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REVIEW PAPER OPEN ACCESS

A review on seaweeds and its bioactive compounds: Implication to the WIO ecosystem health

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Abstract

Seaweeds available in the Western Indian Ocean (WIO) provide several benefits including income, nutrients, medicine and as primary producers, they are foundation species important for marine ecosystems capable of modifying their surrounding abiotic and biotic environments. The WIO coast provides natural and necessary environments for seaweed existence. In this review article the potential of seaweeds and their bioactive compounds was investigated; their contribution to the provision of ecosystem services; medicinal and nutritional value for the wellbeing of the WIO ecosystem. It was observed that seaweeds and their bioactives have the potential to humans, other animals, agriculture, and the whole ecosystem. Therefore, for the sustainability of the WIO ecosystem, the potential given by seaweeds and their bioactives in the provision of nutrients, mitigation of health conditions, organic farming, and restoration of environments must be utilized.

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Introduction

Seaweeds denote thousands of species of macroscopic, multicellular, marine algae, such as Chlorophyta (green), Rhodophyta (red), and Phaeophyta (brown) (Rathour *et al.*, 2021, Pereira, 2011). The importance of seaweeds in the provision of ecosystem services are known, for example, species such as kelps provide essential nursery habitat for fisheries and other marine species and thus protect food sources (Howard *et al.*, 2017); species of algae, play a vital role in capturing carbon, producing up to 50% of earth's oxygen (Macreadie, 2017). Widely available seaweed taxa in WIO are *Eucheuma spp., Saccharina japonica, Sargassum fusiforme, Gracilaria spp., Pyropia spp., Undaria pinnatifida,* and *Kappaphycus alvarezii* (Rathour *et al.*, 2021). Seaweeds are used for different applications, for example, *Gracilaria* is used for agar production; *Eucheuma* and *K. alvaraezii* are used as a gelling agent (carrageenan); while the rest are for food (Hentati *et al.*, 2020, Olasehinde *et al.*, 2019). China, the Philippines, and Indonesia are the largest seaweed producers, others include Zanzibar (Tanzania), Japan, North Korea, South Korea, and Malaysia (Buschmann *et al.*, 2017). seaweeds dominate aquatic plants, their production has been observed to increase by more than 60% from 1995 to 2016 as of 2014, seaweed contributed only 27% of all marine aquaculture (Duarte *et al.*, 2017).

Marine aquaculture is considered as restorative farming as provides twin benefits environmental protection and source of bioactives for medicinal applicability. A great diversity of compounds exhibiting a broad spectrum of biological activities are currently produced from seaweeds hence attracting the attention of biotechnological interest (Renato C. Pereira, 2012). Bioactives from marine organisms have shown capabilities such as antiviral, anti-tumor, anti-inflammatory, and anti-lipidomics, which creates the burning need for management options for a sustainable approach to their use, hence motivation to their medicinal use (P. Ferraces-Casais *et al.*, 2011, Archana Pal, 2014). Therefore, this work aims to assesses the benefits of seaweed available in the WIO to communities. Also, knowledge of the health and commercial benefit of seaweeds should be given to the community to increase their utilization for different application such as provision of nutrients, medicine, and income to societies for helthier and sustainable WIO.

Chemistry of seaweeds

Seaweeds are reported to contain innumerable minerals and bioactive molecules such as carbohydrates, proteins (Lafarga *et al.*, 2020), and a lesser degree of lipid along with small molecules such as alkaloids, saponins, pigments, and peptides (Abbott *et al.*, 2020). Alginate is an example of polysaccharides composed of an unbranched chain made of (1- 53 4)-β-D-mannuronic acid residues and (1-4)-α-L-guluronic acid residues (Chater *et al.*, 2015). These polyureas exist in seaweeds as salts of more than 50 different metals frequently in the form of sodium and calcium (Chater *et al.*, 2015). The structure of some bioactive compounds is known; Fig. 1 presents the structure of bioactive compounds from seaweeds available in the WIO.

