Elemental composition and nutritional potential of wild seaweeds from Northwest Africa: Implications for agro-food applications

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Abstract

Seaweed, like other living resources of the sea, can contribute to meeting the food and nutritional needs of African populations. Although food neophobia is likely, pressures from fish scarcity, climate change, and population growth make the inclusion of novel food from seaweeds increasingly necessary. The chemical content of various seaweeds in four locations over Senegal was determined, including minerals and heavy metals. A majority of the samples have cadmium concentrations exceeding the threshold for toxicity, and approximately half exceed the threshold for lead. We observed elevated levels of sodium (Na) and potassium (K) in *Codium cylindricum*, surpassing the nitrogen abundance. In one *C. cylindricum* sample, their concentrations were even higher than carbon, a rare occurrence in seaweeds. Some seaweed were highlighted for their significant contributions to key nutrients based on *Codex Alimentarius*'s nutrient reference values: *Caulerpa* sp. for iron (77 – 84 %), *C. cylindricum* for potassium (15 %), *Ulva* sp. for magnesium (51 – 54 %), and *Ellisolandia elongata* for calcium (118 – 134 %). The Na/K ratios were below the WHO recommended ratio in *C. cylindricum*, *Ulva* sp., and *E. elongata* but exceeded it in *Caulerpa* sp.. Except for one Rhodophytae, all Chlorophytae in the Bryopsidales order exceeded the Na/K WHO recommendation. The presented insights, including review of half a century of phycological research in Senegal, provide a foundation for developing strategies to incorporate Senegalese seaweed into diets and agri-food products while supporting blue jobs and food in the framework of the blue economy in West Africa.

Keywords: Blue food, *Codex alimentarius*, Seaweed, Human diet, *Codium cylindricum*, Senegal.

1. Introduction

With more than 700 km of coastline on the Atlantic Ocean and more than 200 species of seaweeds, Senegal is a promising area for blue development with seaweeds (DGEFM, 2006). Wild harvested and cultivated seaweeds are promising alternative marine resources for blue development, creating alternative seafood to exploit and income-generating activities. Compared to Asia, Europe (Chopin & Tacon, 2021), and East Africa, *i.e.,* Tanzania or Madagascar (Msuya et al., 2022), seaweed production in Senegal and West Africa is in its infancy, and there are many gaps regarding their development. The economic, social and environmental interest of seaweed exploitation in Senegal is comparatively new. In this respect, it is important to bring together previous knowledge and increase scientific activities to frame the exploitation. Food security is a global concern, as rapid population growth demands more resources. Additionally, a growing understanding of health and nutrition requirements drives the search for more nutritious food alternatives (Fasogbon et al., 2024). Seaweeds are under-utilized bioresource for food and medicine. Recent studies have focused on access to these readily available natural resources and their use for nutritional and medicinal purposes (Fasogbon et al., 2024). Seaweeds can have interesting nutritional properties for human nutrition due to their richness in essential minerals and trace elements (*e.g*., iron, iodine, magnesium, manganese, and calcium) (Circuncisão et al., 2018; Pereira, 2011). Calcium and phosphorus, major minerals in the human body, are abundant elements in seaweeds, with concentrations that surpass those of apples, oranges, carrots, and potatoes (Circuncisão et al., 2018). Among the brown seaweeds, there are genera such as *Ascophyllum* and *Fucus*, which species are widely consumed and used in current dietary supplements (Salido et al., 2024). For example, these two seaweeds, present in Gdue, a nutraceutical product in a ratio of 95:5 (*Ascophyllum nodosum* 95 and *Fucus vesiculosus* 5), are able to improve body weight balance and stimulate general metabolism, particularly that of lipids and carbohydrates (Nicolucci et al., 2021).

Among Chlorophytes, *Ulva* and *Caulerpa* are edible representatives, used mainly in salads and as side dish for sushi (*e.g*. due to the grape-like appearance of *C. lentillifera*) (Salido et al., 2024). Among Rhodophytes, one of the most popular seaweed for human consumption is dulse (*Palmaria palmata*) (Salido et al., 2024). Either harvested or cultivated, dulse has great potential as a sustainable food containing key nutrients such as protein, fiber, vitamins, and minerals. As regards nutrition, *Palmaria palmata* stands out from other edible seaweeds as one of the best alternatives to cereals for food uses (Xu et al., 2024). *Chondrus crispus* and *Gracilariopsis longissima* (ogonori) are also widely consumed (Salido et al., 2024). Numerous studies have been conducted on the integration of seaweeds in foods on green (Jannat-Alipour et al., 2019; Syakilla et al., 2024), brown (Ballance et al., 2024) and red seaweeds (Aganduk et al., 2024). Overall, consumers appreciate seaweed in bread and spreads. Taste and texture attributes contribute most to consumers' appreciation of these seaweed-based products (Jönsson et al., 2024). The enrichment of pasta with *Himanthalia elongata* brown seaweed and *Spirulina* microalga led to significantly higher levels of protein, fat, soluble dietary fibre, and ash content compared to 100% whole wheat pasta. Seaweeds can be a valuable functional ingredient in pasta production, contributing to food security (Oliveira et al., 2023). The use of *U. lactuca* and *Gracilaria corticata* in the preparation of bakery products (bread, cakes and cookies) enhances conventional products (those without seaweed), both in terms of shelf life (analyzed in terms of microbial load) and nutrition (Turuk & Banerjee, 2023). In recent years, regional seaweed-based cuisines around the world have been rediscovered and reinvigorated, and many chefs up to the top level have launched, often in collaboration with scientists, a trend towards new seaweed gastronomy, phycogastronomy (Mouritsen et al., 2019). Changing people's food preferences is difficult (Mouritsen et al., 2019), and food neophobia was identified as a barrier to acceptance of seaweed-based foods (Embling et al., 2022). People acceptance of incorporating seaweed into foods has been evaluated (Embling et al., 2022; Wendin & Undeland, 2020; Zheng et al., 2024). A suggested form of seaweed consumption was hidden in food products to enhance nutritional benefits (Moss & McSweeney, 2021). Taste, edibility and familiarity have been highlighted as strong drivers of acceptability, with taste in particular seen as an attribute that could further improve consumer acceptance and mitigate the effects of food neophobia as a barrier to acceptance (Embling et al., 2022). The mineral content of seaweeds has been extensively evaluated due to their nutritional importance (Mæhre et al., 2014; Premarathna et al., 2022; Rondevaldova et al., 2023; Smith et al., 2010; Xu et al., 2023). Seaweed contained higher quantities of macrominerals (*e.g.* Na, K, Ca, Mg) and trace elements (*e.g.* Fe, Zn, Mn, Cu) than those reported for most edible land plants (Rupérez, 2002), with a mineral content at least ten times higher than terrestrial plants and reaching 20-50% of its dry weight (Lozano Muñoz & Díaz, 2020). Edible seaweeds can be used as a dietary supplement to help achieve the recommended daily intake of certain essential minerals and trace elements (Rupérez, 2002). The mineral composition of seaweeds can be influenced by different biotic and abiotic factors, including their age, their ability to absorb inorganic substances (Lozano Muñoz & Díaz, 2020), and the type of processing (García-Sartal et al., 2013; Ho & Redan, 2021). Different types of seaweeds have different capabilities to uptake minerals from the environment due to the polysaccharides in their cell walls (Lozano Muñoz & Díaz, 2020). Most seaweeds have a high sodium (Na) content, which can be a drawback for their consumption, especially since sodium intake often exceeds the recommended daily levels. However, seaweeds typically have low sodium-to-potassium (Na/K) ratios, which is considered beneficial for human health (Circuncisão et al., 2018). Seaweed accumulates both essential minerals and harmful metals from the surrounding environment, potentially compromising its safety for human consumption (Lozano Muñoz & Díaz, 2020). Due to their ability to bioaccumulate metals, seaweeds have even been used as bioindicators to monitor metal pollution along coastlines (FAO & WHO, 2022; Morrison et al., 2008; Rakib et al., 2021). Studies on risk assessment and risk exposure to potential hazards associated with seaweed consumption for food use remain scarce. However, cases of morbidity and mortality linked to seaweed consumption are exceedingly rare (FAO & WHO, 2022). In this study, we did a state of the art of macroalgal research in Senegal. We determined the elemental profiling of seaweed samples collected along the Senegalese coast, analyzing 13 elements, including major, trace, and ultra-trace elements. The cadmium (Cd) and lead (Pb) levels were compared with the thresholds for food use. The Na/K ratios were compared with the World Health Organisation (WHO) recommended value. Certain species are recommended for each nutritional element based on their contribution to meeting the nutrient reference value – requirement (NRV-R) established by Codex (Lewis, 2019). Nutrient reference values (NRVs), a term proposed by a 1988 joint FAO/WHO expert consultation, are a set of values used in nutrition labelling; they are derived from authoritative recommendations for daily nutrient intake (Lewis, 2019). These recommendations are based on the best available scientific knowledge of the daily amount of energy or nutrients required for good health (Lewis, 2019). We evaluated the elemental composition of Senegalese seaweeds beyond food applications. The Cd and Pb levels were compared to the thresholds for use in animal feed. The carbon: nitrogen ratios were compared with the recommended range for use as compost. The metal pollution index of the seaweeds were calculated in order to find the most relevant seaweeds for use as bioindicators of site contamination levels. The present study provides a first overview of the evaluation of the elemental composition of a considerable number of Senegalese seaweeds in food applications.

