OPEN ACCESS INTERNATIONAL JOURNAL OF SCIENCE & ENGINEERING

"A Review on the Anticancer Activity of Marine Algae from the Konkan Region Against Breast and Cervical Cancer Cell Lines''

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Abstract: ***Breast and cervical cancers continue to pose a significant health burden globally, particularly in developing countries such as India, where access to effective and affordable treatments remains a challenge. In this context, the marine ecosystem has emerged as a promising source of novel bioactive compounds with therapeutic potential. Among marine organisms, algae are known to produce a wide array of secondary metabolites with cytotoxic, antioxidant, and antiproliferative properties. This review aims to consolidate current research on the anticancer potential of marine algae, with a specific focus on algal species found along the relatively underexplored Konkan coast of Maharashtra, India. The purpose of this review is to provide a comprehensive overview of the cytotoxic activity of marine algal extracts, particularly their effectiveness against MCF-7 (breast cancer) and HeLa (cervical cancer) cell lines. Studies have demonstrated mechanisms such as apoptosis induction, disruption of mitochondrial function, generation of reactive oxygen species (ROS), and cell cycle arrest. These findings suggest that marine algae from the Konkan region may harbor unique compounds with potent anticancer activity. In conclusion, marine algae represent a valuable, yet underutilized, source of anticancer agents. While promising in vitro data exist, there is a need for further research including compound isolation, mechanistic studies, and in vivo evaluations. Exploring the bioactive potential of Konkan algae could pave the way for novel, cost-effective anticancer therapies.***

Keywords: Marine algae, Konkan coast, Breast cancer, HeLa cell line, Anticancer activity, Natural products, Cancer therapeutics

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INTRODUCTION

Cancer remains one of the leading causes of mortality worldwide, with breast and cervical cancers being particularly prevalent among women[1]. According to GLOBOCAN 2022 estimates, these cancers contribute significantly to global cancer incidence and mortality, with a disproportionately high burden in developing countries such as India[2]. Despite advances in medical treatment, including chemotherapy, radiotherapy, and surgical interventions, limitations such as drug resistance, adverse side effects, and recurrence continue to hinder therapeutic success[3]. As a result, there is an urgent need to explore alternative sources of anticancer agents that are both effective and less toxic[4].

Marine algae have emerged as a promising source of novel bioactive compounds with significant pharmacological potential[5]. These photosynthetic marine organisms produce a variety of unique secondary metabolites such as phlorotannins, fucoidans, alkaloids, and sulphated polysaccharides that have demonstrated anticancer properties in vitro and in vivo[6]. While much of the current research has focused on marine algae from globally recognized coastal regions, the Konkan coast of Maharashtra remains relatively underexplored despite its rich marine biodiversity[7]. This coastal belt, part of the Western Ghats, harbors a diverse range of marine algae species that may possess untapped anticancer potential[8].

This review aims to consolidate existing literature on the anticancer activity of marine algae, with a specific focus on studies involving breast (MCF-7) and cervical (HeLa) cancer cell lines[9]. It highlights the therapeutic promise of algae native to the Konkan coast, examines the known mechanisms of anticancer action (such as apoptosis induction, oxidative stress modulation, and cell cycle arrest), and identifies key research gaps that warrant further exploration[10].

The scope of this review includes in vitro studies involving crude or semi-purified extracts of marine algae, primarily targeting MCF-7 and HeLa cell lines[11]. It excludes synthetic derivatives, non-algal marine organisms, and in vivo clinical studies[12]. The goal is to provide a focused overview that will

guide future research efforts and support the development of algae-based anticancer therapeutics[13].

