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REVIEW ARTICLE

A review of sargassum seaweeds' application in the development of eco-friendly building materials

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Abstract: The recent influx of sargassum seaweeds is exerting adverse ecological and socioeconomic footprints on coastal communities in the Caribbean and West African countries. These recurring events have gained worldwide attention, paving the way for intense research and management efforts. Sargassum seaweeds possess several compounds and derivatives, which make them useful additions in the textile, food, pharmaceutical, biofuel, agriculture, chemicals, cosmetics, and medical sectors. Unfortunately, limited studies detail the application of these seaweeds in construction, where environmentally friendly materials with low embodied energy are currently desirable. This article focuses on the practical use and previous work of researchers on sargassum seaweed in construction, focusing on building materials. The study employed a rigorous approach to obtain relevant studies. It highlighted the various compositions and derivatives after sargassum biomass valorizing and their influence on the properties of building materials. Although this article will serve as a reference for practitioners and future research, it also reveals the resourcefulness of sargassum seaweeds in the development of sustainable materials for construction applications.

Keywords: sargassum seaweed, building materials, alginate

1 Introduction

Approximately 10,000 tons of seaweed have been encroaching various coastlines throughout the Caribbean region, extending from the North Atlantic coast to the Gulf of Guinea [1-2], indicating the potential onset of an ecological catastrophe. This uncontrolled influx of seaweed has been considered by experts to be the greatest single threat to the Caribbean [3], echoing what natives along the coasts call the worst and most devastating environmental event in recent times [4]. Marine experts have referred to these massive floating seaweeds as ‘sargassum blooms’ or ‘golden tides’ [5] due to their cascading impact on coastal communities. According to Desrochers et al. [6], seaweeds that invade the Caribbean, the southeast coast of Florida, the Cayman Islands and the coastlines of West and South African countries are dominated by pelagic sargassum species (depicted in **Fig. 1**) found within the Sargasso Sea. Although sargassum seaweed consists of more than 300 species that are distributed throughout the world, these invasive species predominantly consist of sargassum fluitans and sargassum natans [8]; species that are known to reproduce by fragmentation and float freely on sea surfaces throughout their life cycle [5].

Distinctively, sargassum fluitans has thorns, sargassum natans I do not possess thorns but rather

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have smooth stems, while sargassum natans VIII have consistent smooth stems, uncommon bladder spines, and wider blades [8]. Sargassum natans VIII are sometimes referred to as sargassum fluitans, which possesses miniature blades. According to God ńez-Ortega et al. [9], these seaweeds float as individual thalli or in rafts due to their minute pneumatophores. Although these floating masses of seaweed provide habitat for several organisms [9] within the Sargasso Sea, studies postulate that their sudden outpouring has been attributed to several reasons, including changes in the upwelling patterns off the Northeast coast of Africa [7, 9], extreme wind patterns in the central-eastern Atlantic [19], surges in sea temperature, and increases in algae nutrient concentrations from discharging rivers [5, 11].

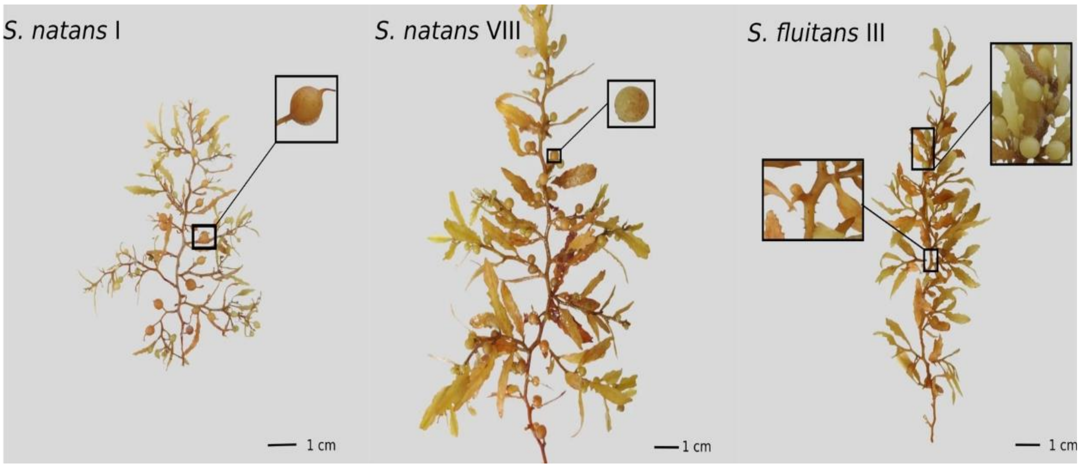

Fig. 1. Morphological differences between the forms of pelagic sargassum [96].

Unfortunately, this recurring beaching event of these seaweeds has had devastating impacts on the coastal environment and livelihoods [9, 12]. Hamel et al. [4] argued that these seaweeds were responsible for the sharp decline of flora and fauna populations and the subsequent destruction of marine habitats. Seaweeds sometimes trap fish, leading to deoxygenation of the surroundings when they decay. This situation often contributes to the release of hazardous components into the sea [12]. Resiere et al. [13] further argued that decaying seaweed emits a rotten egg-like smell consisting of hydrogen sulfide and ammonia gases, which pose severe health risks to visitors and coastal dwellers. As a result, several recreational and tourist sites within coastal areas experience reduced patronage and compromised aesthetic appeal due to the accompanying stench of decomposing seaweed [14]. These seaweeds also entangle the fishing gears and motor propellers, breaking them down or restricting the smooth movement of fishing vessels [9]. As holopelagic organisms, they affect ocean visibility and fish capture, with rippling effects on fishermen' productivity and cash flow [12]. Thompson et al. [3] reiterated that the frequency of these situations has affected the entire value chain, which employs more than 70% of the coastal population. It has also contributed to economic hardship and food insecurity in these coastal communities, where alternative livelihood options are scarce.