2. Material and Methods

2.1. State of the art of macroalgal research in Senegal

This study compiles data from approximately half a century (1973 to 2021) on chemical characterization, processing and estimation of biomass of Senegalese seaweeds from peer-

reviewed papers, project and governmental reports, master as well as PhD-theses (Table S1). From 1973 to date, chemical characterizations, processing and biomass estimations were carried out on several seaweeds (Table S2). Studies have been carried out on the characterization of various seaweed components, including proteins (Sarr et al., 2019; Yagame et al., 2017), lipids (Aknin et al., 1990, 1992a, 1992b; Diop & Samb, 2004; Miralles et al., 1989, 1990), minerals (Dème - Gningue, 1985; Sarr et al., 2019; Yagame et al., 2017), secondary metabolites (Coly, 2008; Diop & Samb, 2000; Guella et al., 1993, 1994, 2006; Guella & Pietra, 1993; N'Diaye et al., 1994, 1996), and metals (Ndiaye et al., 2021). In addition, other studies have focused on the applications of seaweeds as fertilizers and composts (Dème - Gningue, 1985; Leclercq et al., 1985), for biomethane production (Leclercq, 1984; Leclercq et al., 1985; Maiguizo-Diagne et al., 2018), as phycocolloids - mainly carrageenans (Fostier, 1989; Fostier et al., 1992; Mollion, 1973), and for the nutritional rehabilitation of malnourished children (Barboza, 2000; Mbodj et al., 2007; Sarr et al., 2002).
Despite the potential socio-economic potential of seaweed, few studies in the Senegal sub-region have examined the metals and minerals contents, along with the associated risks and benefits for food products.

2.2. Study area

Senegal is a West African country where the climate is characterized by a hot, wet season (from June to October) and a cold, dry one (from November to May) with northeast dominant wind and a seasonal upwelling of cold nutrient-rich seawater (Diankha et al., 2015; Ndoye et al., 2014). The Senegalese coastline is divided into two parts: the "Grande Côte" part, which extends from the north to the centre of Senegal, Cap-Vert Peninsula Dakar and the "Petite Côte" part from Dakar to the Sine Saloum delta in the South (Samou et al., 2023). Three types of coasts are essentially present in the coastal area of Senegal: sandy and rocky coasts and muddy coasts with mangroves (Ren et al., 2015; Samou et al., 2023). The study area covers four sites: three sites in the centre of Senegal, *i.e.*, the Cap-Vert Peninsula (Ngor Island, Bay of Hann, and Cove Bernard in French "Anse Bernard") and one site along the Petite Côte (Somone) (Figure 1). The Cap-Vert Peninsula is characterized by a rocky coast favorable for seaweed habitat (Domain, 1976), whereas sandy beaches with the presence of numerous rocky points characterize the Petite Côte. The Cap-Vert peninsula includes the capital city (Dakar) and is characterized by high urbanization and different pollution levels (Sonko et al., 2022). Hann Bay is a heavily polluted area, whereas Ngor Island, open to the sea, has a better health status (Sonko et al., 2022). On the Petite Côte, there is less urbanization, a presence of touristic infrastructures in Somone, and a natural reserve (Sakho et al., 2015). Seaweeds were collected over two months (14/05 – 01/07/2022) at different points for Ngor Island, Hann Bay, and Somone. Twenty-seven seaweed samples were collected (Table S3) at three levels: at the intertidal zone (intertidal seaweeds, between low tide and high tide), *in situ* (subtidal seaweeds), and from the beach (beach cast seaweeds).

2.3. Analysis of seaweed content

Twenty-seven seaweed specimens were collected (13 in Ngor Island, 7 in Hann Bay, 6 in Somone, and 1 in Anse Bernard). The Anse Bernard site was included to assess the composition of *Codium cylindricum* at the subtidal level, contrary to the ones found in beach cast conditions in Hann Bay. The seaweeds were identified morphologically based on visual characteristics (Figure S1, Figure S2, and Figure S3). For more details on visual characteristics, Supplementary S1 illustrations of the seaweeds collected, associated with pictures of their growth environment and Supplementary S2 give more visual pictures of each seaweed collected. Supplementary S3 give visual support of the seaweeds during collection in video format, and Supplementary S4 provide the herbariums of collected seaweeds. When there was uncertainty about species-level identification, the classification was made at the genus level. All the samples were soaked shortly in demineralized water, dried, and then grounded (MM 200 Retsch; 20 Hz, three to six minutes). Samples were oven-dried (50°C; 48 hours).

2.3.1. Trace metal and mineral contents

Concentrations of ten different elements (Cd, Pb, Cu, Zn, Fe, Mn, Mg, Ca, K, and Na) were measured using a microwave plasma atomic emission spectrometer (MP AES 4200-Agilent) (Agilent Technologies, 2016; Balaram, 2020). The dried seaweed samples were further oven-dried at 60 °C for 30 min to even out residual moisture content. Samples were mineralized according to the following protocol. 0.5 g of dry sample was weighed and placed in a 10 ml tube. Nitric acid (HNO_3) 69% was used as the digesting acid. Next, 3 ml of HNO_3 was added to the tube, gradually to avoid foaming, then left overnight (cold digestion). The tubes were placed in a mineralizer and preheated at 100°C for two hours. The tubes were then left to cool. 1 ml hydrogen peroxide (H_2O_2) and 1 ml HNO_3 were added to the tubes and preheated at 100°C for one hour. After mineralization, the solutions were filtered and adjusted in 100 ml flasks with demineralized water, constituting the solutions to be analyzed. After filtration, chemical element concentrations were measured using the microwave plasma atomic emission spectrometer (MPAES).

2.3.2. Analysis of total phosphorus, carbon, nitrogen, and ash

The total phosphorus (P) content analysis was performed with a continuous flow molecular adsorption spectrophotometer SEAL AA3 Analyzer, following the same mineralization and filtration procedure used for chemical element analysis with the MPAES. The analysis is carried out using the Murphey and Riley method (Cho & Nielsen, 2017). The total carbon (C) and total nitrogen (N) content analyses were performed with a CHN Thermo Scientific Flash 2000 Elemental

Analyzer. The analysis method is based on the principle of the « Dumas method » (Krotz, 2019). The Kjeldahl nitrogen (Nk) content analysis was performed with a continuous flow molecular adsorption spectrophotometer SEAL AA3 Analyzer. Mineralization was carried out in concentrated sulfuric acid and salicylic acid with a selenium-based catalyst, leading to the formation of ammonium ions. The dosage of ammonium ions formed was carried out by automatic colourimetry (Berthelot reaction) (Sáez-Plaza et al., 2013) and using a standard range prepared from a 1g L^{-1} solution of N. For ash content, 0.5 g to 1 g of sample was weighed into capsules. Samples were calcined in an oven at 500°C for 2 hours after a one-hour stage at 200°C, then weighed.

2.4. Cd and Pb content and nutritional profiles

For Cd and Pb, thresholds for food use of 0.5 and 5 mg kg^{-1} DW (dry weight), respectively, are recommended by the French Agency for Food, Environmental and Occupational Health & Safety (ANSES, 2018; Banach et al., 2020) and the « Centre d'Étude et de Valorisation des Algues » (Banach et al., 2020; CEVA, 2014) for dry edible seaweeds. For Cd and Pb, thresholds for feed uses of 1 and 10 mg kg^{-1} (relative to a feed with a moisture content of 12%), respectively, were used to assess the measured concentrations (Banach et al., 2020; European Union, 2002). A 5.2 g of seaweed consumption per day, a common daily seaweed consumption per person in Japan and China (Chen et al., 2018; Khandaker et al., 2021), was used to assess the nutritional profile of the seaweeds. The nutrient intake that corresponds to the amount of daily seaweed consumption was calculated as shown below.

$$\mathrm{Intake_i} = \mathrm{C_i} \times \mathrm{D} \qquad \text{(Eq. 1)}$$

Where $Intake_i$ (mg day^{-1}) is the nutrient (element) "i" intake per day, C_i (mg g^{-1}) is the concentration of the nutrient "i" in the seaweed sample, and D (g) is the daily consumption of seaweed set to 5.2 g.

The nutrient intakes were compared to the nutrient reference values – requirements (NRV-R) or the nutrient reference values – non-communicable diseases (NRV – NCD) established by Codex (Lewis, 2019). NRVs are used to convert these nutrient intakes expressed in metric units (mg) into a percentage of the daily requirement (% NRV). Two types of NRVs are further defined: NRVs-R and NRVs-NCD. Nutrient reference values – requirements (NRVs-R) refer to NRVs that are based on levels of nutrients associated with nutrient requirements. NRVs-R are established for vitamins, minerals and protein. Nutrient reference values – non-communicable diseases (NRVs–NCD) refer to NRVs that are based on levels of nutrients associated with the reduction in the risk of diet-related non-communicable diseases, not including nutrient deficiency diseases or disorders. To date, NRVs-NCD have been established for saturated fat, sodium and potassium (Lewis, 2019). The daily references of the nutrients recommended by *Codex Alimentarius* are either encouraged to be met or discouraged from being exceeded (Lewis, 2019). A mineral claim must be made for a food product if the serving size contains an amount of the mineral not less than 15 % of the NRV-R value of that mineral (Lewis, 2019). The serving size is the amount of food that an individual consumer consumes on one eating occasion (Meijer et al., 2023). Codex establishes two NRVs-R for iron of 14 mg (15 % absorption) and 22 mg (10 % absorption). 15 % absorption corresponds to a dietary of diversified diets, rich in meat, fish, poultry and/or rich in fruit and vegetables, while 10 % absorption corresponds to diets rich in cereals, roots or tubers, with some meat, fish, poultry and/or containing some fruit and vegetable (Lewis, 2019). For the nutritional profiles assessment, beach cast samples of seaweeds were excluded. Only intertidal and subtidal ones were considered.

The Na/K ratio of seaweed specimens was compared to the WHO recommended ratio (≤1) (Morrissey et al., 2020; Vulin et al., 2022). For agricultural applications, *i.e.* compost, thresholds used are not addressed specifically for seaweeds but apply in general to all kinds of materials. We use these limits as there is a lack of specific ones for seaweeds in agriculture. In agricultural applications, permissible maximum limits for Cd, Zn, Cu, and Pb vary depending on the country and governing organization. The reference values considered here were the maximum and minimum limits found among the limits established by several countries and the European Union (Galán Huertos & Romero Baena, 2008; Ituarte, 2007; Ortega-Flores et al., 2023; Rodríguez-Martínez et al., 2020; Serrato et al., 2010).

