Review

Bioremediation potential of *Sargassum* sp. biomass to tackle pollution in coastal ecosystems: Circular economy approach

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A B S T R A C T

During the past years, the ecological integrity and biodiversity of marine ecosystems have been highly threatened due to the controlled or uncontrolled release of high concentrations of pollutants generated through anthropogenic activities. The occurrence of environmentally related hazardous pollutants, such as toxic elements, and recalcitrant compounds in various environmental matrices has raised increasing concern. Different techniques have been developed for efficient removal and complete mitigation or degradation of these toxic elements from the aquatic environment. Among them, biosorption and bioaccumulation by renewable and biodegradable sources are of supreme interest and have not been reviewed much. For instance, the invasive seaweed *Sargassum* sp. has been spotted as a cost-effective natural material to capture targeted pollutants from the coastal ecosystem, which is currently becoming a pressing problem, around the globe, due to its unusual proliferation near tropical shores. This review is an effort to cover the left behind gap to present the multifunctional potentialities of *Sargassum* sp. biomass. Herein, salient information is given to highlight the potential of *Sargassum* sp. biomass for environmental decontamination with particular focus to coastal ecosystems. Bioremediation mechanisms, challenges of implementation and factors involved in adsorption and absorption of pollutants by seaweeds are also discussed in this review. Against this background, a circular economy perspective is given for the integrated use of the algal raw material. The up-taken pollutants can be recovered and reintegrated into the value chain of industrial processes, while residual biomass is refined to obtain added-value products as bioactive compounds with potential applications for biofuel, agriculture, cosmetics, nutraceutical, pharmaceutical industries among others, to make the most of renewable resources.

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1. Introduction

During the last years, the ecological integrity and biodiversity of marine ecosystems have been highly threatened due to the high concentration of pollutants generated mainly through anthropogenic processes (e.g., industrial, domestic and agricultural applications). Due to the circulation and dynamics of matter in the environment, pollutant emissions frequently end up in the sea conveyed via riverine inputs from polluted urban and rural areas near shore, atmospheric deposition and direct dumping (Fig. 1) (Bergmann et al., 2015; Nelms et al., 2017; Beiras, 2018). Marine pollution mainly affects coastal zones because the residence time of pollutants in tidal estuaries is greater than in rivers. Thus the capacity to dilute waste discharges decreases, and in consequence, pollutants accumulate (Aminot et al., 2019; Frid and Caswell, 2017). According to the United Nations Convention on the Law of the Sea, marine pollution is defined as “the introduction by man, directly or indirectly, of substances or energy into the marine environment which results or is likely to result in such deleterious effects as harm to living resources and marine life” (Noone et al., 2013; United Nations, 1982). From this report, Agencies and Institutions of Environmental Protection worldwide established many lists of so-called *Priority Pollutants*, whose escape to marine ecosystem must be universally avoided because they can cause short, permanent or long-term effects that represent a hazard to the environment and human health (Beiras, 2018; Gripp, 2017). The Environmental Protection Agency of the United States (EPAUS), for example, updated a list of priority pollutants from the Clean Water Act, that includes heavy metals such as arsenic (As), mercury (Hg), cadmium (Cd), zinc (Zn), chromium (Cr), lead (Pb), besides other specific chemicals as dyes, phenolic compounds, polychlorinated biphenyls and organophosphates (EPA, 2014; EPAUS, 2009).

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Different technologies have been developed for the recovery and degradation of pollutants from the aquatic environment. Among them are photocatalysis, ion exchange, membrane separation, coagulation/flocculation, filter processing, and other electrochemical methods (Bilal et al., 2018; Hernandez-Vargas et al., 2018; Santos et al., 2018). However, these technologies have presented limitations as chemical precipitation that leads to the production of toxic sludge, high costs, and low efficiency in the total removal of contaminants (Bilal et al., 2018). For these reasons, biosorption, represents a low-cost, simple and safe alternative for the recovery of pollutants (Dodson et al., 2015; Bilal et al., 2018; Santos et al., 2018; Barquilha et al., 2019).

Biosorption refers to the ability of non-living biomass of some organisms, to bind and capture substances of different nature from aqueous solutions, allowing their passive removal from the environment (Dodson et al., 2015). Brown seaweed biomass, particularly, has gained recognition as a sorbent in research areas of water bioremediation due to their biosorption capacity in comparison with other organisms as fungi and other algae (Romera et al., 2007). Their complex cell wall rich in fucoidan, alginate and high content of carboxyl groups (up to 80% of its dry weight) are related to its capacity to uptake heavy metals (Santos et al., 2018), radionuclides (Pohl and Schimmack, 2006), and recovery of toxic elements of special interest such as silver, gold and uranium (Volesky, 2003; Romera et al., 2007; Mata et al., 2008; Mata et al., 2009). Therefore, biosorption using brown algae biomass represents a cost-effective methodology not only for the removal of toxic substances but also as a leading technology for recovery of recyclable elements of industrial interest from aqueous environments, contributing to meet global sustainability and circular economy challenges (Santos et al., 2018).

In this context, Sargassum sp. biomass from the Mexican Caribbean could be considered as a sorbent for the capture of targeted pollutants from the coastal ecosystem, since it is a renewable, cheap, and natural material that is currently becoming a pressing problem due to its unusual proliferation (van Tussenbroek et al., 2017). The causes of the Sargassum sp. bloom near the coastline are not yet well comprehended. However, warmer temperatures of the Caribbean, input of nutrients and pollutants from land activities, changes in ocean circulation patterns associated with climate change, among others, are conditions that promote an accelerated algal growth rate, creating a saturated environment that causes an ecosystem imbalance that triggers an environmental, social and economic havoc near the shore (Smetacek and Zingone, 2013; van Tussenbroek et al., 2017).

