

Marine Plant-Derived Bioactives: A New Frontier in Anticancer and Antimicrobial Drug Discovery

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ABSTRACT

Marine plants, including seaweeds, seagrasses, and mangroves, have been identified as rich sources of bioactive compounds that have significant pharmacological activities. These plants live in extreme and diverse marine environments, which have led to the evolution of new secondary metabolites not found in terrestrial plants. In the past several decades, an increasing number of studies have reported the anticancer and antimicrobial potential of marine-derived substances like alkaloids, flavonoids, polysaccharides, and phenolic compounds. Seaweed species like Sargassum, Ulva, and Gracilaria have been found to exhibit cytotoxic activity against various cancer cell lines, while mangroves' compounds have been shown to exhibit potent antibacterial activity against multidrug-resistant microorganisms. Their mechanisms of action involve apoptosis induction, modulation of oxidative stress, and inhibition of biofilm formation by microbes. While in vitro and in vivo results are promising, large-scale extraction, purification, and clinical translation remain challenging. This mini-review provides an overview of recent progress in the discovery and development of marine plant-derived anticancer and antimicrobial agents and their potential as leads for new therapeutics. It also addresses current limitations and the future direction of research, including the use of biotechnology and synthetic biology in compound production enhancement. By harnessing the plant biodiversity of the ocean, drug discovery can be propelled into a new era of innovation to fight global health challenges such as cancer and antibiotic resistance.

Keywords: Marine Plants; Anticancer Agents; Antimicrobial Resistance; Seaweed Metabolites; Drug Discovery

Introduction

The marine environment, covering over 70% of the surface of the planet Earth, houses a diverse flora with specialized biochemical pathways yielding structurally varied secondary metabolites [1-4]. Marine angiosperms, most notably macroalgae (seaweeds), mangroves, and seagrasses, have been actively searched as treasure troves for bioactive metabolites with very high therapeutic activities [5-7]. Compared to land plants, marine plants have to endure drastic environmental stresses in the guise of salinity, temperature fluctuation, and intense UV radiation. These stresses have shaped the course of evolution of specialized metabolites that exhibit defense, antifouling, and stress-resistance activities, some of which have pharmacological properties active within the human body [7-12].

Recent research has emphasized the antimicrobial and anticancer potential of compounds isolated from sea algae. Sargassum and Gracilaria algae, for instance, have indicated cytotoxic activity against certain cell lines of cancer, whereas mangrove compounds act against drug-resistant microorganisms. Certain of these compounds from nature are alkaloids, terpenoids, flavonoids, sulfated polysaccharides, and phenolics, certain of which have activity by induction of apoptosis, DNA intercalation, and microbial membrane disruption [13]. While they are therapeutically potential, the manufacture of drugs from marine plants is hampered by a series of challenges, including large-scale culturing and extraction of compounds, structural complexity, and poor in vivo validation. However, with the advent of biotechnological means, including omics technologies and synthetic biology, new technologies for large-scale production and enhance-

ment of bioactivity have emerged [14]. This mini-review provides an overview of recent studies on anticancer and antimicrobial marine plant-derived anticancer and antimicrobial agents. It explains their

mechanisms of action, highlights major bioactive compounds, and suggests future directions in drug development based on marine botanical resources (Figure 1).