2.5. Data analysis

A chemometric evaluation was done to elucidate elemental fingerprints or signatures between the samples (Zhang et al., 2018). Elemental fingerprinting is a classification of biological samples using their elemental profiles. Elemental signature is an elemental composition derived from a representative selection of samples that represents some condition or status (*e.g*. geographic origin, genetic origin or health status) (Zhang et al., 2018). Heat map representations were used for the analysis. Heat map representation, an application of hierarchical clustering analysis (Vacanti, 2019), categorizes similar samples into groups called clusters (Bratchell, 1992). Samples within a cluster are, with respect to the chemical data, more similar to each other than to samples in other clusters (Bratchell, 1992). All the analysis was carried out using R Studio software (R version 4.2.2). The heatmap representations were done using the package "pheatmap". The seaweed samples are grouped based on the similarity of their elemental profiling, helping to identify samples that are more similar to each other based on their composition. The metal pollution index (MPI) was used to assess the capacity of accumulation of metals between species (Rahhou et al., 2023; Rakib et al., 2021). All the samples (beach cast, intertidal, and subtidal) were considered for this purpose.

$$MPI = \left(\prod_{i=1}^{n} C_i \right)^{1/n} \quad \text{(Eq. 2)}$$

Where C_i is the concentration (mg kg^{-1}) for the metal "i" in the sample and "n'' is the number of metals analyzed. The metals included in the MPI were Cd, Pb, Cu, Zn, Mn, and Fe.

3. Results

3.1. Metal concentrations and nutritional properties

For seaweed food use, nineteen seaweed samples had Cd concentrations exceeding the threshold of 0.5 mg kg^{-1} DW, and twelve seaweed samples had Pb concentrations exceeding the threshold of 5 mg kg^{-1} DW (Figure 2, Table 1, Table 2). For twenty seaweed specimens, in 35 % of cases, the magnesium content in a serving size of 5.2 g day^{-1} reached 15 % of the NRV-R, while 15 % of the seaweed specimens offered the opportunities to meet between 50-90 % of the NRV-R (Table 3). For 35 % of seaweed specimens, the calcium content in the 5.2 g day^{-1} serving size reached 15 % of the NRV-R, while the two specimens reached 100 %. The iron content in this serving size reached 15% of the NRV-R for 65 % of seaweed specimens, while 10 % (case of 10 % iron absorption) and 25 % (case of 15 % iron absorption) of the seaweed specimens reached 50 – 90 % NRV-Rs (Table 3). In the case of a dietary with diversified diets (15 % iron absorption), two seaweed specimens reached upper 100 % NRV-R. Iron was the element for which the highest number of seaweeds reached a minimum of 15 % of the dietary reference value (Table 3). For each mineral among the seaweeds analyzed, the results outline seaweed species or genus with estimated intakes contributing more extensively to the dietary reference value (Table 3). Nearly three-quarters (70 %) of seaweed specimens showed a Na/K ratio under the WHO recommended ratio (≤1). The *Ulva* sp. have all Na/K ratios under the WHO recommended value. Except for one red seaweed, all seaweeds exceeding the WHO recommended value for Na/K belonged to the Bryopsidales order, green seaweeds (*Caulerpa*, *Bryopsis*, and *Codium* genus) (Table 3, Table S4). The excess of the ratio over the limit is most noticeable with the *Caulerpa* sp. (*Caulerpa peltata*: 9.1 and *Caulerpa racemosa*: 9.1) and *Codium tomentosum* (18.4) (Table 3).

3.2. Interspecies and intraspecies variations in element concentrations and pollution assessment

Among species, *Nemalion* sp. and *Grateloupia lanceola* exhibited relatively higher Cd content (Figure 2, Figure 3). *Padina tetrastromatica* and *Cystoseira* sp. displayed a high relative content of Cu compared to other species, between 2 – 44 fold difference (Figure 3, Table 1). For Pb, a high relative content was found in *Codium* sp. (mean: 11 ± 2 ppm) compared to the other species (mean: 4 ± 3 ppm) (Table 1, Figure 2). For intraspecies variation of [Pb] in *Codium cylindricum*, the subtidal one in Anse Bernard contained less Pb (8 ppm) than the beach cast ones from Hann bay (12 – 14 ppm). The genus *Ulva* is well distinguished by their high and similar [Mg] (Figure 3). Independently of their location, all species within the genus *Ulva* cluster together in a single group due in part to their shared elemental signature. This "elemental signature" refers to the elemental composition derived from a representative selection of samples, each reflecting some condition or status (*e.g*., genetic origin, geographic origin, or health status) (Zhang et al., 2018)) (Figure 3). We observe, with the classification of element concentrations from highest to lowest in each seaweed (Table 5), a relatively high content of sodium (Na) and potassium (K) in the understudied *C. cylindricum*. *Ellisolandia elongata* showed a relatively high content of Calcium [Ca], more predominant than the carbon concentration. Independently of their location, *Ellisolandia elongata* specimens are clustering in the same group mainly due to this elemental signature (Figure 3). High [Cu] in seaweeds sampled in the Somone site compared to the other sites was observed, *e.g.* *Ellisolandia elongata* from Somone site display more than a 10-fold difference [Cu] than *E. elongata* from Ngor Island (Table 1, Figure 4).

The MPI for all seaweeds varied from 8 to 41 (Table 5). The mean MPI was 18, with a maximum of 41, a minimum of 8 and a standard deviation of 7. All high values (> mean + SD) were observed for the Somone site. Three-quarters of the lowest MPI values (< mean - SD) were reported for Ngor Island. All MPI values for Anse Bernard and Hann Bay were in the medium range of MPI values.

4. Discussion

4.1. Metal regulations and nutritional properties for incorporation into agro-food products

Some elements such as calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), and phosphorus (P) are considered essential or beneficial, while others like copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) are considered both essential and potentially toxic. Additionally, cadmium (Cd) and lead (Pb) are recognized as toxic risks (Zhang et al., 2018).

As most of the samples (70 %) have [Cd] exceeding the threshold for food use (Figure 2), caution should be considered principally for this element for food applications in Senegal. As 44 % of samples exceeded the threshold for [Pb], caution should be extended to this element in food use as well. The French Agency for Food, Environmental and Occupational Health & Safety (ANSES) is currently evaluating whether this maximum level for Cd (0.5 mg kg^{-1} DW) will be maintained or increased (Kreissig et al., 2021) to reach the European level (3 mg kg^{-1} wet weight) (European Commission, 2014).

We found considerable levels of essential or beneficial elements based on the evaluation of estimated intake and comparison with recommended intake (Table 3). However, depending on the element targeted, some species are more beneficial than others. For calcium, *E. elongata* can be recommended due to their high % NRV-R (118 – 134 % NRV-R) per serving size (5.2 g day^{-1}). Calcium deficiency is a worldwide problem, particularly in the ageing population (Fujita, 2000). Malnutrition is a public health problem in low- and middle-income countries. In Senegal, 35% of adolescent girls were undernourished, and 99% of adolescents were at risk of calcium deficiency (Giguère-Johnson et al., 2021). 5.2 g serving size of Senegalese *E. elongata* contained more calcium content (1181 – 1336 mg) than 227 g serving of yoghurt, plain, low fat (415 mg), one cup serving of orange juice, calcium-fortified (349 mg), and 1 cup of milk, nonfat (299 mg) (National Institutes of Health, 2024a). Consumption of 5.2 g day^{-1} of Senegalese *E. elongata* contributes to 118 to 134 % of the daily requirement of Ca (118 – 134 % NRV-R) (Table 3) (Lewis, 2019). However, the daily references of the nutrients recommended by *Codex Alimentarius* are either encouraged to be met or discouraged from being exceeded (Lewis, 2019). Here, 5.2 g day^{-1} of *E. elongata* in foods surpassed the daily reference (% NRV-R over 100). Regarding calcium nutrients, consumption of Senegalese *E. elongata* through enrichment of agri-food products or direct consumption should not exceed 3.8 g day^{-1} (equivalent to 86 – 98 % NRV-R).

The predominance of carbon on the other elements is observed in almost all species in this study, with the exception of some species, such as *E. elongata* (Table 5), which has high calcium content. The Corallinales order (Rhodophyta), which belongs to *E. elongata* (previously known as *Corallina elongata*), is characterized by the presence of calcium carbonate ($CaCO_3$) in their cellular walls in the form of calcite (Oliveira et al., 2023), which explain the highest [Ca] found compared to the other species. *Ellisolandia elongata* from Ngor Island had a lower level of MPI (10) compared to that of Somone (22). To avoid the presence of Cd, a toxic element (13-fold difference between sites) and Cu, an element both essential and toxic (11-fold difference), Ngor Island should be recommended for harvesting for use in food. Their association (cohabitation) with periwinkles seafood might be evaluated for co-valorisation, as a noteworthy presence of these lasts was observed during the collection of *E. elongata* at Somone site. An important point, we found no information on the edibility of *E. elongata*. We outlined the above recommendations concerning Ca content in *E. elongata* if, in the future, the edibility of this seaweed is evaluated. This species has been cited for its potential contribution to feed formulations and as a basis for the development of functional foods (Saygili et al., 2022).

For potassium, *Codium cylyndricum* should be recommended due to its highest % NRV-R per serving size (5.2 g day^{-1}). The effect of potassium on the human body is wide-ranging, involving all cells and tissues, although most evidence points to its role in the cardiovascular system. An inverse relationship between potassium intake and blood pressure was also reported, while it has been shown that the favourable effect of a potassium-rich diet on cardiovascular disease is partly independent of its effect on blood pressure (D'Elia, 2024). Insufficient potassium intake can increase salt sensitivity (meaning that changes in sodium intake affect blood pressure to a greater than normal extent) (National Institutes of Health, 2022b). The main sources of dietary potassium are fruits and vegetables (D'Elia, 2024; National Institutes of Health, 2022b). 5.2 g serving size of Senegalese *C. cylindricum* contained similar potassium content (496 – 545 mg) than 1 cup serving of orange juice (496 mg) and more content than 1 cup of milk, 1 % (366 mg) (National Institutes of Health, 2022b). Consumption of 5.2 g day^{-1} of Senegalese *C. cylindricum* contributes to 15 % of the nutrient reference value – non communicable disease (15 % NRV-NCD) (Table 3) (Lewis, 2019). Nutrient reference values – non-communicable diseases (NRVs–NCD), which refer to

NRVs that are based on levels of nutrients associated with the reduction in the risk of diet-related non-communicable diseases, not including nutrient deficiency diseases or disorders (Lewis, 2019). The Na/K of the *C. cylindricum* (0.92) is under the WHO recommended ratio (≤1) (Morrissey et al., 2020; Vulin et al., 2022). *Codium cylindricum* is an understudied edible seaweed (Miyadai et al., 2022). To our knowledge, no studies have specifically targeted their elemental composition (minerals and metals). *Codium Cylindricum* was found to be a good source of the carotenoid siphonaxanthin (Li et al., 2018). Siphonaxanthin-rich green algae can be beneficial in preventing obesity and regulating lipid metabolism (Li et al., 2018; Zheng et al., 2020). Obesity is a leading risk factor for many diseases (Zheng et al., 2020), so it will be interesting to assess the uses of this seaweed in agri-food products or functional foods by integrating its full chemical profile.