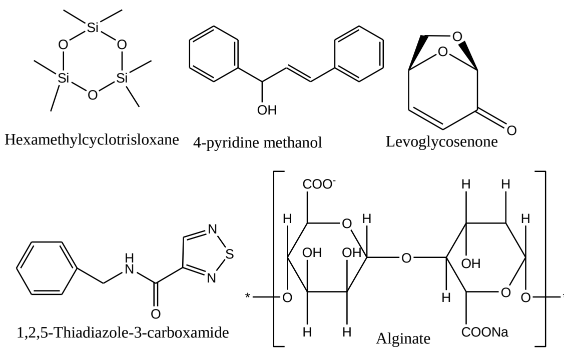

Fig. 1. Structure of bioactive compounds from seaweeds available in the WIO.

Methodology

The research examines peer-reviewed research on seaweed and their bioactives that has been published in conference papers, book chapters, reports, academic journals, and books. The following databases were used as data sources: Google Scholar; Web of Science; Scopus, PubMed; Wiley Online Library, Science Direct; Taylor and Francis online; Sarge Publishing. The major search took place between April and June of 2021. The potential of seaweeds in WIO and its implication to ecosystem health were the topic and scope of this literature review. A review of the literature was conducted on papers containing information on nutritional values, medicinal, and bioactive, from seaweeds. Search criteria involved multiple combinations of search terms and among keywords linked to seaweed. Also, those linked to WIO and other parts of the world for references.

Exclusion and inclusion criteria

Any paper which reports on seaweeds, medicinal value, ecosystem services, sustainability, the nutritional value was included otherwise excluded in the study.

Seaweeds as a source of bioactive compounds

The constituents of seaweeds are more innovative than those of many land plants and because of their varying biological capabilities, have long been recognized as a rich and significant natural resource of bioactive chemicals (Chojnacka *et al.*, 2012, Alboofetileh, 2021). Compounds from marine organisms are pharmacologically bioactive and have shown significant effects against various types of medical conditions (Abdillah *et al.*, 2021, Dolorosa *et al.*, 2020). Natural compounds obtained from marine organisms are used in the treatment of various diseases and disorders since ancient times (V. Gnanavela *et al.*, 2019). Red seaweeds (*Kappaphycus alvarezii*) farmed at the Western Indian Ocean marine sites have been shown to have antioxidant and antibacterial activity against pathogenic bacteria (Bhuyar *et al.*, 2020). Table 1 represents some of the bioactive compounds from seaweeds.

Table 1. Bioactive molecules reported in seaweed extract.

SN	Bioactive molecule	Type of seaweed	Properties	References
1.	Halimedatrial; Caulerpenin; Lanosol	Green Algae Halimeda macroloba	Antibacterial &antioxidant activities	(Latifah *et al.*, 2020, Basir *et al.*, 2020)
2.	Fucoxanthin	Brown Seaweed Himanthalia elongata	Antioxidant and antimicrobial activity	(Rajauria and Abu-Ghannam, 2013)
3.	Bromoform Dibromochloromethane Dromochloroacetic acid Dibromoacetic acid	Red seaweed (Asparagopsis taxiformis)	Antimethanogenic activity	(Machado *et al.*, 2016)
4.	Vitamin E; flavonoids; phenols; hydroquinone and triterpenoids	Sargassum sp. and Eucheuma Cottonii Doty	Sunscreen agent	(Nurjanah, 2017)
5.	Peptides (Gly-GLY-Ser-Lyr and Glu-Leu- Ser)	Red seaweed (Porphyra spp)	α-Amylase Inhibitory Potential	(Admassu *et al.*, 2018)
6.	Salicylic; ferulic acids; phenolic acids	Halimeda incrassata	Antioxidant activity	(Novoa *et al.*, 2011)
7.	n-nonadecane; 1,2,3- propane tricarboxylic acid; 2-(acetyloxy)-, tributyl ester; 2-methylhexadecan-1-ol; 1-docosene; 1-eicosanol and chloroacetic acid, octadecyl ester	C. sinuosa and C. officinalis	Antibacterial activity	(WM Hassan, 2018)

Seaweeds in Western Indian Ocean

Western Indian Ocean covers the area from Somalia, Kenya, Tanzania, Mozambique, South Africa, Comoros, Madagascar, Seychelles, Mauritius, and Réunion (France) (Razafimandimbison *et al.*, 2017). Most seaweed available in WIO countries are *Kappaphycus alvarezii, Eucheuma denticulatum,* and *Kappaphycus striatum* (Kimathi *et al.*, 2018). These species are mostly available in Tanzania with limited availability in Madagascar, Mozambique, and Kenya (Msuya *et al.*, 2014).