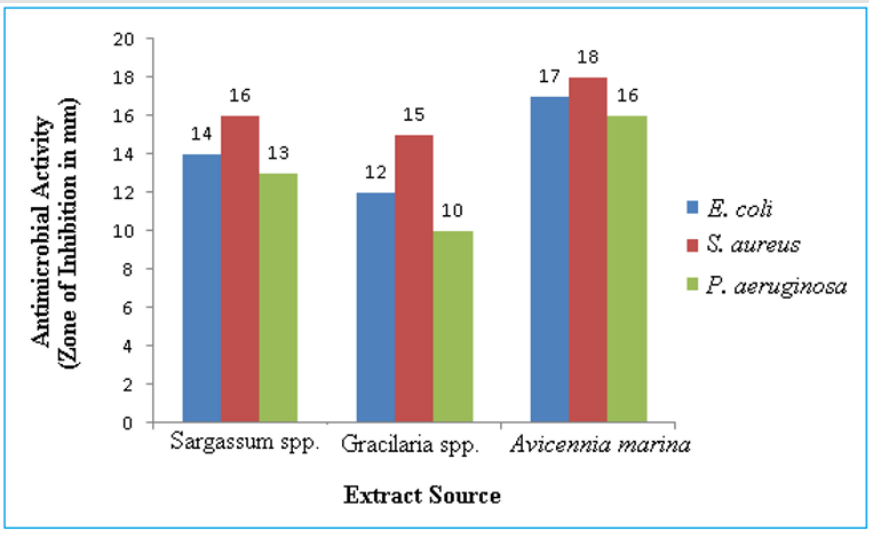


Figure 1: Comparative antibacterial efficacy of marine plant extracts against pathogenic bacteria (zone of inhibition in mm).

Marine Plant Bioactives Diversity

Marine algae such as brown, red, and green, and halophytic mangroves harbor a diverse array of metabolites of medicinal value. Brown algae such as Sargassum harbor high concentrations of terpenoids such as fucoxanthin, a molecule widely reported for its pro-apoptotic and antioxidant activities [5]. Red algae (Gracilaria spp.) produce sulfated polysaccharides such as carrageenan with antiviral and cytotoxic activity [7,9]. Certain mangrove species, such as Avicennia ma-

rina and Rhizophora mucronata, produce alkaloids and phenols with high antimicrobial activity. These are highly diverse plant-specific molecules formulated for survival under a stress-borne sea habitat, thereby suggesting a vast bank of yet undiscovered pharmacophores. In addition to their inherent biological activity, these bioactive compounds also have the prospect of having useful effects on a variety of anticancer therapeutic approaches and the management of infectious diseases (Table 1).

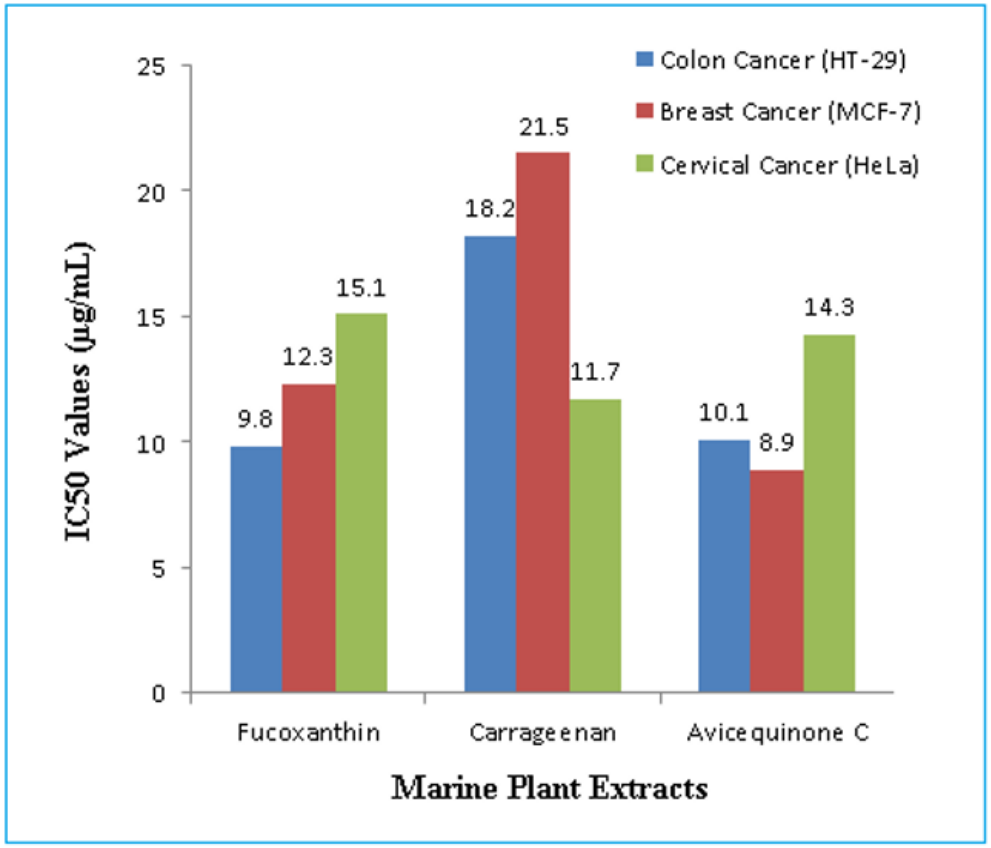
Table 1: Marine plant taxa and their major bioactive compounds.