For magnesium, an essential element for humans, species of *Ulva* genus should be recommended among the species studied due to the high % NRV-R per serving size (5.2 g day^{-1}). 5.2 g serving size of Senegalese *Ulva* species (*U. fasciata* and *U. rigida*) contained more magnesium content (158 – 167 mg) than 28 g of pumpkin seeds, roasted (156 mg), 28 g of chia seeds (111 mg), ½ cup of spinach, boiled (78 mg), and 227 g of yoghurt, plain, low fat (42 mg) (National Institutes of Health, 2022a). Consumption of 5.2 g day^{-1} of Senegalese *Ulva* sp. contributes to 51 to 54 % of the daily magnesium requirement (51 – 54 % NRV-R) (Table 3) (Lewis, 2019). Magnesium is the second or third most predominant element in *Ulva* sp. (Table 5). The range contents of magnesium in *Ulva* sp., reported in Jacobsen et al. (2023) (min: 300 mg kg^{-1}, max: 86900 mg kg^{-1}), showed a large fluctuation of the magnesium content of *Ulva* sp. The content range of Senegalese *Ulva* sp. (30366 – 32075 mg kg^{-1}) was within this range. The Na/K ratios of *Ulva* sp. (0.48 – 0.73) (Table 3) were under the WHO recommendation (Morrissey et al., 2020; Vulin et al., 2022). *Ulva* sp. are edible seaweeds (Botany, University of Hawaii, 2001; FAO & WHO, 2022). The French authorities have authorized the human consumption of several species of seaweed, including *Ulva* sp. (Khan et al., 2024). As a result, seaweeds have emerged as valuable vegetables for human consumption. Some countries are making faster progress than others in this domain. Chile encourages the use of seaweed for the development of new food products, dietary supplements and recipes, for which the seaweeds used include *Ulva* sp. *Ulva* chips have proved to be a more nutritious and environmentally-friendly alternative to typical potato chips (Khan et al., 2024). In Senegal, malnutrition remains a public health problem, with a prevalence of 20 %, including 5 % of severe malnutrition in children aged zero to five (Mbodj et al., 2007). In Senegal, as part of the development of low-cost diets, *U. lactuca* was tested (Barboza, 2000). The experiment consisted of integrating this seaweed into the local food preparations of malnourished children and studying their biological parameters following this intake. The aim was to improve the children's nutritional status during rehabilitation in malnourished children. A significant improvement in the nutritional status of children who had been supplemented with *U. lactuca* was observed (Barboza, 2000). In terms of hygienic quality, hot incorporation of *U. lactuca* into various foods is recommended for its beneficial effect (Barboza, 2000). The effects of meal preparation methods or the formulation process of agri-food or functional foods on the variation in magnesium content of *Ulva* sp. should be taken into account to optimize the content of this element in the final product. *Ulva* blooms damage marine ecosystems and impair local tourism (Dominguez & Loret, 2019). In Senegal, a case has been reported where its proliferation is harming business activities by affecting the correct operation of machinery and involving manoeuvres for the disposal of these *Ulva* sp. (Diallo, 2019). We recommend mapping the most suitable sites, where there is a large proliferation, for their collection for use in agri-food formulations, taking into account the health risk aspect for consumption.

For iron, species of *Caulerpa* sp. should be recommended due to the highest % NRV-R per serving size (5.2 g day^{-1}). Iron is an essential component of haemoglobin, an erythrocyte (red blood cell) protein that transfers oxygen from the lungs to tissues (National Institutes of Health, 2024b). 5.2 g serving size of Senegalese *Caulerpa* sp. (*C. racemosa* and *C. peltata*) contained more iron content (17 – 18 mg) than 85 g of oysters, eastern, cooked with moist heat (8 mg) and 85 g of beef liver, pan-fried (5 mg) (National Institutes of Health, 2024b). Consumption of 5.2 g day^{-1} of Senegalese *Caulerpa* sp. contributes to 77 % – 84 % of the daily iron requirement when iron absorption is at 10 %. This level of absorption typically occurs in diets rich in cereals, roots or tubers, with some meat, fish, poultry and/or fruit and vegetables. In contrast, it contributes to 122 % – 131 % of the daily iron requirement with 15 % absorption, which is characteristic of a more diversified diet rich in meat, fish, poultry and/or fruit and vegetables (Table 3) (Lewis, 2019). However, the daily references of the nutrients recommended by the Codex are either encouraged to be met or discouraged from being exceeded (Lewis, 2019). Here, in the case of dietary of diversified diets, 5.2 g day^{-1} of *Caulerpa* sp. in foods surpassed the daily reference (% NRV-R over 100). Regarding iron nutrient, in the case of dietary of diversified diets, consumption of Senegalese *Caulerpa* sp. through enrichment of agro-food products or direct consumption must not exceed 3.9 g day^{-1} (equivalent to 91 – 99 % NRV-R). In contrast, the Na/K ratios of the Senegalese *Caulerpa* sp. (9.07 – 9.13) were above the WHO recommendation. *Caulerpa racemosa* is an edible seaweed, while *C. peltata* is not (Tapotubun et al., 2020). We outlined the above recommendations concerning Fe content in *C. peltata* if, in the future, the edibility of this seaweed is evaluated. *Caulerpa racemosa* has been used as food and folk medicine since ancient times in the Indo-Pacific region, particularly in southeast Asia (Aroyehun et al., 2020). *Caulerpa* is known as the sea grape (Tapotubun et al., 2020). People living in coastal regions have long eaten *Caulerpa* as a fresh vegetable, especially during the lean season when fish is hard to find. Several reports have shown that *Caulerpa* sp. is highly suitable for processing into a variety of processed products and has great potential as a functional food (Tapotubun et al., 2020). Nevertheless, in Senegal nobody eat it (unpublished data).

4.2. Recommendations on initial seaweed incorporation in agri-food products

For initial seaweed incorporation into the formulation of agri-food products and functional foods, sustainable use of the natural stock could be envisaged after mapping the distribution and abundance of each species and evaluating the harvesting process in financial terms. However, for large-scale and long-term use of each seaweed in agri-food products, cultivation must be carried out to obtain sufficient biomass and ensure availability all the time. As an example, currently, *Caulerpa* sea grapes have been cultivated on a large scale in countries such as the Philippines and Thailand (Tapotubun et al., 2020). Some aquaculturists co-culture seaweed with commercially viable aquatic organisms, such as abalone, in integrated multi-trophic aquaculture systems to ensure good management and sustainability of their nutritional characteristics and composition (Largo et al., 2016). Healthily growing *C. racemosa* has been harvested in earthen fish culture ponds at Tanjung Kupang, Malaysia (Aroyehun et al., 2020). Depending on the species, cultivation of some of them works well in the open sea, and others do not. For example, *C. lentillifera* did not work well in an open sea cultivation system due to the impact of sea waves (Largo et al., 2016). The feasibility of seaweed farming along the coasts of Senegal was studied between 2013 and 2015 (JICA, 2015). With the fishing crisis observed since the 1990s characterized by overexploitation of fishery resources, the degradation of fish habitat and the income of fishermen, the exploitation of algae has emerged as an alternative activity capable of bringing wealth to fishing stakeholders. In Senegal, the "Petite Côte," shielded from the Atlantic north swell by the Cap-Vert Peninsula, is more suitable than the northern coast. Beyond the cultivation aspect, a strong meeting between science and gastronomy is crucial when planning the formulation of agri-food products for non-common food in a country's diet, in the case of seaweed in Senegal. Many Asian countries (principally Japan, China, and Korea) are phytophagous, they have incorporated seaweeds in their day-to-day menus since ancient times. Chefs or food formulators can create modern, novel seaweed dishes on the basis of scientific advice and information regarding the nutritional value and taste provided by scientists (Mouritsen et al., 2018, 2019). Even though seaweed has been declared food of the future, health food, and brain food, and even though seaweed is promoted as edible, nutritious, and healthy, and can even be prepared as a tasty food, it is hard to change people's food preferences (Mouritsen et al., 2018, 2019). The consumption of edible seaweed is becoming popular worldwide due to its nutritional benefits and umami taste, referred to as the fifth taste (in addition to salty, sweet, sour, and bitter) (Milinovic et al., 2021). Numerous studies have been carried out on the inclusion of seaweeds in foods (*e.g.* Jönsson et al., 2024; Oliveira et al., 2023; Syakilla et al., 2024). In the Senegal sub-region, similar studies must be led for incorporating seaweed into Senegalese diets or agri-food products in order to take advantage of the mineral richness of seaweed. At this level, everything remains to be done.