This review aimed to discuss the potential of Sargassum sp. from Mexican Caribbean coasts as a biosorbent for the removal of coastal pollutants, its mechanism, and drawbacks. Following a brief introduction and problem statement, Section 2 of the review focuses on the occurrence of pollutants of high concern in the coastal ecosystem. Section 3 mainly covered the eco-concerns, composition, and potentialities of the Sargassum sp. A particular focus is given to the bioremediation, biosorption, and bioaccumulation potentialities of Sargassum sp. biomass. Next, several influential factors and their role in the biosorption capacity are discussed with suitable examples. Finally, the last part is focused on the circular economy perspective along with current challenges, recommendations, and future considerations. While the prospective application of the algae related to the recovery of high-value products, such as biofuel, agriculture, cosmetic, nutraceutical and pharmaceutical industries representing an important trend in the context of sustainability and circular economy.

2. Pollutants of main concern in coastal ecosystems

As a result of the direct and indirect emission of pollutants to surface water systems, most aquatic environments are affected to some extent. Here are some of the main pollutants of ecological importance in coastal ecosystems, their main characteristics, and effects on the environment. Although metals are found in trace amounts, they accumulate in the food chain and have harmful effects on the environment and living organisms, especially in human health (Jaishankar et al., 2014). Removal of heavy metals is a challenge due to its recalcitrant characteristic, so its self-purification is impeded when entering the marine environment. The heavy metals with the highest priority are arsenic, mercury, cadmium, zinc, chromium, lead and iron (Bilal et al., 2018; World Health Organisation, 2010). Biosorption by seaweed represents a cost-effective alternative for the removal of these pollutants (Rezania et al., 2016).

Phenolic compounds are enlisted as a priority pollutant by the United States and European Union since they are highly persistent in the environment, have toxic effects on living organisms, and can trigger the growth of tumorous tissues and mutations (Aruhugum et al., 2018). Phenolic compounds are precursors of a wide variety of chemical industry products (e.g., pesticides, drugs, cosmetics,
topic antimicrobials, dyes, antibiotics, bisphenol A, resins, etc.). They are difficult to remove from aquatic environments conventionally, different approaches have been evaluated for treatment, including biosorption using seaweed through a donor-acceptor interaction (Soto et al., 2017).

The main consequence of excess nutrients in coastal ecosystems is eutrophication that triggers algal blooms, which in turn limits the entry of light in the sea, causing hypoxia and the general deterioration of the marine environment (Anderson et al., 2002). Eutrophication is mainly caused by the surplus of nitrogen and phosphorus and has become a problem of water quality concern in most surface waters of the planet. Seaweed has been studied as nutrient scrubbers, due to its ability to bioaccumulate it in its tissues and use it in its metabolic processes (La Barre et al., 2018). Therefore, seaweed can be used as biofilters on focused emitters such as fish farms, wastewater treatment plants, and effluents from land activities.

The pollution of aquatic ecosystems by synthetic dyes has become an environmental problem of global concern as it represents a threat to the integrity of the environment and health of living organisms since dyes are very persistent, toxic, and carcinogenic (Vikrant et al., 2018). The main sources of dye contamination are effluents from textile, paper pulp, leather, food, and plastics industries, which use dyes to color their products (Chu and Phang, 2019). Azo dyes are the most common synthetic dyes in the textile industry and possess the major environmental risk since they could form toxic aromatic amines when undergoing reductive cleavage (Bräuscheiwer and Merlot, 2017). Conventional physicochemical remediation of dyes is being implemented, however, its application generates high operating costs (Chu and Phang, 2019). Seaweed is noted to have a good retention capacity for the removal of synthetic dyes from aquatic systems, and attractive biosorption approach in the treatment of dye water pollution (Rubin et al., 2005; Tabarak and Heidarizadi, 2017; Omar et al., 2018).

In general, the effects of pollutants on aquatic ecosystems and living resources are negative. Reduction in fish biodiversity; loss of nesting habitats; degradation of coastal habitats and biodiversity; disruption of fish life cycles in aquaculture; massive death of fish from contaminated water and changes in water chemistry are just some examples of the environmental pressure exerted by pollutants in marine ecosystems (Shahidul Islam and Tanaka, 2004). Therefore, it is urgent to generate sustainable strategies for the removal of pollutants in aquatic systems to mitigate the environmental damage that reaches the coasts through industrial and domestic effluents.

3. Sargassum sp.: eco-concerns, composition, and potentialities

*Sargassum* sp. is a brown macroalgae distributed around tropical oceans of the world. It used to reach the Mexican coasts in a seasonal way dragged by the currents of the North Equatorial Recirculation Region (NERR) coming from the Sargasso Sea and Small Sargasso Sea located within the Atlantic Ocean (Fig. 2). In 2014, an unusually large mass of floating seaweed (Bloom), was reported in the Mexican Caribbean coasts, consisting of the species *Sargassum fluitans* and *S. natans* (Széchy et al., 2012; van Tussenbroek et al., 2017). In 2015, around 9726 m² of seaweed per month per km of coastline were reported. Currently, the massive quantities of *Sargassum* sp. still reaching the Caribbean shores becoming an invasive threat (Sheet, 2015; Djakouré et al., 2017; van Tussenbroek et al., 2017).

