* as a foliar spray. He has reported enhanced fruit attributes in on *Zizyphus mauritiana* such as 11.23% length, 9.2% breadth and 25.23% weight in response to it. The continuity of this work led to technology transfer by CSIR-CSMCRI to M/s. Herbal Agro, Rajkot, India, for the process of manufacturing a plant bio-stimulant. This is now being transferred to at least 7–8 different Indian industries (Supplementary fig. 3). The protocol for preparation of plant bio-stimulant, effective concentrations and response from various sources is given in Supplementary table 5. They are more effective in enhancing seed germination and seedling growth, high yield and flowering pod setting, etc. *S. wightti* extracts at lower concentration have been found to be more effective. The further improvement has resulted into developing integrated process for preparation of plant bio-stimulant, mannitol and alginic acid (Ghosh et al. 2000). The high-throughput and integrated process for diverse bio-products of commercial importance has been developed for valorising fresh *Sargassum* biomass. The batch-scale processing of 1 kg biomass in laboratory yielded 541.33 ± 5.50 mL sap, 32 ± 1.5 g alginic acid, 3.8 ± 0.2 g protein concentrate and 10 ± 0.5 g cellulose. Furthermore, the processing of effluent resulted in production of 115 ± 5 g salt (Baghel et al. 2020), but scaled-up approach is essential for the sustainable implementation.

Alginate manufacturing, quality, grade and product specifications, environmental interventions on processing

We describe in this section the alginate manufacturing by one of the largest alginate-producing companies M/s. SNAP Natural and Alginate Products Pvt Ltd in India. The company—established 1976—is oldest manufacturing facility in the country. It has two campuses, main 12 ac at Ranipet and other 7 ac at Tirupallani both in Tamil Nadu in South India. The former houses county's first alginate plant that is ISO 9001, ISO 14001 and GMP Certified. The factory manufactures sodium alginate, potassium alginate, calcium alginate, ammonium alginate and alginic acid. Food-grade, pharmaceutical-grade and industrial-grade alginates have also been produced. The company has a drug licence to manufacture API (Active Pharmaceutical Ingredients) as per the Drugs and Cosmetics Act 1940. The food grade, INS 401-sodium alginate, INS 402-potassium alginate and INS 404-calcium alginate, is produced as per the 'Bureau of Indian Standards' as well as 'ISI standard compliance for Food Grade products' prescribed by Joint Expert FAO/WHO Committee on Food Additives. These are used as stabilizer for ice cream, yogurt, cream and cheese. Alginic acid and sodium alginate produced are IP, BP and USP NF grades, whereas calcium alginate, potassium alginate and ammonium alginate are of industrial grade (personal communication with SNAP Natural Products and Alginate (P). Ltd). Alginate production in the last decade has registered an upward trend. The highest production of 262 t was in 2018–2019 (Supplementary fig. 4). The year after reported a slightly reduced production trend. This has been attributed to the implementation of new goods and service tax (GST) regime and de-monetisation. Nevertheless, production is poised to improve by looking at high consumption demand. Further, the company is the first to comply with zero discharge through phycoremediation to treat acidic effluent liquid waste using microalgae in an environment friendly process (personal communication with SNAP Natural Products and Alginate (P). Ltd) (Supplementary fig. 5).

Import–export trend in Indian market

The last decade in export–import export trend revealed that India still largely relies on import, while export trend is improvising steadily. The total import has increased three times from 891.43 to 2629.71 t during the decade, while the export has increased 16 times from 6 to 152 t (Supplementary figs. 6 and 7). This remarkable growth in alginate trade has drawn considerable attention on demand supply front globally. India imported sodium alginate from 11 different countries, while exported to over 17 nations during 2018. It may be noted that China was the major contributor (with > 90% of share) for import. The import was about 2488 t of with a value of 9.31 million US$ (Fig. 6). However, Algeria, Bangladesh and United Arab Emirates were the nations to which over > 70% sodium alginate export took place. The cumulative export stood at 130.43 t with a value of 1.26 million US$ (Fig. 7). Special attention at national level is necessary for regulating the import and export, decision-making, planning and policy development.