Existing literature has revealed derivatives of sargassum biomass for various applications in the food, health, textiles, pharmaceuticals, biofuels, agriculture, chemicals, cosmetics and medical fields [6, 20]. Unfortunately, the construction sector has not yet benefited from the resourceful nature of sargassum seaweed due to limited information regarding their influence on the properties of building materials. However, the scarce literature on the application of sargassum seaweed serves as a major setback, limiting its application in construction. This paper reviews existing applications of these macroalgae in the development of eco-friendly building materials. It also presents the composition and derivatives from sargassum seaweed. This article aims to elucidate the potential of sargassum seaweed as a sustainable resource for the production of building materials.

2 Structure of the Review

This review covered studies on sargassum composition, its derivatives, and recent applications of these seaweeds. The review focused primarily on the utilization of these seaweeds as building materials or in the development of building materials. Databases such as Google Scholar and ScienceDirect were considered during the literature search for practical applications and research publications on the use of sargassum-based construction materials. Journal, books, chapters and conference articles were accepted for review, while notes, letters and short communications were excluded. Research publications available between January 2005 and January 2025 were considered in view of the period during which sargassum influx along coastlines gained popularity. The search used phrases and keywords in conjunction with Boolean operators such as 'AND' and 'OR.' The phrases and keywords used included 'sargassum building materials,' 'composition of sargassum', 'sargassum building applications', 'sargassum in concrete', 'sargassum composite', 'alginate from sargassum', 'sargassum alginate in construction', and 'Sargassum ash'. In total, 172 records were identified from the databases. Of this number, 54 duplicates were eliminated, leaving 118 records. These records had their titles, abstracts and other details like year of publication (i.e., between 2005 and 2025) screened. Subsequently, records (*n* = *69*), which consisted of research articles, case studies, and reports, were successfully recovered and examined. Further scrutiny was carried out, aided by the following questions.

i. What are the primary components and derivatives of sargassum seaweed?
ii. How do these components and derivatives influence the properties of developed building materials?
iii. What are the current applications of sargassum seaweed in the development of building materials for the built environment?

After thorough examination, 32 of the documents were successfully included in the review. The flow chart illustrating the procedure is shown in **Fig. 2**. The procedures ensured a robust and sequential review of the subject under study. During the review, common research findings and discrepancies were established to provide an understanding of the application of sargassum in construction.

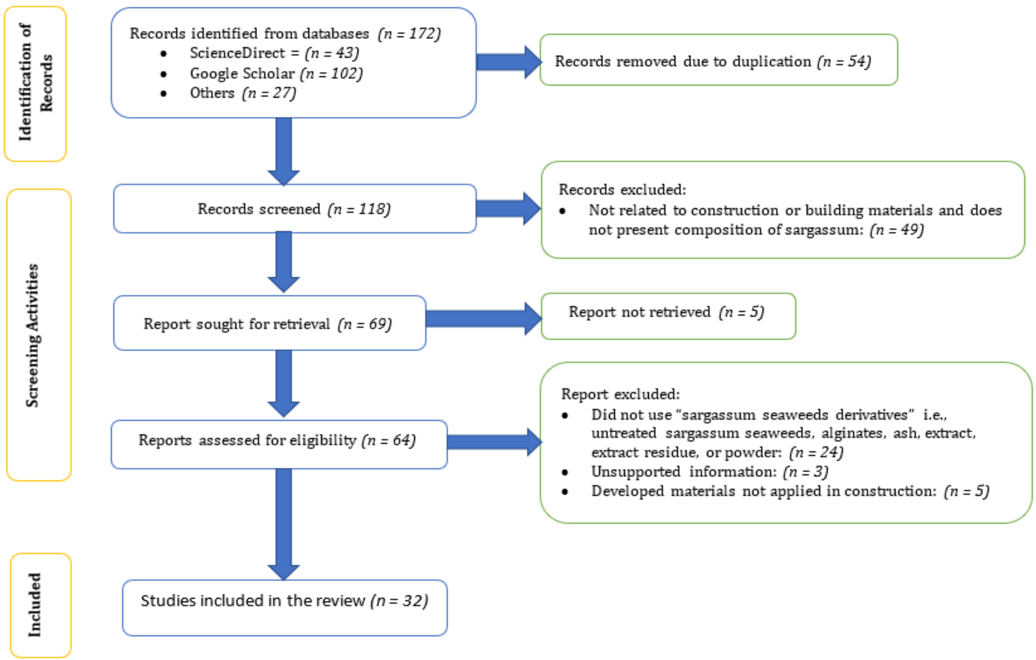

Fig. 2. Flow diagram of the literature search

3 Composition and Properties of Pelagic Sargassum

3.1 Composition of Sargassum biomass

Pelagic sargassum is known to contain numerous phytochemicals and other compounds [7, 15]. Unfortunately, the various environmental conditions that surround these pelagic seaweeds have a persistent impact on their morphology and the quality of their derivatives [10]. The composition and properties of derivatives extracted from sargassum seaweed vary greatly depending on the environment, the location of cultivation, age and harvest periods [17]. Fresh sargassum seaweeds have been known to contain 80% water content when freshly evaluated [10, 27, 35]; although this phenomenon is not surprising due to the environment. Desrochers et al. [6] reported that the dry weight of these macroalgae mainly contains carbohydrates, fiber, proteins (amino acids), lipids (fatty acids) and trace amounts of vitamins, minerals, macro and microelements, and secondary metabolites (as seen in **Table 1**) [6]. The cell wall structure of these seaweeds is dominated by carbohydrates and dietary fibers [22]. Some species, such as sargassum naozhouense found in Zhanjiang, China, contained a carbohydrate content, dominated by alginates and fucoidans [21]. On the other hand, the sargassum species found in Indonesia revealed a carbohydrate content between 46.59% and 50.98% [25], while those collected along the west African coast exhibited higher levels (> 50%) of carbohydrates [17]. When comparing the analysis of the content (as presented in **Table 1** below), the existing literature revealed the diversity of the carbohydrate content between the sargassum species and even similar species obtained from different locations because of the surrounding conditions.