Linked issues related to human health, local economy, and environment emerge when the *Sargassum* sp. is not recollected from the coast. After 48 h onshore, the algae start decaying and releases toxic gases like hydrogen sulfide and ammonia, which are reported to affect respiratory, cardiovascular, and neurological system (Resiere et al., 2018). Besides health problems, tourism, which is the main economic activity of the Caribbean, is also negatively impacted because the alarming amount of *Sargassum* sp. on the beaches does not allow access to the sea, it colors the clear water into murky brown, generates an unpleasant view and expel an ominous smell (van Tussenbroek et al., 2017). Free navigation is also limited by *Sargassum* sp. because it gets stacked in propellers of fishing boats and other ships, damaging the engines. Besides, these brown algae also affect sea life, by reducing oxygen, limiting the entry of sunlight into the water, generating organic matter and even acting as a barrier for some animals to get to the sand and nest (Haas et al., 2010; van Tussenbroek et al., 2017). All the above-discussed examples highlight the environmental threat and issues related to the coastal ecosystems.

Although the reasons for the invasion of *Sargassum* sp. on Mexican Caribbean coasts are not well defined, it is largely related to water pollution and climate change (Djakouré et al., 2017). Thus, strategies must be generated to reduce the number of pollutants that enter the coastal waters that promote the growth of invasive algae species. From that perspective, *Sargassum* sp. biomass could be used as a sequester of toxic elements in strategic points of pollution confluence as estuaries, fisheries or/and aquaculture and domestic and industrial Wastewater Treatment Plants. At the end of pollutants up-take, *Sargassum* sp. could be transformed into high-value compounds by extracting its bioactive molecules and retrieving the metals and nutrients adsorbed and recycle them into industrial processes (La Barre et al., 2018). Brown seaweeds, as *Sargassum* sp., are known for having a wide range of bioactive metabolites with potential applications for biofuel, cosmetic, nutraceutical, and pharmaceutical industries (Table 1) (Chandra et al., 2019). Also, residual brown seaweed is suitable for agriculture due to its physicochemical characteristics and biological activities that may supply plant nutrients and enhance soil quality in coastal ecosystems (Negreanu-Pirjol et al., 2011; Torres et al., 2019).

3.1. Bioremediation perspective of *Sargassum* sp.

Bioremediation refers to the use of plants or microorganisms and/or their novel enzymes to remove, neutralize, or degrade toxic substances under established and controlled conditions (Karigar and Rao, 2011; La Barre et al., 2018). Currently, the protagonists of bioremediation in marine environments are bacteria, microalgae, and macroalgae (seaweeds), which have helped the treatment of pollutants...
in sediments, effluents and sea surfaces (Chen et al., 2019). Bioremediation has two approaches, bioaccumulation which refers to the absorption of pollutants by living cells through its metabolic activity, generating biomass in the process and, bioaccumulation that consist in the adsorption or passive binding of toxic elements to the non-living biomass that could be dried or immobilized for this purpose (Chojnacka, 2010; La Barre et al., 2018).

Marine microalgae (Chlorella vulgaris) and macroalgae (seaweeds) are increasingly used in different biotechnological applications, including the bioremediation of contaminated wastewater with low C/N ratio (Sepehrí et al., 2019). Recently, much focus has also been given to the algae-bacteria consortia as a novel strategy to treat or remediate the contaminated wastewater (Liu et al., 2017; Sepehrí et al., 2019). Seaweeds can uptake active macronutrients (e.g., P and N) and metals (e.g., Fe, Zn, Ni, Cu, Mn, and Co) as food source for growth, while passively attach to its surface other potentially toxic ions (e.g., Hg, Pb, Cd, Zn, etc.) (Fig. 3) (Bilal et al., 2018; Bulgariu and Bulgariu, 2017; La Barre et al., 2018). Brown seaweeds, especially, have cell walls rich in phycocloids, that confers higher adsorption capacity because the affinity to metals ions is directly related to polymer binding sites (Zeraatkar et al., 2016). Bioaccumulation and biosorption by macroalgae are mainly used for the removal of metal cations from aqueous systems. Its biomass can concentrate metals 1000 times. The process is reported to be selective. Thus metal recovery is possible (Naja and Volesky, 2017). Sargassum sp. biomass, accumulated on Mexican Caribbean coasts is a cheap, renewable and natural residue, which is currently in alarming amounts on the beaches and need to be removed. If used as a biosorbent, only expenses related to transportation and preparation are involved. In this way, a problem can turn into a resource (Santos et al., 2018).

### 3.2. Biosorption potential of Sargassum sp. biomass

In brown algal biomass, the main mechanism of biosorption reported is ion-exchange that entails chemical bonding and electrostatic attractions through several functional groups present on its surface (Verma et al., 2008). The union of cationic metals depends directly on the presence of hydroxyl, carboxyl, amino, and sulfate groups, which are predominant surface groups of brown seaweeds (Ungureanu et al., 2018). These functional groups are present mainly in lipids, polysaccharides, and proteins on the cell surface (He and Chen, 2014). Carboxylic acids are the most abundant binding sites groups in

![Fig. 3. Biosorption and bioaccumulation processes involved in the presence of macroalgae cells. Active and passive uptake mechanisms of metals ions and other macromolecules are shown, such as (1) Bioaccumulation into vacuoles through active uptake in the presence of living biomass, and (2) Biosorption through passive uptake via surface adsorption in the presence of living/dead biomass. Functional entities available at the cell surface facilitate the overall process.](image-url)
brown algae because the cell wall is mainly comprised by alginic acid (alginate) a linear copolymer of mannuronic acid and guluronic acid residues, that are responsible for the chelation of metals ions (e.g., Cd\(^{2+}\), Pb\(^{2+}\), Zn\(^{2+}\), Cu\(^{2+}\), Ca\(^{2+}\), etc.) (Santos et al., 2018). At lower pH, sulfonic acid groups of fucoidan polysaccharide (that is found in a minor amount in the cell wall), can also perform heavy metal uptake (Davis et al., 2003; Volesky, 2003).