MATERIALS AND METHODS

A. Collection and Identification of Marine Algae

Marine algae samples have been collected from specific Konkan coastal sites within the Konkan region e.g., Ratnagiri and Sindhudurg. [*Jagtap, 1991; Untawale, 1980*]. Collected specimens will be cleaned to remove debris and epiphytes using fresh seawater and soft brushes to avoid damage, followed by proper preservation using 4% formalin or shade drying based on the intended analysis [*Dhargalkar & Pereira et al., 2005*]. Identification will be carried out using standard taxonomic keys and reference literature for morphological classification [*Silva, Basson & Moe, 1996*]. These bioactive extracts will then be subjected to in vitro anticancer assays on HeLa and MCF-7 breast cancer cell lines using assay methods to determine cell viability [*Mosmann 1983; Skehan et al., 1990*].

B. Preparation of Extracts

The collected algae have been shade-dried to preserve thermolabile and volatile bioactive components, ensuring minimal degradation during processing [*Kumar et al., 2015*]. The dried samples are then finely ground using an electric grinder to increase surface area for efficient solvent penetration during extraction [*El Shafay et al., 2016*]. Sequential extraction will be carried out using solvents of increasing polarity methanol, ethanol, chloroform, and water using Soxhlet or maceration techniques to isolate a broad spectrum of phytoconstituents [*Radhika et al., 2012; Shanab et al., 2012*]. Each solvent fraction will be filtered and concentrated under reduced pressure using a rotary evaporator and stored at 4°C for further phytochemical and biological assays [*Abd El-Baky et al., 2009*]. These extracts will then be screened for key secondary metabolites using standard qualitative phytochemical methods to determine the presence of alkaloids, phenols, flavonoids, tannins, saponins, and terpenoids [*Karthikeyan et al., 2015*].

C.Phytochemical Screening

The prepared marine algae extracts will undergo both qualitative and quantitative phytochemical analyses to assess the presence and concentration of bioactive secondary metabolites [*El-Baky et al., 2009*]. Standard phytochemical screening methods such as Mayer's and Wagner's tests for alkaloids, ferric chloride for phenolics and Alkaline Reagent tests for flavonoids, and Salkowski and Liebermann Burchard tests for terpenoids will be applied [*Karthikeyan et al., 2015; Sasidharan et al., 2011*]. Quantification of major constituents like total phenolic content and total flavonoid content has been measured using spectrophotometric methods [*Zubia et al., 2009*]. These bioactive compounds are often correlated with antioxidant, anti-inflammatory, and anticancer properties, supporting the therapeutic potential of marine algae [*Manivannan et al., 2008; Matanjun et al., 2010*]. Advanced analytical tools such as HPLC, FTIR may be used for further profiling and structural elucidation of active constituents in promising extracts [*Machado et al., 2015*].

D.In Vitro Anticancer Activity

Cytotoxic effects of the marine algal extracts have been evaluated using in vitro against breast cancer [MCF-7] and cervical cancer [HeLa] cell lines [*Sathya et al., 2017*]. The MTT assay will be employed to measure cell viability, where mitochondrial dehydrogenase activity reduces MTT to formazan crystals, indicating metabolic activity of viable cells [*Mosmann, 1983; modified by Denizot & Lang, 1986; Yuan et al., 2010*]. Decrease in cell viability will suggest anticancer potential and allow the calculation determine the effective concentration of algal extracts [*Hemaiswarya et al.,2011*]. Additional assays such as staining, DAPI staining, and flow cytometry may be utilized to assess apoptotic morphological changes [*Sanjeewa et al., 2017*]. Previous studies have shown that marine macroalgae, especially from the genera Gracilaria, Sargassum, and Ulva, exhibit significant anticancer activity by inducing apoptosis and inhibiting proliferation in various human cancer cell lines [*Abu-Serie & Habashy, 2020; Park et al.,2012*].