Legal issues related to the collection of natural biomass

The initiative for designing biosecurity policy framework and legislation for the global seaweed aquaculture industry concentrated primarily on disease and pest outbreaks. It was identified that expansion of seaweed sector is convincingly limited by the high prevalence of recalcitrant diseases and epiphytic pests (Campbell et al. 2019). But at the regional level, the limitation is compounded mainly due to inadequate policy guidelines on sustainable harvesting (Feeney 2001). For example, a joint federal/provincial management strategy for sustainable harvesting of *A. nodosum* was implemented in Nova Scotia allowing the mechanical gathering of 50–150 t day^{-1} with a strict 25% exploitation rate since 1999 (Ugarte and Sharp 2012). The judicial implementation of the Continental Shelf Act (1994) ensured the sustainability of the Norwegian seaweed resource. Similarly, 4–5-year rotational management plan through the Ministry of Fisheries and Coastal Affairs—the FKD for *Laminaria* spp. was implemented in Norway (Vera and Ask 2011). The overall efforts are centred on conservation and sustainability of national resources.

Establishment of the Gulf of Mannar bio-sphere reserve and its effect on livelihood of artisanal fisherman

Like in several maritime countries, seaweed collection is viable alternative for livelihood to artisanal fisherwomen from Tamil Nadu (Mantri et al. 2019). The Government of Tamil Nadu has exempted seaweeds and their products from Nadu Value-Added Tax (VAT) (Govt. Order MS. No. 79 dt. 23.03.2007) to encourage seaweed business. But establishment of bio-sphere reserve by the Govt. of India on 18 February1989 under the UNESCO-sponsored Man and the Biosphere Program. Subsequently, Gulf of Mannar Bioreserve Trust (GMBRT) has been established by the Govt. of Tamil Nadu in 2005. These new legislations have radically affected livelihood of about 2000 fisherwomen, who have been diving deep around GoM islands between Pamban to Thoothukudi for collecting seaweeds (Supplementary fig. 8). To perform a controlled harvesting activity, the calendar has been developed for harvesting each species considering their growth and reproductive season for proper resource management (Supplementary table 6).

Litigations related to seaweed collection and processing of biomass

Despite these initiatives, seaweed collectors are in conflict with forest officials who have control over the marine protected area. The short supply of resources badly affected

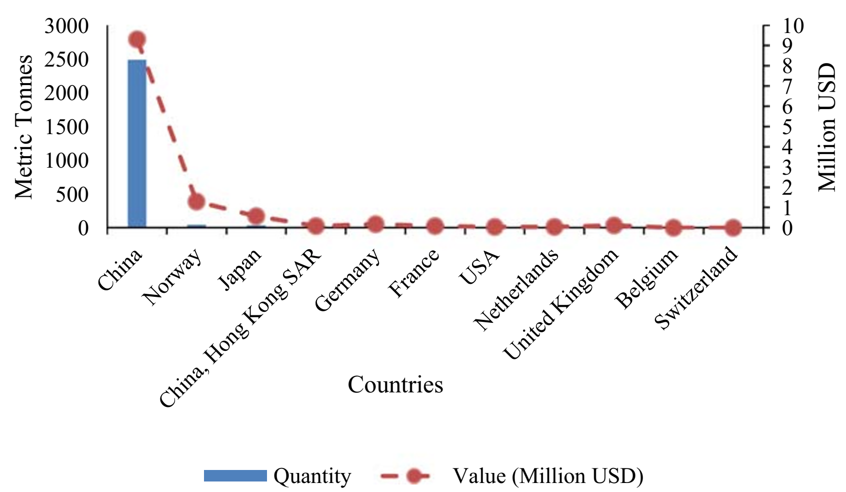


Fig. 6 Import details of sodium alginate during 2018. Source: https://connect2india.com/in/index.html

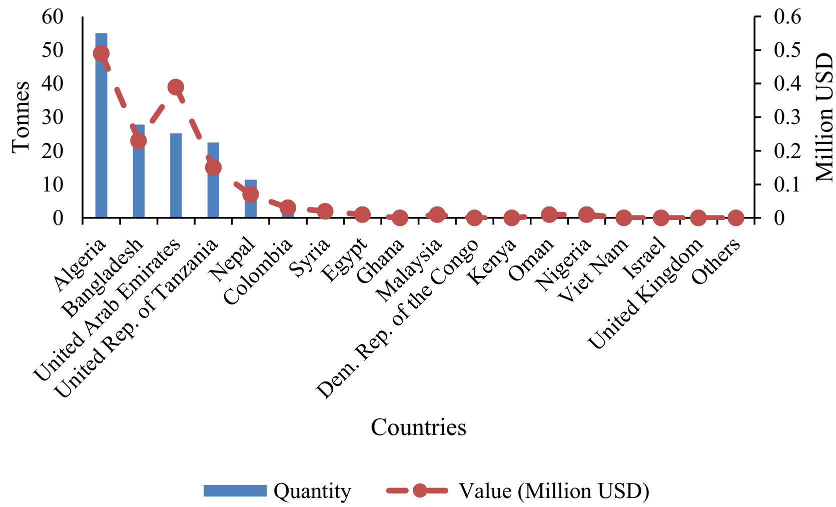


Fig. 7 Export details of sodium alginate during 2018. Source: https://connect2india.com/in/index.html