Ion exchange occurs between metals when binding to alginate. Light metals (e.g., Na\(^{+}\), K\(^{+}\), Ca\(^{2+}\), Mg\(^{2+}\)) abundant in seawater, are originally bound to the cell surface, when reacted with a heavy metal solution the pH increases, leading to the release of light metal ions. The increase in pH is related to the fact that heavy metals occupied all interchangeable sites on the surface of the cell wall. Therefore, the maximum adsorption capacity of the biomass was reached (Schiewer and Volesky, 1995). In general, biosorption mechanisms are complex, and are subject to different factors that can interfere with the efficiency of the process in terms of kinetics and equilibrium, among them: pH, ion concentration, temperature and contact time (Ahmad et al., 2018; Bilal et al., 2018).

3.3. Bioaccumulation potential of Sargassum sp. biomass

Brown seaweeds can capture macronutrients and pollutants such as heavy metals intracellularly. This mechanism of retention and removal is known as bioaccumulation, which consists of the incorporation of potentially toxic elements by cystein-rich proteins (e.g., metallothionein MT), as well as its immobilization in organelles such as vacuoles and other vesicles through enzymatic action (Segrelin et al., 2018). The capacity of bioaccumulation depends on many factors, especially the composition of the medium, pH, temperature, concentration of pollutants (which are also inhibitors), and the metabolic activity of the algae. The environment must provide the macroalgae the proper conditions to grow (Chojnicka, 2010; La Barre et al., 2018). Generally, the targeted pollutants are the algae's food resource (e.g., N, P), since they are in excessive concentrations due to the anthropogenic activity near the coastal ecosystems. When the concentration of nutrients is high, and the conditions of light and temperature are favorable, the rapid proliferation of marine algae occurs.

Research on bioaccumulation of pollutants using seaweed is mainly focused on nutrient remediation and metal capture in integrated aquaculture systems (IMTA) (La Barre et al., 2018). Yu et al. evaluated the ability of two Sargassum species to bioaccumulate nutrients and capture metals from effluents of fish and oyster farms. Both studies conclude that Sargassum is a potential candidate for bioremediation of polluted effluents, due to its rapid growth rates and higher nutrients (N, P) and metal uptake (Cu, Zn, Pb, Cd, and Cr) compared with seaweed maintained in nearby reference locations (Yu et al., 2014; Yu et al., 2016). In this context, bioaccumulation by seaweed provides an instrument for nutrients and toxic metals bioremediation of effluents, to mitigate the impact of eutrophication and metal pollution on coastal ecosystems (Aminot et al., 2019; La Barre et al., 2018; Naja and Volesky, 2017).

4. Influential factors and their role in the biosorption capacity

4.1. Influence of pH level

pH is usually the most important factor to consider in terms of biosorption since it influences the charge of biomass surface as well as the speciation and solubility of adsorbates from solution (complexes or free ions) (Bulgariu and Bulgariu, 2017). Normally, the biosorption of cationic metals is carried out under acidic conditions related to the pK (dissociation constant) of carboxylic acids. At pH5, biomass can reach up to 98% of its adsorption capacity (Bilal et al., 2018). However, an increase or decrease in pH can reduce capacity considerably. A strong acidic environment promotes the protonation of sulfonic and carboxylic groups due to the presence of H\(^{+}\) ions that compete with metals ions thus, decrease biosorption (Ibrahim, 2011). An augment in pH (from strong to middle acidic conditions, up to pH5) promote the deprotonation of binding groups in the cell wall, then, active sites become available for the uptake of cations (Ghoneim et al., 2014). Upper increase in pH leads to precipitation of metal species, and this influence drastically the efficiency of biosorption (Bulgariu and Bulgariu, 2017; Jiang et al., 2017).

Therefore, adjusting the initial pH solution is a very important step and must be done according to the characteristics of both biosorbent and adsorbate. Generally, several acidic (e.g., HNO\(_3\), HCl, H\(_2\)SO\(_4\)) or alkaline (e.g., KOH, NaOH) mineral solutions are implemented to adjust the initial pH solution before adding the biosorbent into the reaction. Secondary processes as complexation and precipitation need to be avoided by choosing the most suitable solution (Areco et al., 2012; Uzunoglu et al., 2014).

4.2. Influence of alkalinity on the sorption efficiency

The alkaline nature of the reaction environment also considered an important parameter that showed a significant influence on the overall sorption efficiency but only at high concentrations. In an earlier study, Chwang et al. (2007) reported that constant alkalinity resulted in an alleviated phenanthrene (PHE) sorption by Sargassum hemiphyllum (brown seaweed). More specifically, the obtained results revealed that the percentage removals of aqueous PHE at constant alkalinity were under 85%, whereas the percent PHE removal was greater than 90% in all other experimental cases. In the case of other environmentally related pollutants, such as pesticides (e.g., synthetic pyrethroids), the alkaline environment is considered highly effective for complete elimination. This is mainly because the alkaline reaction environment induces the rapid degradation of pesticides (e.g., pyrethroids) by cleaving the ester linkage of the molecules (Laskowski, 2002; Nastunea et al., 2019). The adsorption capacity of a marine alga (Fucus spiralis) for the removal of cypemethrin (CYP), a synthetic pyrethroid, from the water was investigated by Nastunea et al. (2019). CYP is extensively used as a preservative agent in the industrial sector. For instance, it is used in the textile industry for cotton and wool fabrics. Consequently, the controlled or uncontrolled release of CYP-containing industrial waste effluents contributes CYP in the range of 0.1 to 194 µg/L which is frequently detected in our surface water bodies (Marino and Ronco, 2005). The continuous persistence and/or occurrence of CYP and other related environmental pollutants in the surface water bodies signifying the alleviated concern, around the globe. Such threatening concerns can be effectively tackled by designing and deploying alkaline-based reaction strategies. Recently, Zhang et al. (2019) reported an adsorptive removal of polycyclic aromatic hydrocarbons by detritus of green tide algae deposited in coastal sediment. The maximum equilibrium adsorptive capacity of Ulva prolifera detritus for naphthalene and PHE was determined as 1.27 and 2.02 mg/kg at pH 8.0, respectively, at the initial concentration of 10 µg/L.