Marine Plant	Compound Type	Major Compounds	Pharmacological Activities	References
Sargassum spp.	Terpenoids	Fucoxanthin, Sargaquinoic acid	Anticancer, antioxidant	[5,8]
Gracilaria spp.	Sulfated polysaccharides	Agar, carrageenan	Antimicrobial, immunomodulatory	[7,10]
Rhizophora mucronata	Polyphenols	Catechins, ellagic acid	Antibacterial, cytoprotective	[10,12]
Avicennia marina	Alkaloids	Avicequinone C	Anticancer	[6,14]

Anticancer and Antimicrobial Mechanisms

Marine compounds exhibit diverse mechanisms against cancer cells and pathogenic microorganisms. Fucoxanthin induces apoptosis in cancer cells through mitochondrial-dependent pathways and ROS production [5]. Carrageenan inhibits tumor growth by cell cycle arrest and immune system modulation [9]. Avicequinone C and its related

compounds exert antibacterial effects by inducing membrane damage and oxidative stress in bacterial cells [6]. Notably, some of these compounds also modulate host immunity, making combination therapies possibilities [14]. Their ability to disrupt microbial membranes, inhibit viral replication, and cause oxidative stress makes them highly versatile drugs in the fight against drug-resistant bacterial strains as well as viral infections (Table 2 & Figure 2).



Note: Data obtained from references [5,6,9].
Figure 2: IC50 values of marine plant extracts against cancer cell lines (µg/mL).

Table 2: Mechanisms of action of marine-derived anticancer agents.

Compound	Source	Mechanism	Cancer Type Tested	References
Fucoxanthin	<i>Sargassum horneri</i>	Induces apoptosis via caspase-3	Colon cancer	[5]
Avicquinone C	<i>Avicennia marina</i>	ROS generation, DNA damage	Breast cancer	[6]
Carrageenan	<i>Gracilaria corticata</i>	Cell cycle arrest	Cervical cancer	[9]

Technological Issues and Future Directions

The pharmacological potential of marine vegetation is often undermined by problems of compound extraction, reproducibility, and bioavailability [13]. To surmount the aforementioned limitations, new technologies such as metagenomics, omics-based profiling, and synthetic biology are increasingly being utilized [15-18]. These methodologies allow for detection of gene clusters involved in biosynthe-

sis, provide heterologous expression in model systems, and enhance the production of compounds. Interactions among marine biologists, pharmacologists, and bioengineers play a pivotal role to initiate translation of marine drug leads into clinics. Advances in eco-friendly extraction method and sustainable harvesting process will also be equally essential for large-scale production of such bioactive compounds (Table 3).

Table 3: Current biotechnological strategies for marine drug discovery.

Strategy	Application	Advantages	Limitations	References
Metagenomics	Gene mining from uncultured microbes	Novel compound discovery	Data complexity	[15]
Synthetic biology	Biosynthesis pathway reconstruction	Scalable production	High cost	[16]
Omics technologies	Metabolomics/proteomics profiling	Pathway elucidation	Requires expert analysis	[17]

Conclusion

Seaweeds represent an untapped treasure house of bioactive compounds with full anticancer and antimicrobial potential. Their metabolites possess multifaceted mechanism of action and are ideal leads for the establishment of new drugs. Yet more studies are essential to standardize extraction, ascertain in vivo activity, and assure sustainable harvesting. Future research integrating molecular biology, ecological modeling, and pharmacological screening will be of prime importance to unlock the entire potential of marine botanical therapeutics. With the increasing menace of antimicrobial resistance and the immediacy of identifying new antiviral drugs, marine plants are a special and precious platform to expand the pharmaceutical arsenal against infectious diseases and cancer.

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