Table 1. Composition and properties of common species of sargassum species

Sargassum sp.	Location	Protein (%)	Carbohydrates (%)	Fibre (%)	Lipids (%)	Ash (%)	References
Sargassum subrepandum	Alexandria, Egypt	4.98	59.68	9.18	0.91	16.23	[15]
Sargassum zhangii	Zhanjiang, China	13.79	70.25	13.09	1.24	14.54	[26]
Sargassum naozhouense	Zhanjiang China	11.20	47.73	4.83	1.06	35.18	[23]
Sargassum linearifolium	Massawa, Eritrea	6.93	27.82	19.97	1.42	26.86	[27]
Sargassum polycystum	Port Dickson, Malaysia	8.65	36.55	2.75	3.42	21.38	[28]
	Sebesi Island coast, India	4.45	47.62	6.93	0.31	27.74	[29]
Sargassum aquifolium	Quezon, Philippines	16.89	32.29	10.03	3.86	30.19	[30]
Sargassum vulgare	Batangas, Philippines	7.69	34.18	22.59	0.56	27.09	[30]
Sargassum sp.	Central Java, Indonesia	3.048	N/A	N/A	0.62	7.11	[31]
Sargassum hystrix	Lagos, Nigeria	6.55	58.72	17.00	1.90	18.50	[32]
Sargassum wightii	Kanyakumari, India	6.43	45.66	24.93	3.09	19.87	[33]
Sargassum oligocystum	Mombasa, Kenya	5.64	-	9.40	0.64	13.08	[34]
Sargassum natans VIII	Shark Bay,	2.99	21.78	37.41	3.58	34.26	
Sargassum natans	South Caicos,	3.81	18.97	37.00	4.51	35.71	
Sargassum fluitans	Turks and Caicos Caribbean Sea	3.25	27.40	31.15	4.56	33.63	[35]
Sargassum ilicifolium		10.30	50.46	N/A	1.28	23.16	
Sargassum angustifolium	Qeshm Island, Iran	12.45	41.49	N/A	0.50	35.01	[37]
Sargassum muticum	El Jadida, Morocco	8.1	29.03	N/A	0.90	N/A	[38]
Sargassum sp.	Guadeloupe	5.40	23.8	N/A	0.81	N/A	
Sargassum sp.	Dominican Republic	5.27	24.8	N/A	0.50	N/A	[39]
Sargassum sp.	Puerto Morelos, México	12.00	8.30	32.38	22.00	19.30	[40]
Sargassum sp.	Gunung Kidul, Indonesia	13.48	57.82	13.62	0.60	17.56	[41]

Sargassum seaweeds contain proteins that have also been observed to vary between species, geographical location, and extraction methods [15, 26, 31]. Although it does not exceed 18% of the seaweed’s dry weight (as can be seen in Table 1), the protein content found comprises leucine, lysine, and valine [18]. Peng et al. [21] revealed that sargassum naozhouense, which was grown purely in China, had a protein content of 11.20%, while those grown in the wild had a protein content of 13.5%. Furthermore, sargassum has relatively limited quantities of lipids, but has an abundance of polyunsaturated fats [23], which also differ according to the source, species, and cultivation method. The lipid content manifests itself as myristic, oleic, palmitic, and arachidonic acids [21].

Minerals such as calcium, potassium, chlorine, phosphorus, sodium, nitrogen, zinc, iron, and magnesium [17, 38] have been found in substantial quantities in these seaweeds. In addition to these macro-minerals, Davis et al. [43] detected heavy metals and trace elements, including iodine, copper, arsenic, selenium, and molybdenum, in some species of sargassum. Studies conducted on sargassum seaweed showed a calcium (Ca) content ranging between 2, 035 ppm and 136, 146 ppm, a nitrogen (N) content identified as nitrate (NO_3) ranging between < 1 ppm and 2, 377 ppm, and a phosphorus content identified as (PO_4) varying between 110 ppm and 1,460 ppm [15, 18, 30]. The potassium (K) found in sargassum samples also ranges between < 1 ppm and 69, 359 ppm according to [18], while the sodium (Na) content and the magnesium (Mg) content range between 109 ppm and 78, 094 ppm and 30 ppm and 18, 241 ppm, respectively [7, 42]. Some studies found quantities of hazardous compounds such as lead, mercury, and cadmium in sargassum seaweed found in Ghana [7, 17]. The authors attributed this observation to illegal mining activities on most rivers that open into the sea. Although the presence of minerals such as potassium, nitrogen, calcium, phosphorus, and magnesium in sargassum seaweed is not substantial as that of cementitious materials, their availability and diversity are capable of impacting the engineering properties of cement-based building materials.

3.2 Ash and Oxides Content

The ash content derived from sargassum seaweed reflects the inorganic residue that remains after the combustion of organic biomass [44-46]. This allows organic ash to influence the behavior and performance when used in composite materials. As presented in Table 1, the ash content derived from these seaweeds varied between 5% and 40%, depending on the geographical location, species, and combustion temperature. To obtain favorable ash with desirable characteristics for application in cement composites, an optimal combustion temperature of 600 ℃ for three (3) hours, producing light ash, was postulated in studies [48, 49, 50]. Bilba et al. [48] argued that sargassum ash combusted between 500 ℃ and 700 ℃ exhibits limited pozzolanic characteristics despite the diverse oxide composition, crystallinity, and structural surface of the particles. At an optimal combustion temperature, sargassum ash has an average density of 2.55 g/cm ^{3}and a specific surface area of approximately 45.29 m ^{2}/g with enhanced adsorption properties [55], making it suitable for light applications in cement. However, exceeding the 700 ℃ combustion temperature produces dense ash that does not have pozzolanic characteristics due to changes in mineral structure and excessive loss of volatile components [49].