4.3. Evaluating elemental composition of Senegalese seaweeds beyond food applications

Regarding animal feed, half (56 %) of the studied samples had Cd concentrations exceeding the toxicity threshold (Banach et al., 2020) and 15 % for Pb (Figure 2, Table 1). While the general low concentrations of Pb in Senegalese seaweeds are attractive for valorization in animal feed, caution should be taken regarding the general high cadmium concentrations. Regarding agricultural applications, all the seaweed specimens had Pb, Cu, and Zn concentrations under the most common limits (Table 4). For Cd, the minimal value limit and maximal one found were equal to 1 ppm and 37 ppm, reported from Britain and Mexico, respectively (Galán Huertos & Romero Baena, 2008; Ituarte, 2007; Rodríguez-Martínez et al., 2020). All seaweed specimens had Cd concentrations under the maximal limit, while half (56 %) of the specimens exceeded the minimal limit. It can be unambiguously stated for all the seaweeds and sites studied that Pb, Cu and Zn did not pose a problem for agricultural applications. The C:N in the seaweed specimens were all under the recommended range (22–40), which can compromise their use as compost (Michalak et al., 2016) (Table 4). The ratio of carbon to nitrogen is an important parameter influencing the seaweed composting process. In general, seaweed biomass has a relatively low C:N ratio, typically between 8 and 11 (Michalak et al., 2016). An effective way of adjusting seaweed feedstock to an appropriate C:N ratio (around 22-40) is to mix it with a high C:N co-composting material. Sawdust, bark, straw and manure are commonly used as co-composting materials (Michalak et al., 2016). In Senegal, co-composting of seaweeds with other locally available feedstock, such as *Jatropha curcas* cake, must be explored. *Jatropha curcas* cake has a higher C:N ratio (32) (Maiguizo-Diagne et al., 2018) compared to seaweeds. The fishing industry produces large quantities of waste in fish markets and processing industries. Fish remains have also traditionally been used as fertilizer due to their high nutrient content (mainly N and P) and rapid decomposition (López-Mosquera et al., 2011). In Senegal, co-composting fish waste and beach-cast seaweeds might be a promising approach from environmental and economic points, as these raw materials can be collected in the same place, reducing the costs of gathering raw materials. The associated feedstock was explored, along with the evaluation of compost properties—both positive and negative—and the precautions to be taken (Illera-Vives et al., 2013, 2015). It is not recommended to compost seaweed biomass without knowing the C:N ratio of the individual starting materials, as without this information, the quality of the compost cannot be guaranteed, and this represents an inefficient use of the seaweed resource (Cole et al., 2016). Among the studied seaweeds, *E. elongata* (C:N = 17 – 18) and *Cystoseira* sp. (C:N = 14) had the highest C:N ratios (Table 4) and were therefore more promising for composting in regard to the C:N ratio.

4.4. Metal accumulation capacity of the seaweeds

Among the studied seaweeds, *P. tetrastromatica*, *C. peltata*, and *Cystoseira* sp. showed the highest metal pollution index (Table 5), suggesting a greater capacity to accumulate metals and be indicators of site contamination levels. However, to be used as indicators to classify sites according to contamination level, they need to be present in a significant number of sites in Senegal, so their geographic distribution can be explored. In our case study, we get a poor overlay of similar species in the four sites studied. It is so difficult to use our results to estimate marine pollution. Nevertheless, it is surprising to report a so high level of MPI in Somone, which is a national marine reserve, particularly in comparison to MPI found in Hann bay, which is known as highly polluted (Sonko et al., 2023). We recommend that future investigations be led in order to understand the origin of Somone contamination.

5. Conclusion

Senegalese seaweeds are mineral-rich and beneficial for health. However, spatial and seasonal variations in desirable and harmful elements mean careful site selection is a prerequisite for safe exploitation. This underscores the need for better marine pollution monitoring in West African waters to support the development of the blue economy, particularly around urbanised sites. Among the seaweeds analyzed, at least five species (*Ellisolandia elongata*, *Codium cylindricum*, *Ulva* sp., *Caulerpa* racemosa, and *Caulerpa peltata*) stand out for their contribution to NRV-R and can be used incorporated into agri-food products or meals. However, nineteen out of twenty-seven seaweed samples had Cd concentrations exceeding the food safety threshold, and twelve exceeded the recommended threshold for Pb. As seaweeds are not part of the Senegalese diet, collaboration between scientists, artisanal cooks, and food product developers is necessary to explore ways of incorporating seaweeds into foods. Although food neophobia is likely, pressures from fish scarcity, climate change, and population growth make this shift increasingly necessary. Little is known about the ecology of Senegalese seaweeds. According to our results on elemental profiling for *C. cylindricum*, time appeared valuable; it is necessary to study their ecology before future exploitation. More generally, as several species appeared interesting to exploit, we recommend leading a study on the financial and environmental implications of harvesting them in large quantities for use in agri-food products or functional foods. For the most promising seaweeds, cultivation should be planned if biomass demand is high, knowing that this activity has social, environmental, and economic impacts. Moreover, Senegalese artisanal fishers, who are numerous and possess relevant skills, can be mobilized to carry out this cultivation activity.

Author contributions

Conceptualization – NCB, PB; Data curation – NCB; Formal analysis – NCB; Methodology – NCB, HAB, MPT; Project administration – PB, WN; Software – NCB; Supervision – PB, CK; Visualization – NCB, PB; Writing original draft – NCB; Writing – review & editing – NCB, PB, BQ, FD, CK, WN, HDD, AF; Funding- BQ, WN, PB.

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Table 1*:* Elemental chemical composition, total Kjeldahl nitrogen and ash contents (ppm dry weight) of analyzed Senegalese seaweed samples (for the associated taxonomy identification to each sample ID, see Table S4); nd: not determined. For cadmium (Cd), lead (Pb), zinc (Zn), and manganese (Mn), the concentrations above the limit of quantification (LOQ) are in bold.

Sample ID	C	N	P	Cd	Pb	Cu	Zn	Fe	Mn	Mg	Ca	K	Na	Nk	Ash
P.NG1	326159	26822	1464	1	1	8	47	3540	**23**	3207	82380	618	5608	22374	304966
P.NG2	359172	55562	3508	**10**	2	3	109	883	16	8085	74381	2106	10549	46169	267360
P.NG3	418771	35058	1372	3	3	6	88	1374	15	5146	39202	5618	1814	29030	185037
P.NG4	392258	57676	3072	1	5	7	38	627	14	2998	7873	16826	26207	nd	nd
P.NG5	200661	21860	1518	1	9	8	16	282	12	5372	8608	7534	138478	19274	499900
P.NG6	161820	9467	808	1	0	3	34	682	**20**	26725	256962	4506	4217	7804	787715
P.NG7	291567	29814	1271	1	4	5	14	107	10	31333	11417	8494	4083	26219	278144
P.NG8	326966	23862	1912	2	**10**	5	20	1635	**21**	5121	81713	22292	7240	18244	nd
P.NG9	330966	40261	2270	2	4	7	64	173	16	7229	21654	42168	5742	nd	230078
P.NG10	380607	57319	3011	2	5	6	30	1118	19	3641	10709	21008	30337	27002	nd
P.NG11	292275	26481	1680	3	7	6	30	276	9	5021	9441	97743	11080	nd	330132
P.NG12	356125	39578	3050	6	4	2	40	152	16	7855	6139	21703	17978	31498	167367
P.NG13	300556	34022	1434	1	5	5	18	137	10	30366	227	13188	6323	27250	218800
P.HA1	123013	15049	899	0	12	**30**	10	620	**32**	7984	7994	101936	107950	13304	671121
P.HA2	88956	10038	740	0	14	10	12	940	12	9128	7637	104763	110094	9312	718869
P.HA3	299034	40770	1941	0	6	8	42	550	10	31215	12830	8755	3450	nd	185111
P.HA4	415783	45670	2029	0	4	8	30	1266	10	3785	6611	2760	8216	nd	nd
P.HA5	301392	39371	1671	0	6	6	26	510	8	31019	13705	6242	1655	32816	172600
P.HA6	415035	46290	2212	2	4	6	34	2148	8	3605	13143	152	881	38731	88348
P.HA7	143740	16366	1091	0	12	**22**	10	456	**24**	9818	9241	95303	90553	14684	638072
P.AB1	156117	15080	999	0	8	8	40	1001	26	10314	16817	102397	93788	15080	599884
P.SO1	284399	24867	1118	0	6	6	16	306	8	32075	9594	8169	5964	23030	306960
P.SO2	338299	24713	1817	4	4	**66**	10	875	**68**	7889	19211	44050	6715	21604	226207
P.SO3	153575	8628	877	8	0	**34**	16	755	**36**	29359	227169	4559	3417	6698	758586

P.SO4	323611	29301	1631	4	2	**26**	50	3274	**28**	4711	76070	1343	12257	22693	322750
P.SO5	301036	33556	1690	2	8	**38**	14	1409	**40**	3067	17222	56302	29113	27827	331173
P.SO6	295189	24539	1639	4	8	**88**	16	1154	**90**	23435	27548	29856	6386	20971	300099

Table 2: Chemical content of Senegalese seaweed samples (in ppm dry weight) for various elements. n: number of samples. C – Carbon; N – Nitrogen; P – Phosphorus; Cd – Cadmium; Pb – Lead; Cu – Copper; Zn – Zinc; Fe – Iron; Mn – Manganese; Mg – Magnesium; Ca – Calcium; K – Potassium; Na – Sodium; Nk - total Kjeldahl nitrogen; Ash – a measure of the inorganic non-combustible component.

	Mean	Standard deviation	Min.	Max.	n
C	288040	95015	88956	418771	27
N	30816	14188	8628	57676	27
P	1731	738	740	3508	27
Cd	2.11	2.61	0.00	10.34	27
Pb	5.79	3.67	0.00	14.00	27
Cu	15.78	20.44	1.99	88.00	27
Zn	32.37	23.87	10.00	109.00	27
Fe	972	864	107	3540	27
Mn	22.29	18.78	8.00	90.00	27
Mg	12945	11198	2998	32075	27
Ca	39833	63448	227	256962	27
K	30755	36686	152	104763	27
Na	27781	40516	881	138478	27
Nk	22801	12599	6698	46169	22
Ash	373447	238798	88348	787715	23

Table 3: Current status on edibility, comparative analysis of elements contents with the nutrient reference values – requirements (NRV – R) or nutrient reference values – non-communicable diseases (NRV – NCD) set by Codex (Lewis, 2019), and ratios between elements. Colours in the table denote instances where the % NRV-R per serving from the study is higher (indicated in brown) or lower (indicated in yellow) than Codex requirements for nutrient content claims (15 % NRV-R). *10 % absorption of iron (diets rich in cereals, roots or tubers, with some meat, fish, poultry and/or containing some fruit and vegetables); **15 % absorption of iron (dietary of diversified diets, rich in meat, fish, poultry and/or rich in fruit and vegetables) (Lewis, 2019). For Na/K ratio, those that are upper or under the World Health Organisation (WHO) recommended value (≤ 1) (Morrissey et al., 2020) are in red and green, respectively. Sources: a (Tapotubun et al., 2020), b (Yadav et al., 2015), c (Miyadai et al., 2022), d (Augusto et al., 2018), e (Botany, University of Hawaii, 2001), f (FAO & WHO, 2022), g (Anggadiredja, 2016), h (Palaniveloo et al., 2021), i (Al Monla et al., 2020), j (Seo et al., 2013). X: the samples identified at the genus level could not be assessed for edibility.