4.3. Influence of concentration of ions

Another factor that influences the efficiency of biosorption is the concentration of ions in the solution. In general, the greater the concentration of ions in the solution, the greater the adsorption capac-
ity of the biomass (Bulgariu and Bulgariu, 2017). This is explained by the fact that increasing the ion concentration generates a driving force that overcomes the resistance in the mass transfer between the biomass and the contaminated solution. Badescu et al. (2015), reported an increase in the adsorption capacity (up to 18 times) of Ulva lactuca sp. dried biomass, when subjected to an initial concentration of Cu\(^{2+}\) from 1.12 to 20.28 mg/L. However, the adsorption process is not linear between the concentration of ions and the biosorption capacity of the biomass, once all the active sites are occupied in the cell wall, the biosorbent is saturated, and a steric blockage is generated avoiding the interaction between the ions and the functional groups of the biosorbent surface (Bulgariu and Bulgariu, 2017).

### 4.4. Influence of contact period

Biosorption can be largely limited due to inadequate contact time, even if the removal efficiency is high. The biosorption is carried out in two phases: a fast stage at the beginning, where the ions retained by the binding sites increase in the first hour. Followed by a slower stage where biosorption reaches equilibrium (Ibrahim et al., 2016; Montazer-Rahmati et al., 2011). The optimal contact time varies according to the biosorbent, when using macroalgae, the contact times reported have not been greater than 4 h (Ahmad et al., 2018; Volesky, 2003).

### 4.5. Influence of temperature

Temperature defines the thermodynamics of biosorption. Its optimum value depends on the general biosorption system, and it is usually established experimentally. Based on the literature, an increase in the temperature (up to 50°C) improves the biosorption capacity of marine algae biomass as a result of an endothermic process (Gupta et al., 2010; Johansson et al., 2016). The reasons of this improvement in biosorption could be related to the following key points, i.e., (1) an increase of active sites in biosorbent surface (Mehta and Gaur, 2005), (2) a decrease in mass transfer resistance in biosorption (Meena et al., 2005), and (3) an increase in the binding stability between the adsorbate and the functional groups of the algae biomass (Bulgariu and Bulgariu, 2017). However, the elevated temperature above the optimal limits (beyond 35–50°C) can degrade algal biomass (Montazer-Rahmati et al., 2011). In contrast, other studies agree that temperature does not have a significant effect on biosorption (Lodeiro et al., 2006; Lupea et al., 2012). For economic considerations, it is recommended to carry out biosorption at an environmental temperature (25°C) (Bulgariu and Bulgariu, 2017).

In summary, all the above parameters must be evaluated experimentally for the removal of potentially toxic ions from an aqueous solution, the results obtained will allow optimizing the conditions to reach the maximum efficiency of the biosorption process.

### 5. Mechanistic overview - equilibrium and kinetics

Mathematical modeling is a powerful tool to scale-up biosorption applications. It provides the information necessary to analyze the experimental data from the adsorption process of potentially toxic ions onto macroalgae biomass, extracting both equilibrium and kinetics parameters (Segretin et al., 2018). Equilibrium refers to biosorption isotherms, that represent the distribution of the toxic ions in the aqueous solution and on the surface of the sorbent biomass, and kinetics explain biosorption mechanism of ion retention per weight unit of biosorbent at equilibrium and at a time (Montazer-Rahmati et al., 2011). The isotherms of marine seaweed biosorbent are usually explained by Langmuir (homogenous biosorbent surface) and Freundlich (heterogenous biosorbent surface) models, while kinetics with a pseudo-first-order kinetic model (Rangabhashiyam et al., 2014; Ungureanu et al., 2018; Khan et al., 2019; Ali et al., 2020).

Langmuir isotherm has been reported as the model that fits the most the characteristics of the biosorption process by macroalgae since the seaweed has a quite homogeneous surface and the biosorption of potentially toxic ions occurs until a monolayer is formed and cover the biomass surface (Benaïsa et al., 2018; Bulgariu and Bulgariu, 2017; Rangabhashiyam et al., 2014). Langmuir model allows calculating the maximum biosorption capacity (qmax) of a given biosorbent in terms of mmol or mg of toxic-ion per gram of biosorbent (mmol/g, mg/g) under established experimental conditions, biosorbents with the highest qmax is the most appropriate (Davis et al., 2003). Table 2 shows the values of qmax of the biosorption of some potentially toxic elements or pollutants by *Sargassum* sp. biomass.

### 6. Circular economy perspective

One of the great challenges facing the current economy is to decouple economic growth from the consumption of finite resources, which have fed industrial activity since XVIII century by the model extract-make-dispose. This linear behavior has led to massive exploitation of natural resources whose regeneration rate is much lower than the current demand for products derived from them. Fuels, pesticides, textiles, electronic parts, high-tech machinery, and so on are goods made by finite supply and usually, after their shelf life, end up as a contaminant residue in the environment (Korhonen et al., 2018). The circular economy concept takes as a basis the idea of feedback and/or real world-systems which are cyclical. The waste generated is the resource of other biochemical processes. Thus, the aim of transforming the actual economy into a redesigned circular economy is to meet the principles of (1) Design out waste and pollution, (2) Keep products and materials in use, (3) Regenerate natural systems (Maguire et al., 2019). The way in which we attach the circular perspective to the management of *Sargassum* sp. is related to taking the waste-treated algae as a primary resource for its use in different applications, including bioremediation.