Similarly, to other ash derived from aquatic biomass, Murugappan and Muthadhi [50] revealed that sargassum ash has a limited silica (Si) content but rather significant amounts of calcium oxide (CaO), sodium oxide (Na_2O), and sulfur trioxide (SO_3) [55] that can influence the behavior of cement-based materials. Cruz and García-Uitz [57] opined that calcium oxides in sargassum ash can aid in the formation of calcium silicate hydrates (C-S-H) during cement hydration, thus contributing to improving strength in cement composites. In addition to the fineness of the ash, the oxides of magnesium, potassium and sodium found in the ash can potentially influence the setting time and affinity to water molecules in cement products [31], leading to flexibility and better fluidity in mixes. The different oxides identified among the sargassum species in this review provide ample evidence of their potential impact on the properties of developed materials, especially cement composites. Unfortunately, this also provides an avenue for a comprehensive compositional analysis when using them in materials for everyday use, as they can also be potentially hazardous because of the presence of certain heavy metals.

3.3 Alginate

Alginates extracted from sargassum seaweed are used as biocompatible polymers in the development of sustainable products for sectors such as food, pharmaceuticals, and agriculture [88]. Rhein-Knudsen and Meyer [17] explained that alginates are anionic hydrophilic heteropolysaccharides in the intercellular space matrix and cell walls of brown seaweed. Although sargassum seaweed produces between 12% and 35% of its dry weight, this depends on several conditions [25, 89]. With the right extraction methods, alginates can exist as a matrix of alginic acid bound (gels) containing sodium, calcium, barium, magnesium and strontium ions [17]. Jayakody et al. [60] indicated that structurally alginates consist of linear polymers made of two monomeric uronic acids, β-D-mannuronic acid (M) and α-L-guluronic acid (G). The mannuronic acids (M-blocks) form β-1, 4 linkages, while guluronic acids (G-blocks) give rise to α-1,4 linkages, which serve as carboxylic compounds in uronic acids with negative charges [61, 62]. Baghel et al. [63] posited that the two uronic acids are irregularly arranged in a block formation comprising blocks of MM, MG, and GG, depending on the source of algae, the extraction technique, and the harvest time (see **Fig. 3**). In practical terms, when the G content is high, the gel formed tends to be stronger (i.e., it has low M/G ratios) [58, 59].

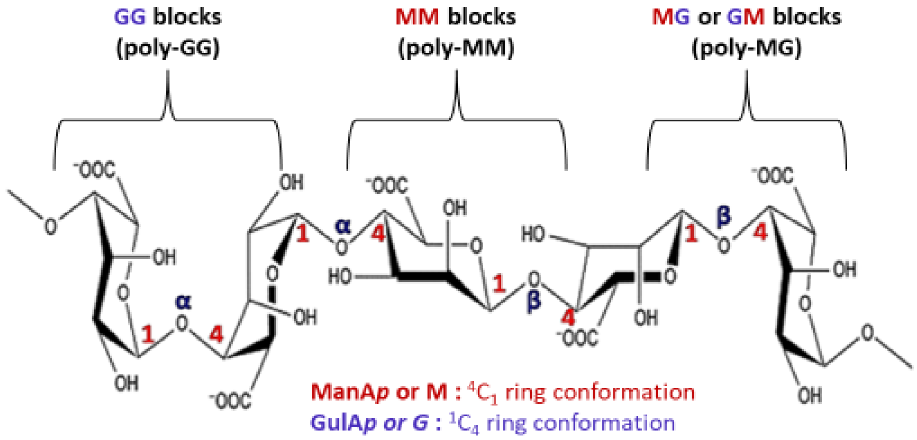

Fig. 3 Chemical structure of alginates [66]

Alginate is also capable of reacting with divalent and trivalent cations such as magnesium (Mg^{2+}), calcium (Ca^{2+}), iron (Fe^{2+}), aluminum (Al^{3+}) and iron III (Fe^{3+}) [67], forming gels in a convoluted manner. The gelation process, which involves cations, especially calcium ions, leads to the formation of a strong egg-shaped structure consisting of Ca^{2+} and carboxyl groups (COO-) of guluronic acids (G blocks) [62] with a monomeric ratio (M/G) typically 0.8: 1.5 [66]. This ratio, which directly influences the viscosity, ion reaction, solubility, and other functional properties of alginates independently of temperature changes [17], is affected by extraction procedures, plant species, age of algae, exact plant, geographical location, environmental conditions, and harvest season [62, 66, 86]. Alginates from sargassum seaweed are extracted using conventional extraction methods, which use alkaline or acidic treatment or green extraction methods such as microwave-assisted extraction (MAE), enzyme-assisted extraction (EAE), reactive extrusion, supercritical fluid extraction (SPE), ultrasound-assisted extraction (UAE), pressurized solvent extraction (PSE), and photobleaching processes [68, 86].

Alginate is commonly extracted from sargassum by soaking seaweed in an acidic solution before precipitating it with calcium or sodium salts [67]. The extracted alginate powder, which is rich in sulfated polysaccharides and constitutes approximately 17 - 28% of dry weight, is then dried, sprayed or freeze-dried to produce alginate powder [62] or left in its gel form for commercialization purposes. The hydrophilic nature makes it suitable for applications requiring moisture management and thermal insulation. According to studies, alginate films crosslink with calcium cations, produce rigid gels, improve cohesion bonds, and tensile strengths between molecules [17, 52, 69]. The films formed are stronger but with low solubility in water, which can be described as shear-thinning behavior [66]. These multifunctional characteristics have made these extracts remarkable components in various uses in the food, textile, paper, biotechnology, health, pharmaceutical and materials engineering sectors [69].