			%NRV-R/5.2 g serving					%NRV-NCD/5.2 g serving		Ratios				
Sample ID	Species	Current status on edibility	Ca	Mg	P	Fe*	Fe**	K	Na	Na/K	Na/Mg	Ca/P	Ca/K	Ca/Mg
P.SO4	*Caulerpa peltata*	Not edible[a]	40	8	1	77	122	0.2	3	9.13	2.60	46.64	56.64	16.15
P.NG1	*Caulerpa racemosa*	Edible[a]	43	5	1	84	131	0.1	1	9.07	1.75	56.27	133.30	25.69
P.NG4	*Bryopsis plumosa a*	Edible[b]	4	5	2	15	23	2	7	1.56	8.74	2.56	0.47	2.63
P.NG10	*Bryopsis plumosa b*	Edible[b]	6	6	2	26	42	3	8	1.44	8.33	3.56	0.51	2.94
P.AB1	*Codium cylindricum d*	Edible[c]	9	17	1	24	37	15	24	0.92	9.09	16.83	0.16	1.63
P.NG5	*Codium tomentosum*	Edible[d]	4	9	1	7	10	1	36	18.38	25.78	5.67	1.14	1.60
P.NG11	*Chaetomorpha antennina*	Not found	5	8	1	7	10	15	3	0.11	2.21	5.62	0.10	1.88
P.NG7	*Ulva fasciata* a*	Edible[e]	6	53	1	3	4	1	1	0.48	0.13	8.98	1.34	0.36
P.NG13	*Ulva fasciata* b*	Edible[e]	0	51	1	3	5	2	2	0.48	0.21	0.16	0.02	0.01
P.SO1	*Ulva rigida**	Edible[f]	5	54	1	7	11	1	2	0.73	0.19	8.58	1.17	0.30
P.NG3	*Dictyota dichotoma*	Edible[g]	20	9	1	32	51	1	0	0.32	0.35	28.57	6.98	7.62
P.SO6	*Padina tetrastromatica*	Edible[h]	14	39	1	27	43	4	2	0.21	0.27	16.81	0.92	1.18
P.NG8	*Colpomenia sinuosa*	Edible[i]	42	9	1	39	61	3	2	0.32	1.41	42.74	3.67	15.96
P.SO2	*Cystoseira sp.*	X	10	13	1	21	33	7	2	0.15	0.85	10.57	0.44	2.44
P.SO5	*Laurencia natalensis*	Not found	9	5	1	33	52	8	8	0.52	9.49	10.19	0.31	5.62
P.NG6	*Ellisolandia elongata a*	Not found	134	45	1	16	25	1	1	0.94	0.16	318.02	57.03	9.62
P.SO3	*Ellisolandia elongata b*	Not found	118	49	1	18	28	1	1	0.75	0.12	259.03	49.83	7.74
P.NG9	*Caulacanthus ustulatus*	Not found	11	12	2	4	6	6	1	0.14	0.79	9.54	0.51	3.00
P.NG12	*Grateloupia lanceola*	Edible[j]	3	13	2	4	6	3	5	0.83	2.29	2.01	0.28	0.78
P.NG2	*Nemalion sp.**	X	39	14	3	21	33	0.3	3	5.01	1.30	21.20	35.32	9.20

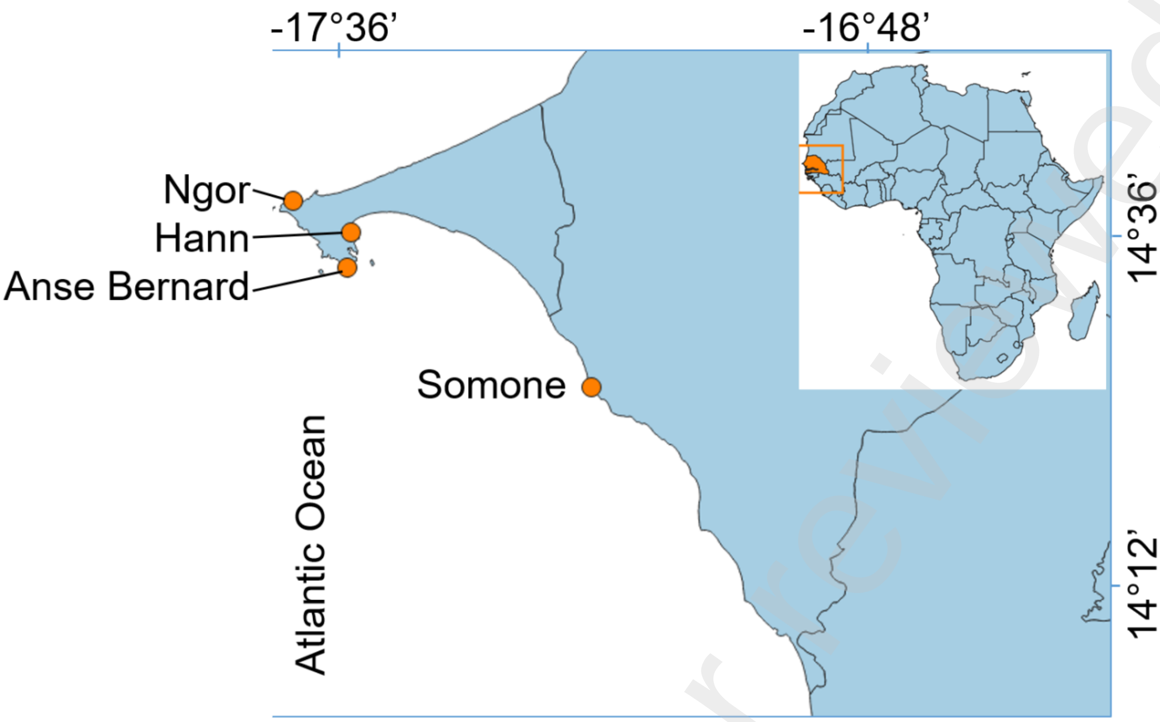
Table 4: Comparison of cadmium (Cd), lead (Pb), copper (Cu), and zinc (Zn) values with minimum (Min.) and maximum (Max.) levels found among the limits established by different countries in agricultural soils (ppm) per elements (Galán Huertos & Romero Baena, 2008; Ituarte, 2007; Ortega-Flores et al., 2023; Rodríguez-Martínez et al., 2020; Serrato et al., 2010). Comparison of the carbon-nitrogen ratios (C/N) with the recommended threshold for composting (range 22-40). Colours in the table denote instances where the values from the study are higher (indicated in red) or lower (indicated in green) than the recommended limits or range.

	Cd		Pb		Cu		Zn		C/N
Allowed limits	Min.: 1	Max.: 37	Min.: 100	Max.: 10000	Min.: 100	Max.: 200	Min.: 250	Max.: 600	range: 22 - 40
Caulerpa mexicana a	0	0	4	4	8	8	30	30	9
Caulerpa mexicana b	2	2	4	4	6	6	34	34	9
Caulerpa peltata	4	4	2	2	26	26	50	50	11
Caulerpa racemosa	0.997	0.997	1	1	7.978	7.978	47	47	12
Bryopsis plumosa a	0.999	0.999	4.59	4.59	7.39	7.39	38	38	7
Bryopsis plumosa b	1.594	1.594	4.78	4.78	5.978	5.978	30	30	7
Codium cylindricum a	0	0	12	12	30	30	10	10	8
Codium cylindricum b	0	0	14	14	10	10	12	12	9
Codium cylindricum c	0	0	12	12	22	22	10	10	9
Codium cylindricum d	0	0	8	8	8	8	40	40	10
Codium tomentosum	1.2	1.2	9	9	8.2	8.2	16	16	9
Chaetomorpha antennina	3.196	3.196	6.59	6.59	5.992	5.992	30	30	11
*Ulva fasciata** a	1.194	1.194	3.78	3.78	4.576	4.576	14	14	10
*Ulva fasciata** b	0.994	0.994	4.57	4.57	4.773	4.773	18	18	9
Ulva lactuca a	0	0	6	6	8	8	42	42	7
Ulva lactuca b	0	0	6	6	6	6	26	26	8
*Ulva rigida**	0	0	6	6	6	6	16	16	11
Dictyota dichotoma	2.588	2.588	2.99	2.99	5.973	5.973	88	88	12
Padina tetrastromatica	4	4	8	8	88	88	16	16	12
Colpomenia sinuosa	1.99	1.99	10.15	10.15	4.775	4.775	20	20	14
Cystoseira sp.	4	4	4	4	66	66	10	10	14
Laurencia natalensis	2	2	8	8	38	38	14	14	9
Ellisolandia elongata a	0.798	0.798	0	0	3.192	3.192	34	34	17
Ellisolandia elongata b	8	8	0	0	34	34	16	16	18

Caulacanthus ustulatus	2.19	2.19	4.38	4.38	6.57	6.57	64	64	8
Grateloupia lanceola	5.981	5.981	3.59	3.59	1.994	1.994	40	40	9
Nemalion sp.*	10.342	10.342	1.99	1.99	2.784	2.784	109	109	6

Table 5: Metal pollution index (MPI) and classification of element concentrations from highest to lowest of Senegalese seaweed samples (sample ID) analyzed. MPI mean was 18, maximum 41, minimum 8 and standard deviation 7; high value in red (> mean + SD), low in green (< mean - SD) and medium in yellow.