Seaweed farming is named among activities that contribute toward attaining several targets of United Nations sustainable development goals (SDGs) and blue economic development in different parts of the world (Beal *et al.*, 2018, Hossain *et al.*, 2021) including the Western Indian Ocean.

Contribution of seaweed available in the WIO ecosystem

Currently, seaweeds are a significant component of marine aquaculture production and as the human population increases rapidly it is expected to play an increasing role in global food security (Langton *et al.*, 2019). Seaweed farming is similar to plant-based agriculture, except that the crop is cultured in a marine environment (Mateo *et al.*, 2021). Therefore, seaweed farming does not require arable land, fertilization, or freshwater, which are resources that may ultimately constrain the expansion of agriculture. Hence can be considered as restorative ocean farming, but also the source of green vegetables and animal feeds (Corino *et al.*, 2019, Lucy Mohapatra*, 2013). Adoption and increased seaweeds farming in Western Indian Ocean ecosystem will help increase the quality and sustainability of WIO ecosystem.

Provision of ecosystem services

Wild and cultured seaweeds play a significant role in the provision of ecosystem services, such as habitat for other marine organisms, mitigation of climate change, localized control of ocean acidification, and bioremediation for coastal pollution (V. Gnanavela *et al.*, 2019, Howard *et al.*, 2017). Also, Seaweeds as an autotroph species, produce energy and food for themselves due to the presence of chlorophyll (Dolganyuk *et al.*, 2020) and provide food for other marine animals especially for herbivores that only eat herbs such as other marine plants, algae, and seagrass (Dolganyuk *et al.*, 2020, Hossain *et al.*, 2021). Habitats such as mangroves, coral reefs, and other marine habitats are given by seaweed (Tano *et al.*, 2017, Tregarot *et al.*, 2020). Brown algae can make a forest in the ocean. Like a forest, seaweed provides all that other marine species need. Food, nutrients, energy, and others (Perez, 2021, Wade *et al.*, 2020). On the other hand, seaweed is a sensitive organism that can be used as bioindicators of marine chemical pollution. As practice disposal of untreated or partially treated wastewater from the household, aquacultural, industrial, and others enter the ocean (Kennish, 2000, Babaranti, 2019) carrying materials such as nutrients. Disturbance to nutrient balance in the ocean cause population leading to increased growth of seaweed, the phenomenon is known as algae bloom which is the bioindicator of marine chemical damage (Levent *et al.*, 2018, Le Moal *et al.*, 2019). Therefore, all species of seaweeds available in WIO can further be utilized to protect the ecosystem. Hence, it is important to increase the scale of seaweed farming in the Western Indian Ocean to provide for ecosystem balance and protect marine biodiversity. Fig. 2 summarizes the benefits of seaweeds in the marine ecosystem which can be adopted in the Western Indian Ocean for a greener ecosystem.

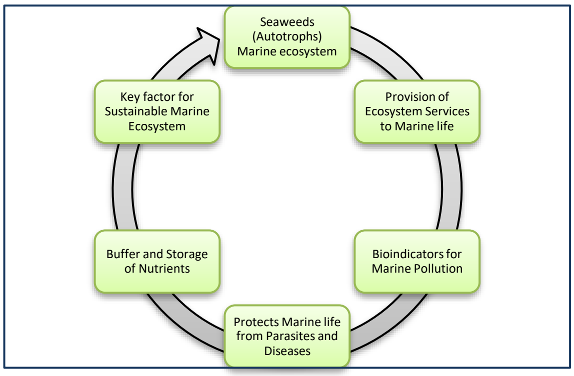

Fig. 2. Seaweed farming for greener Western Indian Ocean marine ecosystem.