industrial production of phycocolloids. The Madras High Court in its order on 11th and 26th August 2009 has given the judgement on the writ petitions filed by SNAP Alginate and Natural Products Pvt. Ltd and All India Agar and Alginate Manufacturers Association clarified that seaweed collection, trading and processing are legitimate activities (WP No. 16189 of 2009; MP No. 2, 3, and 4 of 2009 and WP No. 17264 of 2009; MP No. 1 and 2 of 2009 respectively). Thereafter, the Principal Chief Conservator of Forests & Chief Wild Life Warden, Chennai, has stated that there appeared some communication gap in understanding the provision of the law and sustainable practice is encouraged (Circular Instruction No. 1/2009 dt. 16.09.2009). The Madras High Court in another order has given the judgement on 29th March 2005 on the writ petition filed by M/s. Kaypee Industrial Chemicals (P) Ltd. clarified that possession of seaweed gathered with the attachment of dead coral stones to the harvested seaweed—by seaweed collectors, traders and processors is not the crime under wild life protection law (WP Nos. 26363 of 2001; 1511, 40350 of 2002; 723-725 of 2004; MP No. 3026, 3027, 4393 to 4395 and 1351 to 1353 of 2004). In yet another case, the Madras High Court on 29th September 2009 on directed various forest departments that the transporting the naturally collected seaweed and manufacturing of alginate and also other seaweed-based products from it is legitimate activity (WP 16189 of 2009; MP No. 1–4 of 2009). Thus, the rights of traditional dwellers of GoM for collecting of seaweeds for their livelihood are protected by judicial machinery. It is prudent to develop and implement ecosystem-based management approach taking into account the need of local artisanal fisherwomen. This also should ensure sustainable management practice for the long-term benefits. The shifting of livelihood from natural gathering to commercial farming is therefore a preferred option.

Oospore output, zygote germination, seedling production and cultivation

As sexual reproduction is common, asexual reproduction is absent and vegetative reproduction is not viable, alginophytes are cultivated employing spore culture (Aaron-Ampera et al. 2020). The cultivation methods use seed frames in Asia, while that of seed spools in the West is primarily due to competency in nursery rearing and operation scale. The process of reproductive assessment is central to developing farming strategies. Life cycle-based investigation in *Sargassum horneri* confirmed that (i) by manipulating temperature and light, sexual reproduction could be accelerated by at least 3 months prior to wild population; (ii) eggs under in vitro conditions could be successfully fertilised up to 48 h (much longer than other related species); (iii) both suspension and fixed culture techniques facilitated growing the seedlings in long-line cultivation stage; and (iv) the life cycle under controlled conditions could be shortened to 4.5 months. These findings have implications on management and farming (Pang et al. 2009).

Seasonal periodicity in oospore release and ontogeny of fertilised zygotes

It may be noted that several studies have addressed seasonality in fruiting, oospore liberation mechanism, oospore output, factors affecting the release of oospores and developmental stages of oospore to germlings in *Sargassum*, *Cystoseira*, *Turbinaria*, *Padina* and *Rosenvingea* species from Indian waters (Chauhan and Krishnamurthy 1966; Umamaheswara Rao and Kalimuthu 1972; Umamaheswara Rao and Kaliaperumal 1976; Chennubhotla et al. 1978). Generally, the fruiting period of these genera is from October to April. The distinct seasonal periodicity in oospore output was recorded during November and December in *Turbinaria decurrens* at Mandapam, Tamil Nadu

Table 4 Oospore output reported in different alginophytes

Name of the species	Geographic location	Spore output (number g fresh weight^{-1})	Reference
Sargassum wightii	Mandapam, Tamil Nadu	109,494–370,272	Umamaheswara Rao and Kaliaperumal 1976
Turbinaria ornata		Up to 33,810	Kaliaperumal et al., 1977
T. decurrens		Up to 28,196	Kaliaperumal et al., 1977
T. conoides		Up to 11,312	Kaliaperumal et al., 1977
P. boergesenii		4900–19,260	Ganesan et al. 2000
Rosenvingea nhatrangensis	Bhimili, Andhra Pradesh	167,968–369, 674	Narasimha Rao et al. 2012
S. ilicifolium	Visakhapatnam, Andhra Pradesh	20–36,576	Appa Rao et al. 2014
S. vulgare		696–305,983	Subbarangaiah and Appa Rao 2005
C. indica	Okha, Gujarat	5423–511,251	Mairh and Krishnamurthy 1969
S. swartzii		Up to 553,331	Chauhan and Krishnamurthy 1966