Despite its unique properties, the use of alginate powders and gels in construction has not been extensively documented. According to the existing literature, the characteristics of sargassum-derived alginate can be significantly beneficial when incorporated into building materials that require specific fluidity, such as self-healing concrete and grouts, which require viscosity-enhancing additives. However, few studies [55, 66, 70] have explored their application as admixtures and bio binders with significant improvements in mechanical strength and thermal insulation. Some composite materials developed with alginate extracts have shown sufficient mechanical properties and durability characteristics due to their notable stability, biodegradability, and biocompatibility [50, 51, 65]. Furthermore, their ability to form stable hydrogels has made them suitable for the manufacturing of biodegradable insulating materials that can offer ecofriendly alternatives to traditional insulators [69]. Although existing studies provide some data, further research is needed to develop standardized extraction and gel formation processes.

3.4 Cellulose

In addition to alginates, Siddhanta et al. [33] indicated that sargassum seaweed contains cellulose in relatively low quantities. It is present in plant cell walls as fiber content, providing structure, but can be extracted as fibers for the reinforcement of composite materials [79]. Cellulose is an organic, homogeneous polymer that is structurally made up of β-(1, 4)-linked β-D-glucopyranose units [80]. Its dominance in industrial applications has been due to its versatility, low density, mechanical strength, hydrophilic and hygroscopic nature, biodegradability and recyclability [81]. Sargassum biomass has been processed into lignocellulose material to develop multilayer particleboards [79]. Cellulose in some species of sargassum has been used for construction applications by developing cellulose nanofibers (CNFs) and nanocrystals (CNCs). For example, Elizalde-Mata et al. [83] found that cellulose derivatives could improve the mechanical and durability properties of composite materials for building purposes.

3.4 Fucoidans

Fucoidans are water-soluble sulfated polysaccharides present in intercellular tissue of the mucilaginous matrix (cell walls) of certain species of sargassum [61, 63]. They are composed of a structured α-fucopyranose backbone with sugar monomers of fucose, galactose, mannose, xylose, glucose, uronic acids, sulfate substituents and occasionally acetyl groups [91]. Due to their adhesive characteristics, these sulfated polysaccharides are utilized in cancer treatment, wound healing, and bone and tissue engineering in living organisms [64]. Although not found in all species, sargassum fusiforme and sargassum horneri are the main sources of fucoidans. These compounds have immunomodulatory, antiviral, anti-inflammatory and antitumor properties, making them an essential component in the pharmaceutical, food and other biomedical industries [37, 26]. Although there is limited data on its use in construction applications, fucoidans can form hydrogels when combined with some polymeric materials [63].

4 Applications of Sargassum Seaweed in Building Materials

As sargassum seaweed invades coastlines, its possible use to develop sustainable building materials can provide environmental and economic advantages. This can also serve as an avenue to advance sustainable construction while providing an alternative to the disposal of these wastes. After carefully reviewing current studies, various applications of sargassum seaweed were highlighted.

4.1 Utilization in Cement Composites

Derivatives obtained after the valorization of sargassum biomass, such as sargassum ash, alginate gel, and alginate powder, have been studied in some cement-based composites, where they act as supplementary cementitious materials, admixtures, or mineral additives. Specifically, sargassum extracts in the form of powder and gel have been known as viscosity-modifying admixtures (VMA) in concrete composites [52].

Sargassum biomass ash, according to studies [57, 65], contains a limited amount of amorphous silica, but Cruz and Garc á-Uitz [57] opined that it possesses other characteristics that can improve the durability properties of cement composites. The physical characteristics and oxides present in the ash can be used as fillers in cement composites [43]. These fillers, according to Rossignolo et al. [83], significantly lead to the nucleation reaction and matrix packaging in cement composites. This influences the absorption behavior, density, insulation and thermal regulation properties during the hydration and strengthening of cement composites [84].

Asante et al. [70] also studied the effects of agricultural and aquaculture residues, including sargassum species, such as bio-admixtures and bio-ashes, in cement mortars. The extracts from these agricultural biomasses were incorporated at 1% or 0.1% of the water weight, while the ashes generated from the selected plants partially replaced 10% and 25% of the cement content. The authors found that among the agricultural and aquaculture residues used, the sargassum species comparatively achieved improved compressive strengths at both concentrations. Cement mortar incorporated with bio admixtures and ashes generally showed a reduced strength compared to the reference mortar. They reported that sargassum fluitans III produced the highest compressive strengths of 26.51 MPa and 32.53 MPa for curing ages of 7 days and 28 days, respectively, at 10% cement replacement. The authors also reported that higher replacement levels (that is, 25%) significantly compromised both the mortar strength and workability characteristics.

In another study, sargassum ash was used as a partial replacement material for limestone in fiber cement [85]. The test samples were produced with a content of sargassum ash comprising 0%, 25%, 50%, 75% and 100%, partially replacing the limestone content of the fiber cement. The findings of the study revealed that, as the percentage of sargassum ash increased, there was an increase in apparent void volume, water absorption, and better environmental performance [85]. They reported that the total replacement of limestone with sargassum ash led to a 74% gain in specific energy relative to the reference specimen after accelerated aging.

López-Sosa et al. [54] developed a composite material by mixing cement and sargassum for bioconstruction applications at concentrations of 5% and 7.5% by weight in a study by [54]. The composite material developed achieved a solar spectrum absorbance between 54% and 70% and thermal conductivity ranging between 0.65 and 1 W/mK. Furthermore, the cost-environmental analysis showed that using the developed material in the construction of 5% of homes in Quintana Roo, which is in a tropical savanna climate, could result in annual energy consumption reductions of approximately 67 GWh, which would translate into more than US$33,000 in energy savings.

Chabhi et al. [53] partially replaced the cement content with powdered sargassum seaweed to investigate its role as a bio admixture in cement mortar. The authors varied the cement content between 0% and 20% by mass with sargassum muticum. They reported that the compressive strengths of the modified cement mortar increased when the seaweed content reached 10% addition. A further increase in the seaweed content (i.e., > 10%) resulted in a decrease in strength characteristics. In conclusion, they reported that replacing the cement content with 10% sargassum-extracted alginate powder was ideal to improve the strength characteristics of cement mortar.