Seaweeds can detect danger and alert other marine species via signals. For example, diseases in seaweed can affect the color or smell of the seaweed, signaling its presence in the marine ecosystem (Hay, 2009). On the other hand, seaweed has a bigger contribution to oxygen production as it produces 50-80% more than terrestrial plants. This is contributed by the fact that photosynthetic processes can take place at all parts of the plants (Boyd *et al.*, 2020, Weigel and Pfister, 2021, Van Ginneken and Technology, 2017, Jampílek *et al.*, 2021). Though feeding energy is generated for living, seaweed provides energy as a portion of food for other marine species and also supplies organic nutrients for other marine life (Olasehinde *et al.*, 2019, Kadam *et al.*, 2015, Corino *et al.*, 2019, Lomartire *et al.*, 2021). On the other hand, seaweed functions as nutrient absorbers in the marine ecosystem, this is important as not all nutrients entering the ocean have a good effect some may kill marine life and damage the marine ecosystem (Batini, 2021, Todd *et al.*, 2019). In this case, seaweed will absorb and trap excess nutrients and make the marine ecosystem safe (Zheng *et al.*, 2019). Although iron is essential for seaweed to undergo photosynthesis and another autotrophic organism, excessive iron ion in the oceanic ecosystem may damage marine life (Jiang, 2020, van Ginneken and de Vries, 2018, Naylor *et al.*, 2021). Therefore, the existence of seaweed in the WIO marine ecosystem is important for the continuation of life forms.

Application of seaweeds

Seaweeds are converted into a variety of goods, such as food and nutritional supplements for humans and livestock, fertilizer, unique biochemicals, and biofuels (Tiwari and Troy, 2015). Seaweeds have gained its diverse application in agriculture (Nabti *et al.*, 2017, Cornish *et al.*, 2020) such as enhancement of health and growth of plants specifically root and shoot elongation (Mannino *et al.*, 2020), stimulation of seed germination (Verkleij and Horticulture, 1992), improvement of nutrient and water uptake (Youzhi *et al.*, 2020), biocontrol and resistance toward phytopathogenic organisms (Mukherjee and Patel, 2020), frost and saline resistance, biocontrol and remediation of pollutants of contaminated soil and fertilization (Sangha *et al.*, 2014). Table 2 indicates selected applications of seaweeds in differing aspects of life.

Table 2. Some of the reported applications of seaweed.

Applications	Seaweed's species	Responsible components	Remarks	References
Animal feed (nutrition)	All edible species	Biomass	Sustainable source leading to greener ecosystem	(Corino *et al.*, 2019, Evans and Critchley, 2014)
Bioindicator of marine pollution	*Dichotomaria marginate* (Rhodophyta) All species	Live organism	Sustainable ecosystem	(Garcia *et al.*, 2020, Bonanno *et al.*, 2020)
Bioremediation and biomonitoring	All species	Live organism	Sustainable ecosystem	(Roveta *et al.*, 2021, Michalak, 2020)
Improve chlorophyll content	Ascophyllum nodosum	Extrct	Sustainable ecosystem	(Yao *et al.*, 2020)
Enhance plant protection against disease		Extrct		(Maluin and Hussein, 2020)
Improve root growth and Development	Ascophyllum nodosum	Extract	Sustainable ecosystem	(Mannino *et al.*, 2020)
Trigger earlier flowering and fruit formation	Ecklonia maxima (Osbeck) Papenfuss, and others	Extract concentrates	Sustainable ecosystem	(Dookie *et al.*, 2021)
Enhance postharvest shelflife& quality of perishable products	Kappaphycus alvarezii and Sargassum tenerrimum	Extract	Sustainable ecosystem	(Vieira *et al.*, 2021, Banu A *et al.*, 2020)
Soil conditioner	All species	Biomass	Sustainable ecosystem	(Liu *et al.*, 2020, Kubavat *et al.*, 2020, Youzhi *et al.*, 2020)
Dietary supplements	Edible seaweeds			(Thépot *et al.*, 2021)