E. Sample Collection and Identification

Marine algae will be systematically collected seasonally from multiple sites along the Konkan coast, including regions such as Ratnagiri and Sindhudurg, to capture variations influenced by environmental parameters such as salinity, temperature, and tidal flow [*Subash Chandran et al., 2011*]. Sampling during different seasons ensures the collection of a representative diversity of species and bioactive profiles [*Sarma et al., 2007*]. Freshly collected samples will be washed thoroughly with seawater to remove sand, debris, and epiphytes, followed by a rise in sterile distilled water to eliminate surface contaminants [*Jha et al., 2009*]. Dried specimens will be stored in airtight containers and labelled appropriately for further analysis. [*Karthikai Devi et al., 2013*].Taxonomic identification will be performed using standard identification keys such as [*Krishnamurthy 2000*] and [*Rao & Gupta 2006*], and compared against authenticated herbarium specimens Expert consultation with marine botanists and phycologists will further validate species classification and avoid misidentification [*Mantri et al., 2011*].

F. Extraction of Bioactive Compounds

The shade-dried algal material will be finely ground using a mechanical grinder to increase the surface area for efficient extraction [*Karthika et al., 2015*]. The powdered biomass will then be subjected to extraction using either the Soxhlet apparatus or cold maceration technique, depending on the heat sensitivity of the bioactive compounds present [*Chennubhotla et al., 2009*]. Soxhlet extraction is particularly effective for exhaustive recovery, while cold maceration helps retain thermolabile phytochemicals [*Dewi et al., 2018*]. Sequential extraction will be performed using solvents of increasing polarity, such as hexane, chloroform, ethanol, methanol, and finally distilled water, to ensure a broad spectrum of secondary metabolites are isolated [*Mekinić et al., 2019*]. Each solvent

will be used with fresh algal material to prevent cross-contamination and maximize individual extract purity. The extraction process will typically run for 24–48 hours per solvent Post extraction, the solvent mixtures will be filtered followed by concentration under reduced pressure using a rotary evaporator at temperatures not exceeding 45°C to prevent degradation of sensitive compounds [*Wijesinghe & Jeon, 2012 & Rathore et al., 2021*].

G. Phytochemical Screening

The crude algal extracts will undergo preliminary phytochemical analyses to identify the major classes of secondary metabolites, including alkaloids, phenolics, flavonoids, terpenoids, saponins, and tannins, which are known to contribute to therapeutic and pharmacological effects [*Kumar et al., 2015*]. After confirming their presence, quantitative estimations will be carried out using UV spectrophotometry or colorimetric assays like the Folin Ciocalteu method for total phenolic content, and the aluminium chloride method for flavonoids [*Singleton et al., 1999; Chang et al., 2002*]. These methods will provide insights into the relative abundance of the phytochemicals and their variation across different solvent extracts. Furthermore, phytochemical profiles will help in correlating bioactivity with specific metabolite groups, thereby serving as a preliminary bio-guided tool for further purification and drug development studies [*Rathore et al., 2021*]. These screening processes are widely used in pharmacognosy for the standardization and evaluation of plant and algal based crude drugs [*Sasidharan et al., 2011*].

H. In Vitro Anticancer Activity

Selected crude algal extracts will be evaluated for their cytotoxic potential against human cancer cell lines, specifically MCF-7 [breast cancer] and HeLa [cervical cancer], which are widely used models for in vitro anticancer screening due to their consistent response to natural products [*Rajauria et al., 2011*]. After treatment with varying concentrations of extracts for 24–72 hours, MTT dye will be added, and the resulting formazan crystals will be dissolved in DMSO, followed by spectrophotometric measurement at 570 nm [*Mosmann, 1983*]. The percentage of viable cells will be calculated. Morphological changes such as membrane blebbing, chromatin condensation, and cell shrinkage will also be monitored under a phase-contrast microscope to detect apoptosis [*Elmore, 2007*]. These initial screenings provide a scientific basis for identifying promising marine algae with potential anticancer properties for further mechanistic or in vivo studies [*Senthilkumar & Kim, 2013*].