Sample ID	Species	MPI	Classification of element concentrations
P.HA4	*Caulerpa mexicana* a	15	C > N > Na > Ca > Mg > K > P > Fe > Zn > Mn > Cu > Pb > Cd
P.HA6	*Caulerpa mexicana* b	17	C > N > Ca > Mg > P > Fe > Na > K > Zn > Mn > Cu > Pb > Cd
P.SO4	*Caulerpa peltata*	31	C > Ca > N > Na > Mg > Fe > P > K > Zn > Mn > Cu > Cd > Pb
P.NG1	*Caulerpa racemosa*	18	C > Ca > N > Na > Fe > Mg > P > K > Zn > Mn > Cu > Pb > Cd
P.NG4	*Bryopsis plumosa* a	15	C > N > Na > K > Ca > P > Mg > Fe > Zn > Mn > Cu > Pb > Cd
P.NG10	*Bryopsis plumosa* b	18	C > N > Na > K > Ca > Mg > P > Fe > Zn > Mn > Cu > Pb > Cd
P.HA1	*Codium cylindricum a*	20	C > Na > K > N > Ca > Mg > P > Fe > Mn > Cu > Pb > Zn > Cd
P.HA2	*Codium cylindricum* b	16	Na > K > C > N > Mg > Ca > Fe > P > Pb > Zn > Mn > Cu > Cd
P.HA7	*Codium cylindricum* c	18	C > K > Na > N > Mg > Ca > P > Fe > Mn > Cu > Pb > Zn > Cd
P.AB1	*Codium cylindricum* d	20	C > K > Na > Ca > N > Mg > Fe > P > Zn > Mn > Pb > Cu > Cd
P.NG5	*Codium tomentosum*	13	C > Na > N > Ca > K > Mg > P > Fe > Zn > Mn > Pb > Cu > Cd
P.NG11	*Chaetomorpha antennina*	15	C > K > N > Na > Ca > Mg > P > Fe > Zn > Mn > Pb > Cu > Cd
P.NG7	*Ulva fasciata** a	8	C > Mg > N > Ca > K > Na > P > Fe > Zn > Mn > Cu > Pb > Cd
P.NG13	*Ulva fasciata** b	9	C > N > Mg > K > Na > P > Ca > Fe > Zn > Mn > Cu > Pb > Cd
P.HA3	*Ulva lactuca* a	15	C > N > Mg > Ca > K > Na > P > Fe > Zn > Mn > Cu > Pb > Cd
P.HA5	*Ulva lactuca* b	13	C > N > Mg > Ca > K > P > Na > Fe > Zn > Mn > Cu > Pb > Cd
P.SO1	*Ulva rigida**	11	C > Mg > N > Ca > K > Na > P > Fe > Zn > Mn > Cu > Pb > Cd
P.NG3	*Dictyota dichotoma*	21	C > Ca > N > K > Mg > Na > Fe > P > Zn > Mn > Cu > Pb > Cd
P.SO6	*Padina tetrastromatica*	41*	C > K > Ca > N > Mg > Na > P > Fe > Mn > Cu > Zn > Cd > Pb
P.NG8	*Colpomenia sinuosa*	20	C > Ca > N > K > Na > Mg > P > Fe > Mn > Zn > Pb > Cu > Cd
P.SO2	*Cystoseira* sp.	29	C > K > N > Ca > Mg > Na > P > Fe > Mn > Cu > Zn > Cd > Pb
P.SO5	*Laurencia natalensis*	28	C > K > N > Na > Ca > Mg > P > Fe > Mn > Cu > Zn > Pb > Cd
P.NG6	*Ellisolandia elongata* a	10	Ca > C > Mg > N > K > Na > P > Fe > Zn > Mn > Cu > Cd > Pb
P.SO3	*Ellisolandia elongata* b	22	Ca > C > Mg > N > K > Na > P > Fe > Mn > Cu > Zn > Cd > Pb
P.NG9	*Caulacanthus ustulatus*	15	C > K > N > Ca > Mg > Na > P > Fe > Zn > Mn > Cu > Pb > Cd
P.NG12	*Grateloupia lanceola*	13	C > N > K > Na > Mg > Ca > P > Fe > Zn > Mn > Cd > Pb > Cu
P.NG2	*Nemalion* sp.*	21	C > Ca > N > Na > Mg > P > K > Fe > Zn > Mn > Cd > Cu > Pb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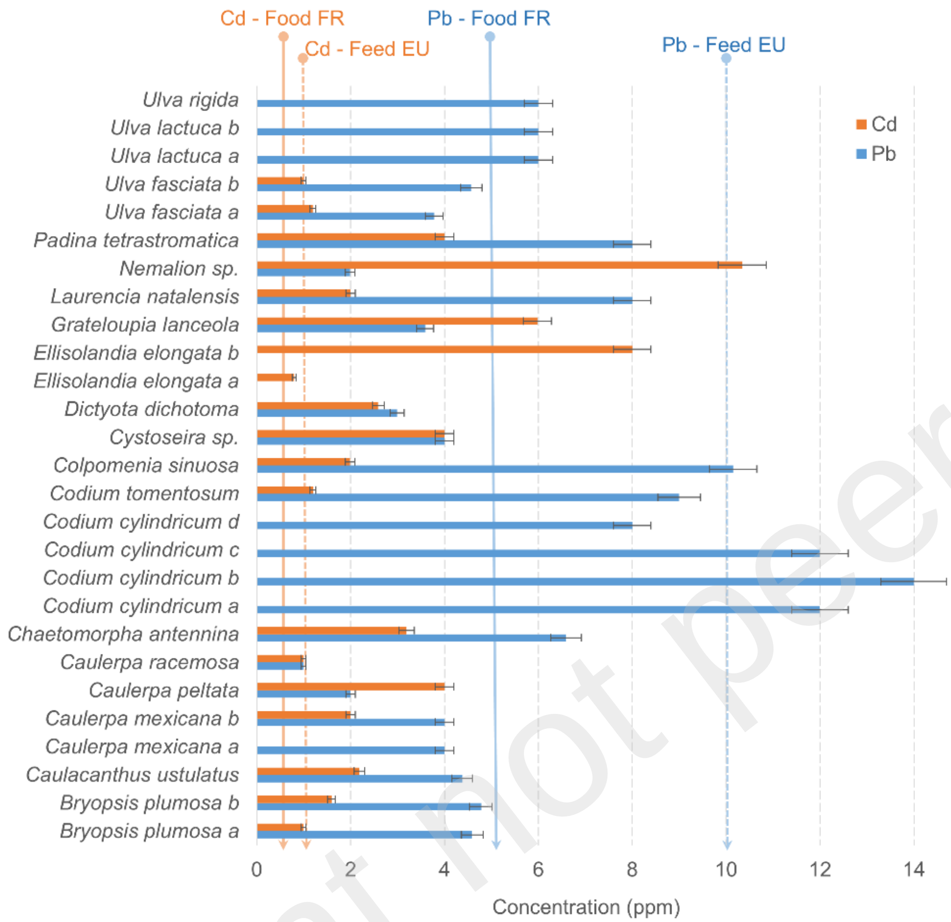
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Ulva lactuca a
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Ulva fasciata a
Padina tetrastromatica
Nemalion sp.
Laurencia natalensis
Grateloupia lanceola
Ellisolandia elongata b
Ellisolandia elongata a
Dictyota dichotoma
Cystoseira sp.
Colpomenia sinuosa
Codium tomentosum
Codium cylindricum d
Codium cylindricum c
Codium cylindricum b
Codium cylindricum a
Chaetomorpha antennina
Caulerpa racemosa
Caulerpa peltata
Caulerpa mexicana b
Caulerpa mexicana a
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Bryopsis plumosa b
Bryopsis plumosa a
0
2
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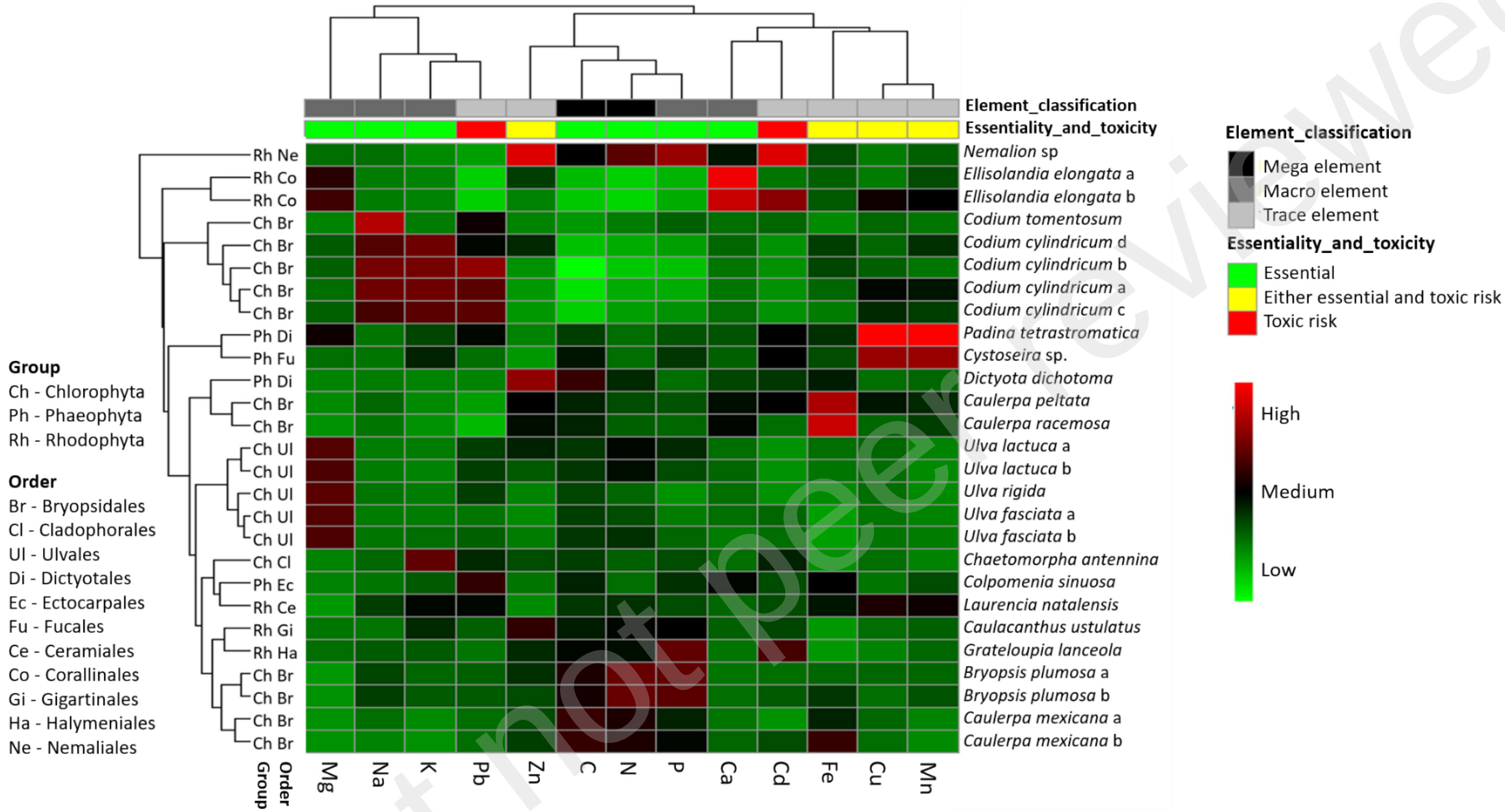
Concentration (ppm)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Macro element
Trace element
Essentiality_and_toxicity
Essential
Either essential and toxic risk
Toxic risk
High
Medium
Low
Group
Ch - Chlorophyta
Ph - Phaeophyta
Rh - Rhodophyta
Order
Br - Bryopsidales
Cl - Cladophorales
Ul - Ulvales
Di - Dictyotales
Ec - Ectocarpales
Fu - Fucales
Ce - Ceramiales
Co - Corallinales
Gi - Gigartinales
Ha - Halymeniales
Ne - Nemaliales
Rh Ne
Rh Co
Rh Co
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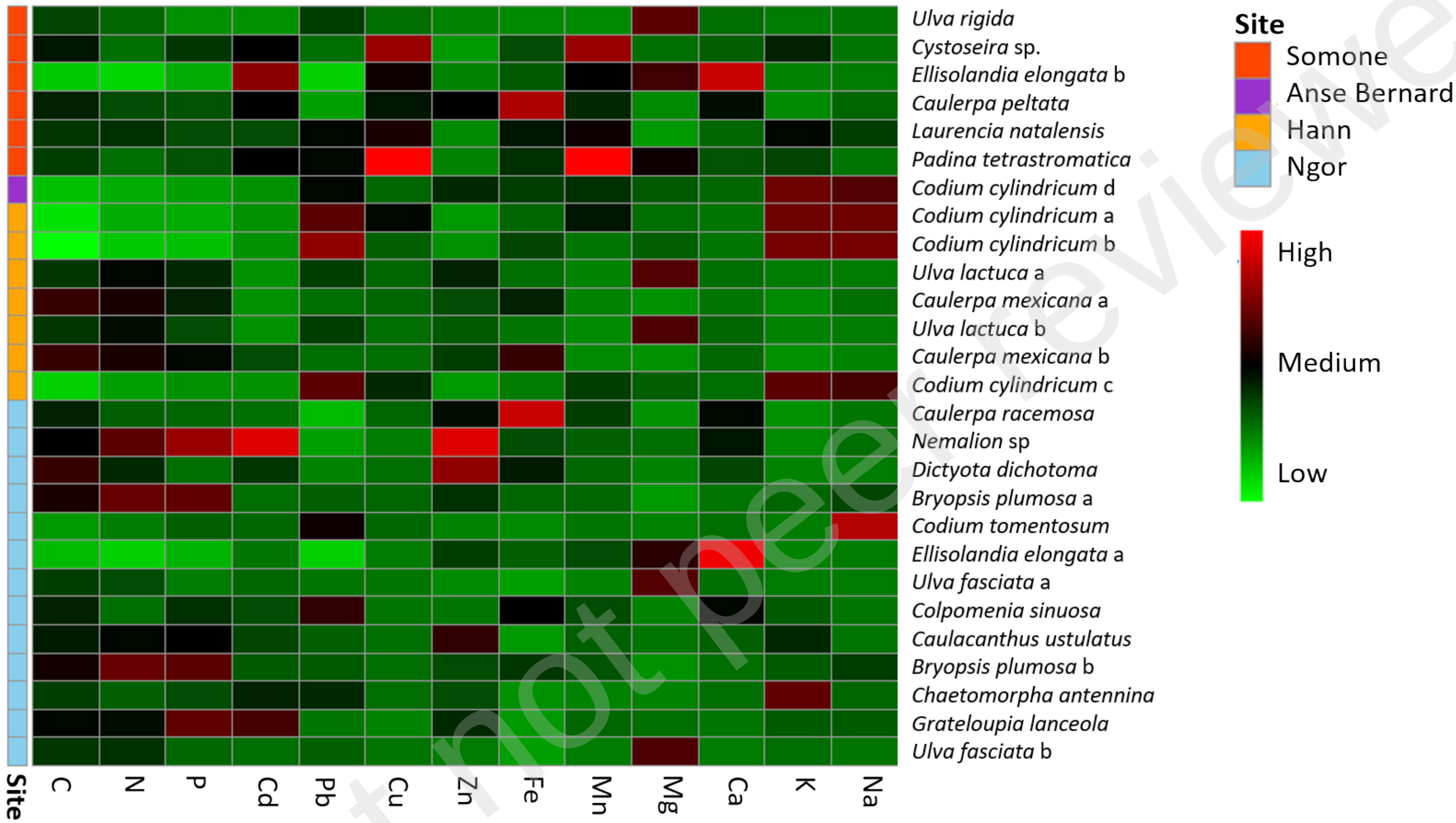
Rh Gi
Rh Ha
Ch Br
Ch Br
Ch Br
Ch Br
Nemalion sp
Ellisolandia elongata a
Ellisolandia elongata b
Codium tomentosum
Codium cylindricum d
Codium cylindricum b
Codium cylindricum a
Codium cylindricum c
Padina tetrastromatica
Cystoseira sp.
Dictyota dichotoma
Caulerpa peltata
Caulerpa racemosa
Ulva lactuca a
Ulva lactuca b
Ulva rigida
Ulva fasciata a
Ulva fasciata b
Chaetomorpha antennina
Colpomenia sinuosa
Laurencia natalensis
Caulacanthus ustulatus
Grateloupia lanceola
Bryopsis plumosa a
Bryopsis plumosa b
Caulerpa mexicana a
Caulerpa mexicana b
Group
Order
Mg
Na
K
Pb
Zn
C
N
P
Ca
Cd
Fe
Cu
Mn