Nutritional value

The seaweeds are cultivated both for commercial and domestic use in most countries of the WIO region such as Tanzania, Kenya, Mozambique, and Madagascar. The use of seaweed as food is well known and several nutrients have been identified in different species of seaweed. They contain valuable nutrients such as carbohydrates, minerals such as iron and calcium, fiber, protein which contains essential amino acids, vitamins, and trace elements such as iodine (Pereira, 2011). Seaweeds are among natural food that provides a highly nutritious but low in calories diet. Seaweeds are therefore the best method that can be used to alleviate nutritional deficiencies of the current food, due to its abundant constituents of nutrients (MacArtain *et al.*, 2007). The use of seaweeds as a staple substance of diet date back to ancient times in several nations like Japan, Korea, and China (Dhargalkar, 2015, Willcox *et al.*, 2009). The nutritional benefit of seaweeds was utilized since the 8th century and there are about 21 species that are used in everyday meals (Chapman and Chapman, 1980). Some seaweed was used since time immemorial for honored guests, even for the king (Pérez-Lloréns, 2020, Roberts, 2004, Gurib-Fakim, 2006). In Western cookery, there is little tradition of using seaweed though currently there is a renewed interest in the use of seaweed as sea vegetables (Cırık). Seaweed is also used as a functional food due to its effect on one or more physiological functions, as increasing the welfare and decreasing the risk of suffering from the onset or development of particular diseases mostly function as preventive rather than curative (Fernando *et al.*, 2018, Mhadhebi *et al.*, 2014). Moreover, seaweed has found its application as a nutraceutical, as supplements rather than whole food, and marketed as pills and tablets which can provide useful health benefits (Bandara *et al.*, 2017). The bioactive compound in seaweed such as *Kappaphycus alvarezii* and *Sargassum tenerrimum* contain a valuable nutritional value that is important to human health (Rick *et al.*, 2013).

Medicinal value

Seaweeds offer a wide range of therapeutic possibilities both internally and externally**.** The medicinal value of seaweed depends on the type and particular species. There are several types of seaweed both wild and cultivated (Roleda *et al.*, 2019), this means seaweeds can be classified by their use such as medicine, fertilizer, and industrial raw materials (Kandale *et al.*, 2011). Utilization of seaweeds as medicine date back to 13,000 years ago in Chile at the late Pleistocene settlement (Rick *et al.*, 2013). Also, there was more archaeological evidence as to the inclusion of seaweed in folk medicine for thousands of years ago in Japan, China, Egypt, and India (Rick *et al.*, 2013). Between 1977 and 1987, the newly discovered chemicals from seaweeds were 35%, followed by sponges 27% and cnidarians 22%.(Kandale *et al.*, 2011, Kolanjinathan *et al.*, 2014). Since then, there is an increasing trend of discovering pharmacologically active compounds from seaweed. This indicates that marine organisms can be utilized as a source of various compounds with pharmacological activities including anticancer, antimicrobial, antifungal, antiviral and anti-inflammatory which are potential sources of new therapeutic agents (María José Pérez *et al.*, 2016). Yi, *et al.* (2001) (heng Yi 2001) investigated the extract from 23 species of marine algae belonging to the Chlorophyta, Phaeophyta, and Rhodophyta, using different solvents such as ethanol, acetone, and methanol-toluene. The results indicated that ethanol extract had the strongest antifungal activity, while the methanol-toluene extract had the weakest, indicating the possibility of using ethanol extract as an antifungal agent.

Similarly, Khanzada *et al.* (2007) (Amina Kabir Khanzada, 2007) tested several fractions of an ethanolic extract of *Solieria robusta (Rhodophyta)* for antifungal activity against five fruit rotting fungi isolated from fruits in Pakistan and found that all fractions inhibited fungal growth; ethanol had the highest inhibition ratios, followed by an aqueous fraction. On the other hand, Saidani, *et al.* (2012) investigated antifungal action of four species of marine algae of Bejaia coast and reported that all experimented extracts displayed antifungal action, the maximum inhibiting effect was noted for *Rhodomela confervoides* (red algae) and *Padin apavonica* (brown algae), respectively against *Candida albicans* and *Mucor ramaniannus* (SAIDANI K., 2012). Furthermore, Indira, *et al.* (2013) presented the antifungal property of seaweed *Halimeda tuna* against nine fungal strains (*Aspergillus niger, Aspergillus flavus, Alternaria, Candida albicans, Epidermophyton floccossum, Trichophyton mentagrophytes, Trichophyton rubrum, Penicillium* sp. and *Rhizopus* sp.) (K. Indira, 2013). Therefore, there is a need to investigate further the medical applicability of seaweeds present in the WIO to explore its benefits for a sustainable ecosystem.