Thematic-Overview:

Algal Classification and Anticancer Properties

Marine algae are broadly classified into three main groups: brown [Phaeophyceae], red [Rhodophyceae], and green [Chlorophyceae], each characterized by distinct pigments, ecological roles, and unique profiles of bioactive compounds [*Guiry & Guiry, 2014*]. Brown algae, such as Sargassum spp. and Turbinaria spp., are rich in phlorotannins and sulphated polysaccharides like fucoidans, which have demonstrated significant anticancer effects through apoptosis induction, angiogenesis inhibition, and immune modulation [*Ale et al., 2011; Fitton, 2011*]. Red algae, including Gracilaria spp. and Laurencia spp., produce brominated metabolites, sulphated galactans, and halogenated compounds with cytotoxic properties against multiple cancer cell lines [*Francavilla et al., 2013; Plaza et al., 2010*]. Green algae such as Ulva spp. and Caulerpa spp. provide polyphenols, glycoproteins, chlorophyll derivatives, and terpenoids that exhibit antioxidant, antiproliferative, and apoptosis-inducing activities [*Ortiz et al., 2006; Yaich et al., 2011*]. Despite this pharmacological diversity, comparative analyses across these three algal groups remain limited, as most studies focus on individual species rather than cross-phyla evaluations that could reveal superior or synergistic anticancer potentials [*Shanmugam & Palpandi, 2008; Sudharsan et al., 2012*]. Moreover, India's Konkan coastal belt remains underexplored, though it may harbor novel or enhanced anticancer compounds due to its unique ecological conditions [*Patra et al., 2015*]. To bridge these gaps, systematic exploration, standardized extraction protocols, and molecular characterization of active constituents from Konkan algae are essential for unlocking new therapeutic avenues in cancer treatment.

A. Methodological Approaches in Anticancer Evaluation

Methodological approaches for evaluating the anticancer properties of marine algae typically begin with the extraction of bioactive compounds using solvents of varying polarities such as methanol, ethanol, chloroform, ethyl acetate, and water, which enable selective isolation of diverse phytochemicals including phenolics, terpenoids, alkaloids, flavonoids, and polysaccharides [*Kharkwal et al., 2012; Murugan & Iyer, 2014*]. Extraction efficiency is often enhanced by advanced techniques which not only improve yield but also preserve thermolabile bioactive compounds [*Sasidharan et al., 2011; Herrero et al., 2015*]. The resulting crude or fractionated extracts are subjected to preliminary phytochemical screening and chemical profiling through Thin Layer Chromatography [TLC], Fourier Transform Infrared Spectroscopy [FTIR], High-Performance Liquid Chromatography [HPLC], and Gas Chromatography Mass Spectrometry [GC-MS] for identification of functional groups and major constituents [*Guedes et al., 2013; Venkatesan et al., 2017*]. In parallel, morphological changes associated with cell death are assessed using fluorescence, confocal [*Senthilkumar & Sudha, 2012*]. Cytotoxicity and antiproliferative effects of algal extracts are most frequently assessed using the MTT assay [*Mosmann, 1983; Riss et al., 2016; Vijayabaskar & Shiyamala, 2011*]. Additionally, DNA fragmentation assays, reactive oxygen species [ROS] generation studies, and mitochondrial membrane potential assays further elucidate mechanisms of cell death [*Li et al., 2011; Heo et al., 2010*] Moreover, inconsistencies in extraction protocols, solvent selection, and choice of cancer cell lines hinder inter-study comparisons, while the influence of geographical and seasonal variation on algal biochemical profiles remains largely underexplored

[*Sathya et al., 2017; Patra et al., 2015*].

B. Temporal Trends in Marine Algal Anticancer Research

The trajectory of marine algal research in the context of anticancer activity has evolved significantly over the past two decades. Between 2000 and 2010, studies primarily explored the broad therapeutic properties of algae, including antioxidant, antimicrobial, and anti- inflammatory effects, with limited emphasis on cancer-specific applications. Research during this period was largely descriptive, focusing on crude extracts and preliminary phytochemical screenings without robust cell-based validations [*Gupta & Abu-Ghannam, 2011; Jiménez- Escrig et al., 2001*].