Phosphorous (P), for example, is one of the essential nutrients for plant growth, nowadays it is considered an important pollutant since it is found in high concentrations in water systems producing watercourse eutrophication, that as a result, promote the accelerated and excessive growth of aquatic plants, that triggers oxygen depletion and threat the wellness of aerobic aquatic life (Karemangingo, 2019). The excess phosphorus in the water is due to agricultural activity, which must look for external sources of phosphorus (P) to be able to fertilize the soil. Phosphate rock (P-rock) is the main agricultural input as a supplement of phosphorus. The use of P-rock, as a source of phosphoric acid, contributed to the dramatic increase in the global yields of crops over the past half-century saving thousands of people from starvation (Schröder et al., 2010). However, due to this product depends on mining, its generation rate is much lower than the consumption rate, leading to phosphorus scarcity, threaten food security in many regions of the world. Hence, food safety discussions around the globe have focused on the emerging challenge of where and how phosphorus will be obtained in the future to ensure the availability of food for the growing population (Nanda et al., 2019). As phosphorous, In general, all minerals extracted for industrial activities as Cu, Zn, Pb, Cd, and Cr, fulfill the characteristic of regenerating slowly, and most of them represent an increasing source of pollution in the environment, especially aquatic systems (Aminot et al., 2019).
Table 2
A literature overview of numerous *Sargassum* sp. biomass used as a biosorbent to remove and/or mitigate environmentally related pollutants from aqueous solutions.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th><em>Sargassum</em> sp.</th>
<th>Biomass configuration</th>
<th>Processing technique</th>
<th>Conditions</th>
<th>qmax (mg/g)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe (III)</td>
<td><em>Sargassum</em> vulgare</td>
<td>N/A</td>
<td>Batch system</td>
<td>pH=2, T=25°C, C&lt;sub&gt;t&lt;/sub&gt;=2 h, AD=5 g/L</td>
<td>19.86</td>
<td>Benaisa et al. (2018)</td>
</tr>
<tr>
<td></td>
<td><em>Sargassum</em> vulgare</td>
<td>Immobilized in Ca-alginate</td>
<td>Batch system</td>
<td>pH=2, T=25°C, C&lt;sub&gt;t&lt;/sub&gt;=2 h, AD=20 g/L</td>
<td>20.82</td>
<td>Benaisa et al. (2019)</td>
</tr>
<tr>
<td></td>
<td><em>Sargassum</em> sp.</td>
<td>N/A</td>
<td>Batch system</td>
<td>pH=3, T=30°C, C&lt;sub&gt;t&lt;/sub&gt;=1.5 h</td>
<td>24.78</td>
<td>Saravanan et al. (2010)</td>
</tr>
<tr>
<td>Hg (II)</td>
<td><em>Sargassum</em> glaucescens</td>
<td>N/A</td>
<td>Batch system</td>
<td>pH=5, T=25°C, C&lt;sub&gt;t&lt;/sub&gt;=2 h, AD=1 mg/L</td>
<td>147.05</td>
<td>Esmaeili et al. (2015)</td>
</tr>
<tr>
<td></td>
<td><em>Sargassum</em> sp.</td>
<td>N/A</td>
<td>Batch system</td>
<td>pH=4, T=30°C, C&lt;sub&gt;t&lt;/sub&gt;=1.5 h</td>
<td>67.09</td>
<td>Saravanan et al. (2010)</td>
</tr>
<tr>
<td></td>
<td><em>Sargassum</em> fusiforme</td>
<td>N/A</td>
<td>Batch system</td>
<td>pH=8–10, T=25°C, C&lt;sub&gt;t&lt;/sub&gt;=1 h, AD=20 g/L</td>
<td>30.86</td>
<td>Huang and Lin (2015)</td>
</tr>
<tr>
<td>Cr (VI)</td>
<td><em>Sargassum</em> sp.</td>
<td>N/A</td>
<td>Batch system</td>
<td>pH=4, T=25°C, C&lt;sub&gt;t&lt;/sub&gt;=60 min, AD=2 g/L</td>
<td>33.25</td>
<td>Khorramabadi and Soltani (2008)</td>
</tr>
<tr>
<td></td>
<td><em>Sargassum</em> muticum</td>
<td>N/A</td>
<td>Batch system</td>
<td>pH=2, T=20°C, C&lt;sub&gt;t&lt;/sub&gt;=60 min, AD=2 g/L</td>
<td>196.10</td>
<td>Bermúdez et al. (2012)</td>
</tr>
<tr>
<td></td>
<td><em>Sargassum</em> siliquosum.</td>
<td>Protonated biomass with HCl (0.1 M)</td>
<td>Batch system</td>
<td>pH=2, T=30°C, C&lt;sub&gt;t&lt;/sub&gt;=6 h, AD=3 g/L</td>
<td>66.40</td>
<td>Cabatingan et al. (2008)</td>
</tr>
<tr>
<td>Co (II)</td>
<td><em>Sargassum</em> sp.</td>
<td>Pretreated biomass with Mg&lt;sup&gt;2+&lt;/sup&gt;</td>
<td>Batch system</td>
<td>pH=7, T=45°C, C&lt;sub&gt;t&lt;/sub&gt;=1.5 h, AD=1 g/L</td>
<td>80.27</td>
<td>Soleymani et al. (2015)</td>
</tr>
<tr>
<td></td>
<td><em>Sargassum</em> wightii</td>
<td>N/A</td>
<td>Batch* Continuous flow system**</td>
<td>pH=4.5, T=25°C, C&lt;sub&gt;t&lt;/sub&gt;=12 h, AD=2 g/L</td>
<td>20.63*</td>
<td>Vijayaraghavan et al. (2005)</td>
</tr>
<tr>
<td></td>
<td><em>Sargassum</em> sp.</td>
<td>N/A</td>
<td>Fixed-bed column</td>
<td>pH=7, T=45°C, C&lt;sub&gt;t&lt;/sub&gt;=40 min, AD=3.5 g/L</td>
<td>3.12</td>
<td>Esmaeili et al. (2007)</td>
</tr>
<tr>
<td>Cd (II)</td>
<td><em>Sargassum</em> angustifolium</td>