(Kaliaperumal and Kalimuthu 1976); December in *Rosenvingia nhatrangensis* at Bhimili, Andhra Pradesh (Narasimha Rao et al. 2012); and October and November in *Padina boergesenii* at Mandapam, Tamil Nadu (Ganesan et al. 2000). The spore shedding continues from day 1 up to day 16, with first few days reporting maximum output which drastically retarded thereafter. The diurnal pattern of periodicity was recorded in spore liberation, wherein spore output increased in dark period between 22 and 2 h. The spore output ranged from 20 g fresh weight^{-1} in *S. ilicifolium* from Visakhapatnam, Andhra Pradesh (Appa Rao et al. 2014) to 553,331 g fresh weight^{-1} in *S. swartzii* from Okha, Gujarat (Chauhan and Krishnamurthy 1966) (Table 4). The high spore output was reported from 10 to 60 psu salinity, 9–18 μmol photons m^{-2} s^{-1} and 25 °C and 12:12 L/D when reproductive bodies were kept submerged (Mairh and Krishnamurthy 1967; Sukumaran and Kaliaperumal 2000; Subbarangaiah et al. 2012; Appa Rao et al. 2014). The oospores in *S. swartzii* after release underwent eight nuclei stages after 24 h. Further multicellular embryo was produced while basal cells eventually developed into rhizoids (Mairh and Krishnamurthy, 1967). A similar developmental pattern was also reported by Kavale and Veeragurunathan (2016). They optimised maximum receptacle regeneration at an irradiance of 45 μmol photons m^{-2} s^{-1}, 35 psu salinity, and 12:12-h (L/D) photoperiod.

Cultivation of Sargassum

Among the alginophytes, field cultivation of *Sargassum* has been attempted. The pond cultivation *Sargassum cinctum*, *Sargassum vulgare* and *S. wightii* using coir net was attempted in the reef area of Porbandar, Gujarat. The fragments of 5–10 cm grew to the height of 15–52 cm in 40 days growth cycle (Thivy 1964). The oospores of *Sargassum plagiophyllum* were allowed to settle on artificial concrete cylinders in the natural habitat. It took 10 months for the germlings to appear on this substratum and anther 8 months to reach these plants to harvestable size. The establishment of new crop from new oospores and regeneration from hold fast was also reported on second year of cultivation (Raju and Venugopal 1971). The cultivation studies in Indian alginophytes are not exhaustive, but are essential to have sustainable resource utilisation.

Opportunities, recommendations and way forward

1. As commercial exploitation is centred around only few species, there has been scope for identifying new species from un-explored areas. Identifying pelagic or planktonic species is helpful, as that can be ideal candidate for farming due to its vegetative mode of multiplication.
2. The existing collection enterprise engage local fisherwomen having no formal training. Their skill set and capacity building in scuba diving is essential for improving collection efficiency as well as harvesting of deep water resources.
3. The current landing practice is haphazard and environmentally non-compliant. The adoption of protocol developed by the Aquaculture Stewardship Council (ASC) and the Marine Stewardship Council (MSC) would help in efficient and sustainable harvest.
4. The existing production technologies need improvement especially by adopting a new cost-effective and eco-friendly approach. The exploration of new functional properties strives towards product diversification with novel functional attributes.
5. Products with niche application can be taken up by start-up companies to ascertain industrial viability. This would pave ways for employment generation in allied industries which will be a welcome step for emerging Indian economy.
6. *Sargassum*-based plant bio-stimulants are readily adopted by local farmers, and studies on environmental

sustainability based on life cycle impact assessment is essential. The understanding of the molecular mechanism of their action on crops is also pivotal.

7. The farming of alginophytes is not yet successful beyond rudimentary initial experiments. To ensure high-quality and consistent supply, nursery development via prototype design of simple, scalable protocol enabling synchronised production of a large number of quality seedlings is therefore crucial.
8. As numerous data sets are available for different environmental parameters on oospore and zygote production and germination, the use of statistical algorithm such as artificial neural network (ANN) modelling and particle swarm optimisation (PSO) would help for standardisation of protocol.

With a surge in recent years in India on seaweed cultivation and valorisation, alginophytes have become of great interest. There is the opportunity to reduce seaweed imports by boosting domestic production. The documentation presented here provides a guide for different stakeholders including government departments in particular on policy interventions. India can also collaborate with other Southeast Asian countries through its special focus in trade and commerce in sync with its 'Act East Policy'. These steps can help entrepreneurs to take advantage on creating new job avenues and doubling the income of fishermen.

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