Murugappan and Muthadhi [51] reported significant improvements in the properties of fresh concrete after the addition of sargassum-extracted gel. They reported that the concrete sample with 5% extract had its setting time increased by 3.33 times, while the thermal conductivity declined by approximately 45% compared to a sample without extract. Murugappan and Muthadhi [51] recommended the use of 5% seaweed gel as a natural polymer to improve the fresh state and durability characteristics of concrete.

From the aforementioned studies, sargassum derivatives sustainably enhance cement-based composites by improving mechanical properties (at replacement levels around 10%), improving fresh concrete compatibility and superior durability. Even with a limited content of amorphous silica, sargassum biomass ash has beneficial fillers that promote nucleation reactions and improve matrix packing, affect absorption, density, insulation, and thermal regulation during cement hydration. The review showed that while a low replacement level for the cement content tends to improve the mechanical and durability characteristics, higher replacement levels impede these properties. This explains the need to have careful dosage control to prevent compromising the structural integrity or workability of cement composites.

4.2 Utilization in Earthen Composites

Sargassum seaweeds are generally incorporated into earthen or clay materials in their pulverized, calcined, or extracted form from alginate [36, 57, 71]. These sargassum derivatives were often used mainly as stabilizing agents, which improve earth properties by effectively binding the particles. Affan et al. [36] used fibers from sargassum mitucum as a partial replacement material for flax fiber in earth-based composites. The authors prepared both flax fiber and seaweed fibers at lengths of 70 ± 10 mm before molding. The results of the study revealed that the modified earth with sargassum muticum achieved improved hygroscopic and thermal behavior (such as insulation and inertia) relative to earth composites with only flax fiber. The authors also reported that the earthen samples with partially replaced flax straw with algae lowered thermal conductivity by 38% compared to the reference earth stabilized with 2.5% flax straw fiber [36]. A numerical simulation conducted by the authors showed a decline in the energy demands of buildings produced with sargassum-based cob relative to the control composite.

Headlining the sargassum's usage as a building material is SargaBLOCK™ in Mexico, where earthen blocks have been produced with a substantial amount of sargassum (approximately 40-60% of raw sargassum) since 2019 [57]. These blocks are produced with a compression of 112 kg/cm ^{2}and are subjected to open drying for 4 hours in the sun [57]. A study by the Ministry of Ecology and Environment of Mexico revealed that the resistance of bricks ranges between 75 kg/cm ^{2}and 110 kg/cm ^{2} and can last up to 120 years, regardless of the temperature or location where they are used [18]. In another study, the compressive and tensile strengths of modified earth mortar increased by 77% and 70%, respectively, relative to the control mortar when sargassum mitucum was incorporated [71]. Unlike [36], the authors pulverized the seaweed into fine particle sizes before incorporating them in varying percentages. The study revealed that the optimal quantity for satisfactory performance was attained at 2% seaweed addition, with finely grained seaweed (i.e., < 0.63 mm) being the best [71].

On the other hand, Tiwa et al. [24] utilized sargassum ash calcined at 600 ℃ and 700 ℃ as a stabilizer in earth bricks [24]. They revealed improved properties for the bricks stabilized with the ash that was calcined at 700 ℃. The study also reported higher levels of calcium oxide and magnesium oxide when seaweed was desalinated before being combusted into ash. A study by da Silva Parente et al. [47] revealed superior mechanical properties when clay and sargassum seaweeds were sintered in an electric oven at temperatures of 900 ℃ and 1000 ℃. Commercially derived alginates from some seaweeds were used in Dove [72] to produce unfired bricks [72] with data indicating that not all alginates samples could improve the flexural and compressive strength of unfired soil bricks.

Fatehi et al. [73] investigated the influence of sodium alginate powder on dune sand in varying percentages (0%, 1%, 2%, 3%, and 5%). They observed increases in the unconfined compressive strength as the sodium alginate content increased compared to the reference dune. A detailed study by microstructural analysis showed linkages between sand particles, revealing the effectiveness of sodium alginate. They reported that the polymeric behavior of sodium alginate can sustainably enhance the properties of poorly graded soil.

Sargassum seaweed derivatives, in multiple forms - fibres, powders, ash, and alginates, have been shown to have a significant influence on the mechanical, durability and thermal properties of earth-based composites and cementitious materials. A thorough review showed that processing parameters such as particle size, calcination temperature and desalination of seaweed before processing affect the performance outcome, highlighting the need for optimized materials procedures.

4.3 Replacement material for Fine Aggregates

Sargassum-derived ash and pulverized seaweed have been used as replacement materials for fine aggregate in cement composites. For example, treated sargassum seaweed was used as a replacement material for fine aggregate (sand) in [74]. The authors replaced the fine aggregates in percentages of 5%, 10%, 15% and 20% with the treated seaweeds to develop a sustainable coating material. The samples with seaweed were reported to have hydrophilic characteristics, necessitating a high-water content in their design to achieve the required fluidity, a situation that increased the water/cement ratio and consequently reduced their strength [74]. The authors concluded that, although the compressive strength decreased, incorporating sargassum seaweed as a substitute for the fine aggregate in small quantities (i.e., ideally 5%) is beneficial since the strength and thermal properties were within acceptable ranges.

Lyra et al. [55] reported a steady decline in compressive strength after the sargassum ash increased from 0% to 20% when used as a replacement material for the fine aggregate in cement mortar. In their findings, the incorporation of sargassum ash also led to an increase in the open pore volume and water absorption but decreased the apparent mass density as replacement increased. The authors also reported that after curing for 63 days, the cement mortar with 10% and 5% ash inclusion was statistically comparable to the control specimen. These sargassum-modified cement mortars, according to the authors, were therefore ideal for non-structural works like plastering, sealing blocks, and rendering.