Ulva rigida
Cystoseira sp.
Ellisolandia elongata b
Caulerpa peltata
Laurencia natalensis
Padina tetrastromatica
Codium cylindricum d
Codium cylindricum a
Codium cylindricum b
Ulva lactuca a
Caulerpa mexicana a
Ulva lactuca b
Caulerpa mexicana b
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Grateloupia lanceola
Ulva fasciata b
Site
C
N
P
Cd
Pb
Cu
Zn
Fe
Mn
Mg
Ca
K
Na
Site
Somone
Anse Bernard
Hann
Ngor
High
Medium
Low

Figure Captions

Figure 1: Sampling sites of seaweeds along the Senegalese coast (West Africa) highlighted with orange points during the year 2022 (14/05 – 01/07). The map was generated using QGIS 3.28 (http://www.qgis.org) with data sourced from GADM maps and data (GADM data (version 4.1) https://gadm.org/download_country.html). GPS coordinates of sampling sites: Cap-Vert Peninsula (Dakar) three sites: Ngor island (N 14.7562°; W 17.5113°), Anse Bernard (N 14.6598°; WO17.4339°), Hann bay (N 14.7102°; W 17.4297°). Petite Côte (South Senegal): Somone (N 14.4904°; WO17.0859°).

Figure 2: Barplot of the cadmium (Cd) and lead (Pb) concentrations of seaweeds in regards to the thresholds for food and feed uses. Solid lines: Thresholds recommended for food by the French Agency for Food, Environmental and Occupational Health & Safety (ANSES 2018) and « Centre d'Étude et de Valorisation des Algues » (CEVA 2014). Dotted lines: Thresholds recommended for feed by the European Union (2002). The letters symbols after the names of species distinguish the repetitive species. *Codium cylindricum* (a, b, and c: triplicate beach cast samplings at different points in Hann Bay; d: Anse Bernard, subtidal). *Ellisolandia elongata* (a: Ngor island, intertidal; b: Somone site, intertidal). *Ulva lactuca* (a and b: duplicate beach cast samplings in Hann Bay). *Ulva fasciata* (a and b: duplicate intertidal samplings at different points in Ngor island). *Caulerpa mexicana* (a and b: duplicate beach cast samplings in Hann Bay). *Bryopsis plumosa* (a and b: duplicate intertidal samplings at different points in Ngor island).

Figure 3: Heatmap representation of element concentrations according to samples in a view to underline the interspecific and intraspecific variations in element concentrations and species with relatively high levels of certain toxic risk elements. The letters symbols after names of species distinguish the repetitive species. *Codium cylindricum* (a, b and c: triplicate beach cast samplings at different points in Hann Bay; d: Anse Bernard, subtidal). *Ellisolandia elongata* (a: Ngor island, intertidal; b: Somone site, intertidal). *Ulva lactuca* (a and b: duplicate beach cast samplings in Hann Bay). *Ulva fasciata* (a and b: duplicate intertidal samplings at different points in Ngor island). *Caulerpa mexicana* (a and b: duplicate beach cast samplings in Hann Bay). *Bryopsis plumosa* (a and b: duplicate intertidal samplings at different points in Ngor island).

Figure 4: Heatmap representation of element concentrations according to samples in a view to underline sampled sites with relatively high levels of certain toxic risk elements. The letters symbols after names of species distinguish the repetitive species. *Codium cylindricum* (a, b and c: triplicate beach cast samplings at different points in Hann Bay; d: Anse Bernard site, subtidal). *Ellisolandia elongata* (a: Ngor island, intertidal; b: Somone site, intertidal). *Ulva lactuca* (a and b: duplicate beach cast samplings in Hann Bay). *Ulva fasciata* (a and b: duplicate intertidal samplings at different points in Ngor island). *Caulerpa mexicana* (a and b: duplicate beach cast samplings in Hann Bay). *Bryopsis plumosa* (a and b: duplicate intertidal samplings at different points in Ngor island).