<td>N/A</td>
<td>Batch system</td>
<td>pH=6, T=38°C, C&lt;sub&gt;t&lt;/sub&gt;=60 min, AD=1 g/L</td>
<td>146.72</td>
<td>Jafari et al. (2015)</td>
</tr>
<tr>
<td></td>
<td><em>Sargassum</em> vulgare</td>
<td>Protonation of biomass with HCl (0.1 M)</td>
<td>Batch system</td>
<td>pH=4.5, T=22°C, C&lt;sub&gt;t&lt;/sub&gt;=3 h, AD=2 g/L</td>
<td>88.79</td>
<td>Davis et al. (2000)</td>
</tr>
<tr>
<td></td>
<td><em>Sargassum</em> filipendula</td>
<td>N/A</td>
<td>Batch system</td>
<td>pH=6, T=35°C, C&lt;sub&gt;t&lt;/sub&gt;=1 h, AD=2 g/L</td>
<td>103.50</td>
<td>Verma et al. (2018)</td>
</tr>
<tr>
<td></td>
<td><em>Sargassum</em> sp.</td>
<td>Crosslinking PEI&lt;sup&gt;a&lt;/sup&gt; &amp; glutaraldehyde</td>
<td>Protocol of Brierley</td>
<td>pH=6, T=30°C, C&lt;sub&gt;t&lt;/sub&gt;=16 h, AD=2 g/L</td>
<td>157.80</td>
<td>Valdman and Leite (2000)</td>
</tr>
<tr>
<td>Cu (II)</td>
<td><em>Sargassum</em> fusiforme</td>
<td>N/A</td>
<td>Batch system</td>
<td>pH=8–10, T=25°C, C&lt;sub&gt;t&lt;/sub&gt;=1 h, AD=2 g/L</td>
<td>7.69</td>
<td>Huang and Lin (2015)</td>
</tr>
<tr>
<td></td>
<td><em>Sargassum</em> sp.</td>
<td>Crosslinking PEI&lt;sup&gt;a&lt;/sup&gt; &amp; glutaraldehyde</td>
<td>Protocol of Brierley</td>
<td>pH=6, T=30°C, C&lt;sub&gt;t&lt;/sub&gt;=16 h, AD=0.2 mg</td>
<td>77.40</td>
<td>Valdman and Leite (2000)</td>
</tr>
<tr>
<td>Pollutant</td>
<td>Sargassum sp.</td>
<td>Biomass configuration</td>
<td>Processing technique</td>
<td>Conditions</td>
<td>q_{max} (mg/g)^a</td>
<td>Reference</td>
</tr>
<tr>
<td>-----------</td>
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</tr>
<tr>
<td>Pb (II)</td>
<td>Sargassum sp.</td>
<td>N/A</td>
<td>Batch system</td>
<td>pH=5.5</td>
<td>32.69</td>
<td>Sheng et al., (2004)</td>
</tr>
<tr>
<td>Ni (II)</td>
<td>Sargassum sp.</td>
<td>N/A</td>
<td>Batch system</td>
<td>pH=5.5</td>
<td>35.80</td>
<td>Sheng et al., (2004)</td>
</tr>
<tr>
<td>Zn (II)</td>
<td>Sargassum sp.</td>
<td>N/A</td>
<td>Batch system</td>
<td>pH=5.5</td>
<td>66.60</td>
<td>Moghazy et al. (2019)</td>
</tr>
<tr>
<td>Ni (II)</td>
<td>Sargassum wightii</td>
<td>N/A</td>
<td>Batch*</td>
<td>pH=4</td>
<td>18.58*</td>
<td>Vijayaraghavan et al. (2005)</td>
</tr>
<tr>
<td>Sargassum sp.</td>
<td>Crosslinking PEI^b &amp; glutaraldehyde</td>
<td>Protocol of Brierley</td>
<td>AD=1 g/L, pH=6, T=30°C, Ct=16 h</td>
<td>118.50</td>
<td>Valdman and Leite (2000)</td>
<td></td>
</tr>
<tr>
<td>Sargassum wightii</td>
<td>N/A</td>
<td>Batch*</td>
<td>AD=1 g/L, pH=4, T=25°C, Ct=12 h, 24 h**</td>
<td>39.74**</td>
<td>Vijayaraghavan et al. (2006)</td>
<td></td>
</tr>
<tr>
<td>Sargassum filipendula</td>
<td>N/A</td>
<td>Batch-system</td>
<td>AD=1 g/L, pH=6.0, T=23°C, Ct=50 min, AD=3 g/L</td>
<td>30.2</td>
<td>Vijayaraghavan et al. (2009)</td>
<td></td>
</tr>
<tr>
<td>Mn (II)</td>
<td>Sargassum wightii</td>
<td>*N/A</td>
<td>Batch*</td>
<td>pH=5.5</td>
<td>38.67*</td>
<td>Henriques et al. (2011)</td>
</tr>
<tr>
<td>Sargassum filipendula</td>
<td>N/A</td>
<td>Batch*</td>
<td>AD=4 g/L, pH=3.0, T=30°C, Ct=25 min, AD=0.2 g/L</td>
<td>99.97**</td>
<td>Tabaraki and Heidarizadi (2017)</td>
<td></td>
</tr>
<tr>
<td>Anionic dyes (SY, EY, IC)^c</td>
<td>Sargassum glaucescens</td>
<td>Protonation of biomass with HCl (0.1 M)</td>
<td>Batch system</td>
<td>pH=3.0</td>
<td>≈46.12</td>
<td>Tabaraki and Heidarizadi (2017)</td>
</tr>
<tr>
<td>Methylene blue</td>
<td>Sargassum dentifolium</td>
<td>N/A</td>
<td>Batch system</td>
<td>pH=7.0</td>
<td>66.6</td>
<td>Moghazy et al. (2019)</td>
</tr>
</tbody>
</table>
A promising way to recover these inorganic compounds from the environment is by using renewable materials to uptake these contaminants that are present in excess in water systems. Consequently, the use of brown algae biomass, as *Sargassum* sp. exposes a favorable and cost-effective alternative for the removal of pollutants as phosphorus from a watercourse, effluents, or coastal systems, allowing the desorption, recovery, and reintegration of them to industrial and land processes. After using *Sargassum* sp. as a biosorbent, the remaining biomass could become a source of added-valued bioproducts through the extraction of its bioactive compounds (e.g., antioxidants and polysaccharides) (Table 1) (Torres et al., 2019). Also, the residual biomass can be used directly in energy source and agricultural soil conditioning. Fig. 4 shows the cyclical flow that *Sargassum* sp. could follow to recycle contaminants into a resource through different industries, representing sustainable management of raw material, minimizing waste, and making the most of resources.