From the studies reviewed, sargassum materials tend to impart hydrophilic characteristics when utilized as a replacement material for fine aggregates. In cement composites, this phenomenon increases the water demand, raises the water/cement ratio and thus reduces the mechanical properties. Therefore, the use of sargassum seaweed and ash is limited to lower dosages (< 5%) to maintain comparable mechanical and durability properties. On the contrary, higher doses (> 10%) lead to enhanced water absorption and open pore volume, which could affect durability and reduce material performance. From the review, sargassum-modified composites are most likely preferred for non-structural applications such as plastering, sealing blocks, rather than high-strength structural elements.

4.4 Modifier in Asphalt Binders

Salazar-Cruz et al. [1] investigated the use of sargassum seaweed as a modifier in asphalt binders, where certain significant changes were identified in the physical and rheological behavior of modified asphalt. The authors processed raw sargassum to obtain particle sizes of less than 850 µm before introducing them into the asphalt binder in varying quantities. They reported that by adding 2.5% processed sargassum seaweed, the elastic behavior and thermal resistance of the modified asphalt improved. In another study, Escobar-Medina et al. [75] investigated the varying sizes of sargassum particles in the properties of asphalt mixtures. They pulverized sargassum seaweed into 500 µm and 850 µm-sized particles before incorporating them into asphalt mixtures. Based on their findings, adding 3% of pulverized sargassum grains that are less than 500 µm into the asphaltic mixture increases the complex modulus by 1.9 times, the viscosity of the binder by 2.5 times and a further 11 ℃ rise in failure temperature compared to the reference asphalt. Based on their recommendation, fine-grained sargassum particles were suitable for enhancing viscoelastic behavior, fatigue performance, and rutting resistance of asphalt mixtures.

The studies showed the promising prospect of utilizing sargassum, which can positively impact asphalt performance. Although the recommended dosage for sargassum inclusion in asphalt binders that ensures balanced modification benefits and materials integration ranges between 2.5% and 3.0%, the particle sizes (especially finer particle sizes) also play a critical role in modifying asphalt performance.

4.5 Application in Microbial Repair

The biocompatibility of sargassum-extracted alginate makes it suitable for microbial repair in cement composites. Alginate provides an environment in which encapsulated bacteria remain viable and metabolically active without adverse effect [76]. Although limited studies have been conducted on the applications of alginates in this area, Cruz et al. [56] used commercially produced alginates for microbial repair of cracks. The authors opined that microorganisms like bacteria tend to fix themselves atop cracks that have been imbued with alginate, thus expediting the mineralization process for the repair of cracks. In a similar study, Rong et al. [76] investigated the influence of sodium alginate on microbial repair of cracks in cement mortar. They reported that the optimal volume ratios of the microbial repair material solution to the bacterial solution were 6:4, 7:3 and 8:2, while the basic characteristics improved when a 1.5% mass concentration of sodium alginate solution was applied. The authors further posited that the surface water absorption was 67% lower than it was before the repair. Even though the utilization of sargassum-extracted alginate in microbial repair is currently limited in literature, it shows significant potential as a biocompatible medium for self-healing, enhances durability and facilitates mineralization in cement mortar. This can also provide a sustainable alternative for developing bio repair agents for cement composites.

4.6 Developing Insulating Materials

Climate change and its associated impacts have ignited the need for eco-friendly insulation materials, as they meet operational demands and have minimal environmental impacts. Seaweeds have been used in vernacular architecture in areas like the Danish Islands, where the quality and quantity of building materials are limited, as they provide better insulation, are non-hazardous, and are fire-resistant

[77]. Sargassum Eco Lumber, a lumber production company, has developed a sustainable solution by transforming sargassum biomass into lumber that provides insulation in a comfortable and energy-efficient indoor environment [95]. The developed lumber blends sargassum biomass with discarded plastics to create synthetic composite planks that are durable, resistant to decay, and ideal for several construction needs [96]. The mechanical and hygrothermal characterization of insulated earth walls containing seaweed showed increased compressive strength, insulating abilities, and capacity to store heat [78]. Based on their findings, the integration of seaweeds up to 20% in the cob matrix improves the properties of the earthen material.

Sargassum seaweed with limited treatment has been used to develop composite materials like particle boards for construction applications. Bauta et al. [39] produced a high-density binder-free particle board after subjecting the powdered sargassum biomass to uniaxial thermocompression in the presence of cooling. The authors reported that after the incorporation of alginate, the ideal conditions necessary to develop particle boards with improved density, high flexural strength, and flexion modulus comprised a temperature of 200 ℃, a molding pressure of 40 MPa, and a compression time of 7.5 min [39].

Duran et al. [79] in their study utilized sargassum biomass with limited treatment as a component of lignocellulosic material to produce multilayer medium density particleboards. The particle board consisted of sargassum particles sandwiched between sugarcane bagasse particles with castor-oil-based polyurethane resin serving as a firm binder. Although [79] Duran et al. reported increased swelling and dimensional instability due to the introduction of the sargassum within the internal layer, the specimen met all the minimum requirements established by the regulations for furniture in dry conditions. Sargassum biomass was also utilized to develop a multilayer composite particle board [24]. The developed particle board consisted of pulverized sargassum seaweed as a filler, coconut leaf sheaths as a reinforcement, and polylactic acid as a natural binder. According to their findings, the material attained an acceptable mechanical performance, yet the biodegradability of seaweed and other organic components had high moisture absorption, which necessitates appropriate treatment.

As a promising material for eco-friendly insulating materials, sargassum seaweed aligns with sustainability goals by reducing plastic waste and promoting the use of renewable biomass, even though its major setback related to moisture sensitivity has to be addressed to expand its application scope, particularly for particleboards exposed to poor ventilation and humid environments.