From 2011 to 2020, there was a marked transition toward more targeted in vitro anticancer investigations. Researchers increasingly used established human cancer cell lines such as MCF-7 [breast], HeLa [cervical], A549 [lung], and HepG2 [liver] to evaluate cytotoxic and antiproliferative effects of specific algal extracts [*Liu et al., 2012; Fernando et al., 2016*]. This period also saw wider application of biochemical assays including MTT, Trypan Blue exclusion, and LDH release, alongside flow cytometry for apoptosis detection and cell cycle arrest analyses. Advanced chromatographic and spectrometric tools such as HPLC, GC-MS, and FTIR were increasingly used to characterize bioactive constituents [*Wijesekara et al., 2011; Zubia et al., 2010*].Post-2020, the research landscape has further progressed toward molecular-level and mechanism-driven studies. In silico approaches such as molecular docking, molecular dynamics simulations, and ADMET predictions are now commonly employed to evaluate drug- likeness and predict mechanistic interactions of algal-derived compounds[*Suresh et al., 2021; Vijayabaskar & Vaseela et al., 2020*]. Simultaneously, sustainable extraction methods such as ultrasound-assisted, microwave-assisted, and ionic liquid-based extraction are being prioritized to minimize environmental impact [*Rodrigues et al., 2021; Sharma et al., 2022*]. Multi-omics approaches [transcriptomics, proteomics, metabolomics] and pathway-focused analyses targeting apoptosis cell death have also been integrated into modern research frameworks [*Zhu et al., 2021; Noda et al., 2020*]. While in vivo models such as zebrafish, mice, and rats are increasingly used to validate anticancer activity, their applications remain relatively limited compared to in vitro systems [*Kim et al., 2021; Heo & Jeon, 2020*].

Table no.1: Temporal Trends in Marine Algal Anticancer Research

Study	Time Period	Focus Areas	Techniques Used	Strengths	Limitations	Research Gaps
Kim *et al.* (2011)	2000–2011	1. General therapeutic properties (antioxidant, antimicrobial)	1.screening Use of crude extracts Simple solvent extraction.	1.Established baseline for marine algal bio activity.	1.No targeted anticancer testing.	1.Absence of cancer-cell line testing
Noda et al. (2020)	2011–2020	1. Shift to in vitro anticancer studies 2. Targeted testing on cancer cell lines.	1.TLC, FTIR, HPLC, GC-MS for compound profiling	1. Specificity screening 2. Reliable bio-assays and profiling tools	1. Variation in methods and solvents	1. Minimal studies on lesser-known coastal areas like Konkan
Bhavan et al. (2021)	Post-2020	1. Focus on green and sustainable extraction methods	1.Molecular docking and dynamics simulation	1. Improved environmental safety 2. High-throughput compound screening	1. Research clustered in East Asia and South India	1. Vey limited exploration of Konkan algae.

Table no.2: Comparative Table of Studies

Study	Algae Species	Region	Cell Line	Method/Mechanism	Key Finding
Kim *et al.* (2010)	Ecklonia cava	Korea	Colon	ROS - mediated apoptosis	High cytotoxicity
El Gamal (2010)	Laurencia obtusa	Egypt	MCF-7	MTT, DNA fragmentation	Apoptosis induction
Bhavan et al. (2016)	Sargassum, Ulva	Tamil Nadu	MCF-7	MTT assay	Strong methanol extract activity
Yang et al. (2013)	Brown algae (fucoidan)	China	HeLa	Cell cycle arrest	Inhibited S-phase

CONCLUSION AND FUTURE DIRECTIONS

CONCLUSION

This review underscores the growing recognition of marine algae as a sustainable and promising natural source of anticancer agents. Numerous studies across the globe and within India have demonstrated the bioactive potential of marine macroalgae, particularly brown [Phaeophyceae], red [Rhodophyceae], and green [Chlorophyceae] algae, in combating human cancers [*Zubia et al., 2010; Gupta & Abu-Ghannam, 2011*]. These organisms have shown notable cytotoxic effects against widely studied cancer cell lines such as MCF-7 [breast cancer] and HeLa [cervical cancer], with mechanisms of action including induction of apoptosis, cell cycle arrest, inhibition of proliferation, and modulation of oxidative stress pathways [*Ale et al., 2011; Kim & Thomas, 2015*]. Extraction methods, particularly those using methanol and ethanol, have been found especially effective due to their polarity and capacity to isolate key secondary metabolites like phlorotannins, terpenoids, and glycoproteins, many of which are strongly associated with anticancer activity in both in vitro and in silico studies [*Wijesekara et al., 2011; Suresh et al., 2021*].