All processes involved in the transformation of biomass must be aligned to a sustainable model. Hence more valuable impact is generated long-term. Though it is still a challenge, however, is a way to take advantage of a renewable waste, and convert it into a source to build capital rather than reduce it.

### 7. Current challenges and barriers

Although brown algae have become a promising alternative for use as a biosorbent, some barriers must be overcome. The first drawback is the lack of recognition of the complexity of the aquatic systems to bioremediate (Vasudevan et al., 2001), the majority of studies related to the use of dried algal biomass as a biosorption tool (Table 2), evaluate the process of adsorption in a synthetic single-component system that involves the removal of a single potentially toxic element under idealized conditions. In contrast, industrial and domestic effluents are complex and include competitive interactions of several toxic elements in multitype of oxidation states and speciation (Naja and Volesky, 2017; Vasudevan et al., 2001). Kidgell et al. (2014), stated that biosorption of real effluents might require multiple stages of treatment to be efficient since factors as pH become critical in the presence of more pollutants. None of their evaluated biosorbent was efficient in a holistically way (Kidgell et al., 2014). The second drawback of biosorption is the low efficiency in the adsorption of anionic metals and metalloids (e.g., AsO₄³⁻, SbO₂⁻, MoO₄²⁻, As³⁺, Se⁶⁻, Sb⁵⁻) that are usually found in effluents. One way to overcome this limitation is to pretreat the biomass, either by modifying the charge of the biomass surface into positive (e.g., Fe wash) or by physical modification as pyrolysis to improve adsorption capacity (Fujita et al., 2006; Yang et al., 2012). However, these biomass modifications represent an increase in the cost and difficulty of the biosorption process, which is meant to be an economical and simple alternative. Therefore, despite the advantages of using brown seaweed biomass for the biosorption of potentially toxic elements in aquatic systems, it is necessary to evaluate all condition requirements for better efficiency in more complex effluents that are related to the priority pollutants of coastal ecosystems.

### 8. Concluding remarks, recommendations, and future considerations

In conclusion, *Sargassum* sp. biomass exhibits a great potential to be exploited as a renewable and environmentally friendly matrix to tackle pollutants in aqueous coastal ecosystems. Its bioremediation capacity depends on the active absorption of pollutants (bioaccumulation) and also on the passive binding of toxic elements to the non-living biomass (biosorption). pH, ion concentration, temperature, and contact time are factors that affect the mechanisms of bioaccumulation and biosorption of the algae. The main advantages related to the use of *Sargassum* sp. as a contaminant scrubber are: (1) Its abundance and low cost; (2) The presence of several binding sites as carboxylic acids groups on cell surface and enzymes for intracellular immobilization; (3) It is a renewable, reusable and biodegradable source of biosorbent material and bioactive compounds; (4) It can be introduced into a circular value chain, where pollutants are reintegrated into industrial processes, to comply the emerging economic models that give value to waste as sources of new products; among others. Although there are many challenges to overcome related to the use of *Sargassum* sp. as pollutants remover, it also represents a feasible alternative that requires a multidisciplinary academic effort to tackle pollution in watercourse and coastal ecosystems.

Bioremediation using *Sargassum* sp. biomass can play a key role in the removal of coastal pollutants as metal ions, and nutrients resulted from land activities. Among the most important challenges to overcome for its implementation as a Biosorbent are (1) The long-term storage of biomass, since being a biodegradable material, it decomposes rapidly, losing its adsorption capacity; (2) The lack of multi-component biosorption research using *Sargassum* sp. biomass. Most of the studies carried out have been done on laboratory-controlled contaminated solutions with one or two pollutants, limit-
ing the reproducibility of the results in complex contaminated matrices such as effluents and coastal outfall; (3) Poor availability of detailed systemic studies of cost-effective implementation of Sargassum biomass as a biosorbent when scaling up to larger capacity, and the modification needed to improve biosorption capacity such as polymeric linkage with other cheap and biodegradable materials; (4) Narrow modeling studies to determine the behavior of the North Atlantic currents. This information can predict Sargassum sp. upwelling and its availability to be used as a resource for future coastal industries, and also to predict the need to implement seaweed cultivation; (5) Finally, it is needed novel technology to reduce the current elevated costs related to biomass biorefinery, to design out waste and pollution, use the most of the raw material to recover pollutants, and also obtain value-added products.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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