Anticancer properties

The global prevalence of cancer is currently significant, necessitating the development of a nature-based mitigation strategy such as the use of bioactives from natural products (Samina Hyder Haq 2019). Natural medicines have lately been acknowledged as a promising option for preventing or suppressing the progression of invasive malignancies (Ghislain Moussavou 2014). It was reported that breast cancer is the leading cause of death in women globally. Cancerous breast cells express survival factors that inhibit apoptotic cell death (Abedin *et al.*, 2007). Studies indicated the ability of seaweed extracts to prevent apoptotic cell death hence their application in the treatment of breast cancer (Moussavou *et al.*, 2014). In addition, some species of macroalgae had exhibited cytotoxicity against the number of cancer cell lines (Mashjoor *et al.*, 2016, Khanavi *et al.*, 2010), indicating the potential of using seaweed extract for the mitigation of cancer.

Antiviral properties

Seaweed has been reported important source of antiviral agents with high efficacy on resistant mutant viral strains and low toxicity to host (Wang *et al.*, 2008, Damonte *et al.*, 2004). Water-soluble extracts from seaweeds demonstrated antiviral activity against a wide range of viruses (Clercq, 1997). Among the bioactive molecule from seaweeds with antiviral activity are polysaccharides from a marine organism which can either inhibit the replication of the virus by interfering with the viral life cycle or improve the host antiviral immune responses to accelerate the process of viral clearance (Gomaa and Elshoubaky, 2016). The life cycle of viruses differs greatly between species, but there are six basic stages in the life cycle of viruses; viral adsorption, viral penetration, uncoating of capsids, biosynthesis, viral assembly, and viral release (Shi *et al.*, 2017). Therefore, Marine polysaccharides can inhibit the viral life cycle at different stages or directly inactivate virions before virus infection.

Antifungal properties

The potential of seaweed as an antifungal agent was tested some decades back in several countries worldwide (El Zawawy *et al.*, 2020). Reports of the adoption of seaweed extract as an antifungal agent in agriculture are available (Ambika, 2015). Hellio *et al.* (2000) (C. Hellio, 2000), reported the significant reduction in the growth of the fungi after treatment with a variety of seaweed extracts, indicating the possession of antimicrobial activity by tested extracts.

Antibacterial

Seaweeds cultivated in different parts of the world exhibit varying antibacterial properties which can be utilized for improving human health. For example, the extracts of *U. fasciata* isolated from the southeast coast of India demonstrated antibacterial properties and a broad spectrum of antibiotic activity against *Bacillus cereus, Escherichia coli,* Bacillus *subtilis, Aeromonas hydrophila, Vibrio fischeri, and Vibrio harveyi* (Lipton, 2004). *Cladophora glomerata* exhibited substantial antibacterial activity against the MDR bacterium *Acinetobacter baumannii* and various human and fish pathogens, such as *E. coli, B. cereus, Vibrio anguillarum, V. fischeri, Vibrio parahaemolyticus, and Vibrio vulnificus (N. Yuvaraj,* 2011*)*. An acetylenic sesquiterpene isolated from *Caulerpa prolifera, caulerpenyne* exhibited antifouling activity against bacteria and the microalga *Phaeodactylum tricornutum (Vangelis smyrniotopoulos,* 2003*)*. Moreover, the ethanolic extracts of *C. decorticatum* displayed antibacterial activity (JAJ Sunilson, 2009). In this trend, there is a need for the researcher to explore more and educate the public and the community in general on the existence and application of several medicinal potentials of seaweed species found in the Western Indian Ocean.

Conclusion and recommendations

Seaweeds in the Western Indian Ocean exist for decades. Despite of their potential, most seaweeds in WIO are sold as raw materials which have low returns, there is the need to add value by converting seaweeds to various products to increase its profitability such as nutritional, medicine and thus, stable income for sustainable WIO. Therefore, it is recommended that educating and motivating societies to utilize seaweeds and cherish them for better ecosystem health.

Conflict of interest

The authors declare no conflict of interest

Data availability statement

This work used secondary data which are available online and referenced

Author's contribution

Authors contributed equally in reviewing and writing up this manuscript

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