Despite these advancements, a considerable regional gap persists in marine algal pharmacology, particularly along the Konkan coast of Maharashtra. This ecologically diverse and nutrient-rich coastal stretch along the Arabian Sea harbours extensive algal biodiversity owing to its tropical monsoon climate and varied intertidal habitats [*Chakraborty et al., 2015*]. However, scientific exploration into the pharmacological potential of Konkan algae remains limited, with only a few studies focusing on compound isolation, bioactivity screening, and anticancer evaluation. Consequently, the therapeutic potential of these locally abundant species remains largely untapped. To bridge this gap, systematic and interdisciplinary research integrating phytochemical analysis, molecular biology, pharmacological assays, and modern computational approaches is urgently required. Such efforts could unlock novel algal-derived anticancer compounds and significantly contribute to the global natural product-based drug discovery landscape [*Rodrigues et al., 2021; Sharma et al., 2022*].

Research-Gaps

Despite the promising anticancer potential of marine algae,

several critical research gaps persist. One of the most significant is the lack of systematic exploration and scientific documentation of marine algal species from the Konkan coast of Maharashtra. Although this coastline is ecologically rich and harbours diverse marine flora, very few studies have investigated its algal biodiversity for pharmacological or anticancer potential [*Chakraborty et al., 2015; Jagtap et al., 2019*]. Another major limitation is that most existing investigations remain restricted to in vitro assays, with little to no in vivo validation or clinical translation, which severely limits the applicability of findings to therapeutic development [*Fernando et al., 2016; Rodrigues et al., 2021*]. Research on the synergistic effects of combined algal extracts or the integration of algae-derived compounds with nanotechnology remains scarce, despite the potential of algal-nanoparticle systems to enhance bioavailability and improve cellular targeting efficiency [*Kadam et al., 2013; Paul et al., 2020*]. Similarly, a lack of standardized extraction and screening protocols continues to hinder reproducibility and comparative evaluation across studies, as variability in solvent systems, extraction techniques, and assay conditions often produces inconsistent outcomes [*Wijesekara et al., 2011; Suresh et al., 2021*]. To address these challenges, there is a pressing need for high-throughput, harmonized methodologies that integrate advanced chromatographic, spectrometric, and molecular tools, thereby accelerating compound discovery and enabling translational progress toward drug development from marine algae [*Kim & Thomas, 2015; Sharma et al., 2022*].

Future Research Directions

Future research on marine algal anticancer potential should prioritize comprehensive biodiversity surveys along the Konkan coast to document, catalogue, and taxonomically profile native algal species, along with their ecological characteristics [*Chennubhotla et al., 2013; Jagtap et al., 2019*]. Such baseline data would provide a foundation for the identification of promising candidates for pharmacological screening. Once potential species are identified, bioassay-guided fractionation should be employed to isolate, purify, and characterize active anticancer compounds using advanced chromatographic and spectrometric techniques [*Kumar et al., 2015; Mhadhebi et al., 2014*]. To ensure translational success, strong interdisciplinary collaboration is vital, bringing together marine biologists, natural product chemists, pharmacologists, and oncologists to bridge the gap between basic research and clinical application [*Fernando et al., 2016; Sharma et al., 2022*]. Such integrated efforts will accelerate the development of algae based therapeutic agents and contribute significantly to natural product driven cancer drug discovery. Additionally, future studies should incorporate modern in silico [*Kim & Thomas, 2015; Rodrigues et al., 2021*]. These computational approaches can considerably reduce both time and cost by prioritizing molecules for laboratory validation. The integration of omics technologies—genomics, proteomics, and metabolomics—can further unravel the mechanisms of action of algal compounds at the molecular level, providing insight into their modulation of cancer-related pathways [*Li et al., 2019; Wang et al., 2021*]. Moreover, the inclusion of in vivo models such as zebrafish and rodents for efficacy and toxicity testing will be essential to progress beyond cell-based assays toward preclinical development [*Kadam et al., 2013; Suresh et al., 2021*]. Such a multi-tiered, interdisciplinary approach will not only deepen the scientific understanding of marine algal pharmacology but also facilitate the discovery of novel, safe, and effective anticancer therapeutics derived from India's underexplored coastal biodiversity.