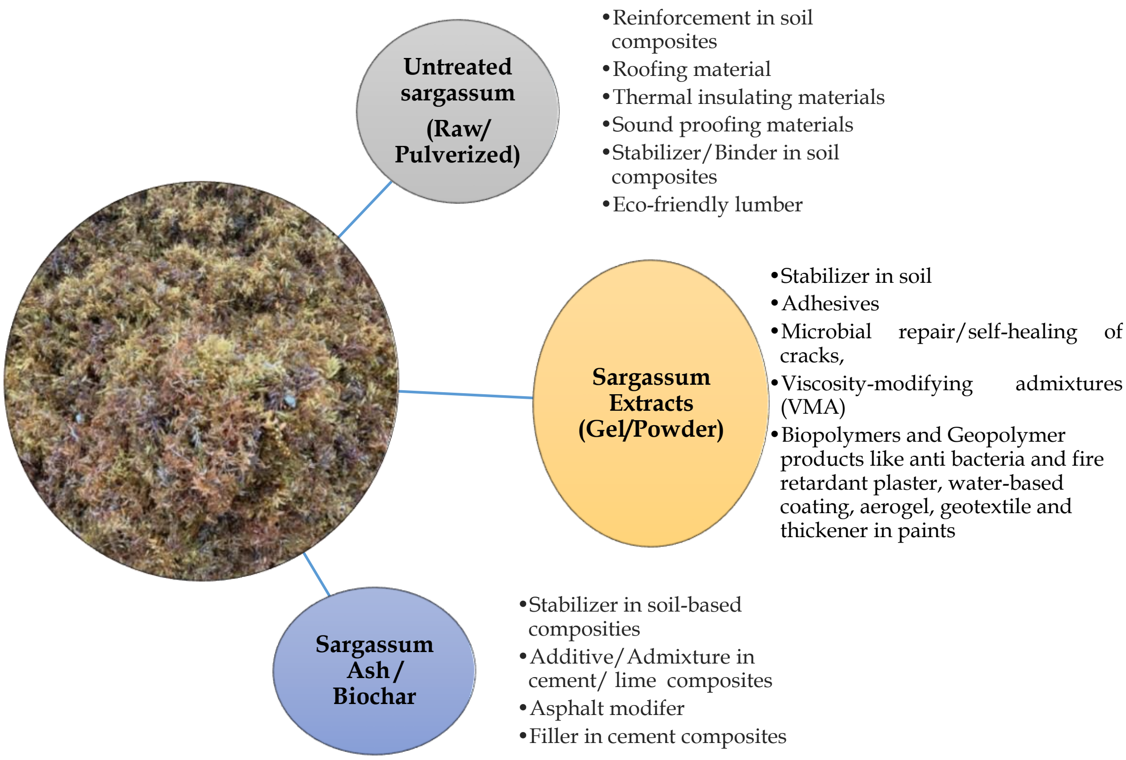

Fig. 4 Applications of Sargassum seaweed in Buildings

4.7 Utilization in Polymeric and Other Construction Applications

Seaweed-extracted alginate has traditionally been a valuable building component in some traditions [93]. For instance, in the Japanese shikkui, sargassum seaweed extracts are used as glue or binder (due to the thickening behavior of the extract) for rendering purposes [94]. The plaster developed was made by mixing lime and seaweed extracts, which were found to be antibacterial, fire-resistant, and even non-toxic after investigation.

Furthermore, Berglund et al. [80] developed alginate–cellulose nanofiber aerogels for insulation applications by detaching cellulose nanofibers to obtain flame-retardant and heat-insulating materials. In other cases, some authors [93] investigated the influence of some alginic salts on the microstructural characteristics of waterborne paints. They argued that although the alginate's ion type had minimal effects on product stability, the dried coating showed varied tensile properties, which primarily depended on the alginate concentration.

As coastal communities initiate efforts to ensure resilience to climate change and promote sustainable development, sargassum can innovatively be repurposed as sustainable building material [65], offering a potential solution to both the ecological issues it creates, and the rising costs associated with traditional building materials. The various potential applications of sargassum seaweed explored from existing studies and practical applications are depicted in **Fig. 4**.

5 Conclusions

There has been an incessant drive for alternative materials that meet the expected demands but also minimize environmental challenges for construction applications. As presented in this review, sargassum seaweed embodies unique characteristics that make it useful, yet in the current paradigm, it has been seen as an environmental threat. The review discussed the composition and properties of these invasive seaweeds and how they can modify the characteristics of composite materials. The authors also highlighted various derivatives from valorized sargassum biomass, such as untreated sargassum seaweed, ash from sargassum, alginate gel, and alginate powder extracted from sargassum. The review provided documented information on existing research and practical applications. This consisted of a careful identification of extracts and properties of sargassum seaweed obtained from various studies in various fields. Despite the few studies related to its use in building materials and construction, this review showed the application of sargassum seaweed extracts and ash in materials such as concrete, cement mortar, asphalt, earth, particleboard, etc. From the review, the use of sargassum seaweed derivatives (in any of the following forms: fibers, powders, ash, and alginates) as an admixture or as a stabilizer, to their use in the development of heat-resistant materials and other biopolymers, remains boundless, especially at optimized dosages.

Unfortunately, certain barriers hamper its use. Currently, there is limited information on the composition, durability, and processing of sargassum derivatives, which serves as a considerable impediment to the development of sargassum-based building materials. Addressing these challenges would provide economic incentives for its use and support localized value chains when integrated into circular economy models. The application can also reduce environmental threats, ensure alignment with global sustainability goals, and promote the formulation of regulatory policies and market adoption of these seaweeds.

In conclusion, sargassum offers a versatile and renewable resource that aligns well with green building and circular economy objectives, if processing and dosage parameters are carefully controlled to balance performance and sustainability. As a result, research and innovation must be enhanced to unlock sargassum’s diverse potential for building applications. This would enable the development of eco-friendly building materials and effectively integrate sustainability principles into construction practices.

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Conflicts of Interest

The authors declare that they have no conflict of interest in reporting regarding this review.

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