Reported Anticancer Activity of Marine Algae

Numerous studies conducted both globally and within India have established the significant anticancer potential of marine algae, highlighting their role as promising sources of bioactive compounds. [Kim *et al*. 2010] demonstrated that phlorotannins extracted from the brown alga [*Ecklonia cava et al*. 2009] effectively induced apoptosis in colon cancer cells, revealing their potential for targeted therapy. Similarly, [El Gamal 2010] reported notable cytotoxic effects in MCF-7 breast cancer cells when treated with extracts from the red alga *Laurencia obtusa*, attributing the activity to brominated metabolites. In the Indian context, [*Bhavan et al.* 201] evaluated the methanolic extracts of *Ulva lactuca* [green algae] and *Sargassum wightii* [brown algae], both of which exhibited significant cytotoxicity against breast cancer cell lines, suggesting the presence of potent anticancer compounds in locally available species. Furthermore, [*Yang et al. 2013*] found that fucoidan, a sulfated polysaccharide from brown algae, disrupted cell cycle progression in HeLa cervical cancer cells, underlining its role in inhibiting tumor cell proliferation. These findings collectively support the therapeutic potential of marine algae and justify further investigation into their anticancer mechanisms, especially in underexplored coastal regions like the Konkan belt.

Furthermore, establishing well curated marine algal biobanks and compound libraries could significantly support long-term research and development initiatives. Such repositories would allow for the preservation of diverse species, enable reproducible studies, and provide readily accessible material for both national and international collaborations. Alongside biobanking, implementing standardized regulatory frameworks and ethical guidelines for sustainable harvesting is crucial to prevent ecological imbalance and ensure the conservation of marine ecosystems. Engaging local communities in algal collection and conservation efforts could foster regional participation, create socio economic opportunities, and promote responsible utilization of coastal resources. By integrating biodiversity preservation, resource management, and advanced scientific approaches, future research can ensure that the exploration of marine algae as anticancer agents is both scientifically robust and environmentally sustainable.Marine algae-based compounds also hold promise for combinatorial therapies, where they can be used alongside conventional

chemotherapeutic agents to enhance efficacy and reduce side effects. Recent studies have highlighted the ability of algal polysaccharides and phenolic compounds to act as immunomodulators.

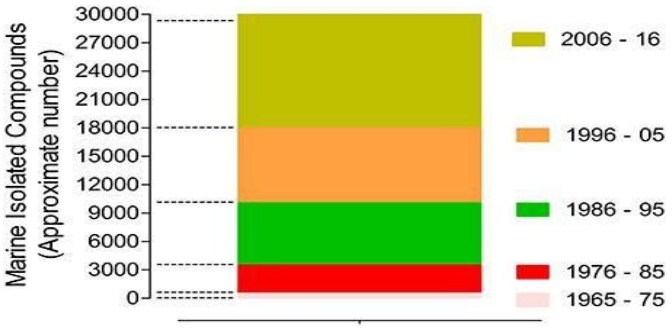

Figure 1. Marine compounds isolated in the last 50 years (approximate number/10 years) (Faulkner, 1984, 1986, 1987, 1988, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002; Blunt et al., 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018).

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